

**DYNAMIC ADJUSTMENT OF TEMPORAL PREPARATION  
IN THE VARIABLE-FOREPERIOD PARADIGM**

**DISSERTATION**

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## LIST OF ABBREVIATIONS

FP	foreperiod
FP <sub>n-1</sub>	foreperiod of the preceding trial
FP <sub>n</sub>	foreperiod of the current trial
IS	imperative signal
WS	warning signal
RT	reaction time

## AUFBAU DER VORLIEGENDEN ARBEIT

Die vorliegende Arbeit wird in Form einer kumulativen Dissertation eingereicht und enthält fünf bereits veröffentlichte Studien mit insgesamt 19 Verhaltensexperimenten. Alle fünf Studien beschäftigen sich mit dem Thema der zeitlichen Handlungsvorbereitung, insbesondere dem Effekt eines variablen Vorperiodenintervalls auf die Reaktionszeit in Einfach- und Wahlreaktionszeitaufgaben. Global geht es um die Dynamik der Vorbereitung, konkret um die im bezeichneten Paradigma beobachtbare sequenzielle Beeinflussung der Reaktionszeit durch vorangehende Vorperiodenlängen. In Studie 1 wurde die Dynamik der Handlungsvorbereitung vergleichend in sehr kurzen und langen zeitlichen Kontexten untersucht. Studien 2 und 3 befassen sich mit der Rolle von Warnsignalen bei der zeitlichen Vorbereitung. Die Studien 4 und 5 befassen sich mit zwei wichtigen Einflussvariablen, dem Effekt von Distraktoren während des Vorperiodenintervalls und dem Effekt kontextueller zeitlicher Unsicherheit auf die Effizienz von Vorbereitungsprozessen. Die fünf Studien stellen das Primärthema der vorliegenden Dissertation dar. Sie entstanden während meiner Zeit als Doktorand in der Abteilung für Allgemeine und Biologische Psychologie der Universität Tübingen.

### Veröffentlichungen (Studien 1 bis 5)

- (1) Steinborn, M. B., Rolke, B., Bratzke, D., & Ulrich, R. (2008). Sequential effects within a short foreperiod context: Evidence for the conditioning account of temporal preparation. *Acta Psychologica, 129*, 297-307.
- (2) Steinborn, M. B., Rolke, B., Bratzke, D., & Ulrich, R. (2009). Dynamic adjustment of temporal preparation: Shifting warning signal modality attenuates the sequential foreperiod effect. *Acta Psychologica, 132*, 40-47.
- (3) Steinborn, M. B., Rolke, B., Bratzke, D., & Ulrich, R. (2010). The effect of a cross-trial shift of auditory warning signals on the sequential foreperiod effect. *Acta Psychologica, 134*, 94-104.
- (4) Steinborn, M. B., & Langner, R. (2011). Distraction by irrelevant sound during foreperiods selectively impairs temporal preparation, *Acta Psychologica, 136*, 405-418.
- (5) Steinborn, M. B., & Langner, R. (2012). Arousal modulates temporal preparation under increased time uncertainty: Evidence from higher-order sequential foreperiod effects. *Acta Psychologica, 139*, 65-76.

## ZUSAMMENFASSUNG

Die Darbietung eines Warnsignals (WS) verkürzt bekanntlich die Reaktionszeit auf ein nachfolgendes imperatives Signal (IS), auf das reagiert werden soll, selbst wenn es keinerlei Informationen über die Art der auszuführenden Reaktion beinhaltet. Dies wird auf einen durch das WS induzierten Prozess der zeitlichen Handlungsvorbereitung zurückgeführt, welcher Personen dazu befähigt, einen internen Zustand optimaler Reaktionsbereitschaft zeitlich mit dem Erscheinen des IS zu synchronisieren. Es gibt Hinweise dafür, dass der Aufbau dieser sogenannten zeitlichen Erwartungen dynamisch angepasst werden kann, um so einer zeitlich unsicheren Umwelt gerecht zu werden. Variiert man zum Beispiel das Zeitintervall zwischen WS und IS (d.h., die Vorperiode, VP) innerhalb eines Experimentalblocks (variables VP-Paradigma), dann ist die resultierende Reaktionszeit eine abfallende Funktion der Vorperiodenlänge. Dies wird als der *variable Vorperiodeneffekt* bezeichnet. Gemäß einer klassischen Sichtweise (strategisches Modell) resultiert der variable VP-Effekt daher, dass über den Verlauf der VP die bedingte Wahrscheinlichkeit für die Darbietung des IS monoton zunimmt. Personen sind demgemäß in der Lage, den objektiven Anstieg dieser Wahrscheinlichkeit strategisch zu überwachen und für die Erhöhung ihrer Reaktionsbereitschaft zu nutzen.

Das strategische Modell bietet jedoch keine plausible Erklärung für die ebenfalls beobachteten Sequenzeffekte der VP-Länge. Die Reaktionszeit im variablen Vorperiodenparadigma ist nämlich nicht nur durch die Länge der Vorperiode im aktuellen Durchgang ( $VP_n$ ) beeinflusst, sondern auch durch die Vorperiodenlänge des vorangegangenen Durchgangs ( $VP_{n-1}$ ). Dieser Sequenzeffekt ist zudem asymmetrisch: Geht einem Durchgang mit kurzer  $VP_n$  ein Durchgang mit langer  $VP_{n-1}$  voran, dann sind die Reaktionen auf das IS sehr langsam; geht einer kurzen  $VP_n$  jedoch eine kurze  $VP_{n-1}$  voran, dann sind die Reaktionen besonders schnell. Bei einem Durchgang mit langer  $VP_n$  gibt es dagegen keine sequenzielle Modulation, die Reaktionen sind konsistent schnell, unabhängig von der Länge der  $VP_{n-1}$ . Dies wird als der (asymmetrische) *sequenzielle Vorperiodeneffekt* bezeichnet. Zwei aktuelle **Erklärungsansätze** sind diesbezüglich aufgestellt worden: Gemäß eines *Trace-Conditioning*-Modells ergibt sich der Effekt aus assoziativem Lernen von Zeitdistanzen. Die Basisannahme ist, dass die Distanz zwischen WS und IS gelernt und von Durchgang zu Durchgang adaptiert wird. Gemäß des *Dual-Process*-Modells ist jedoch eine über Durchgänge variierende motorische (Vor-)Aktivierung ursächlich für die sequenzielle Variation der Reaktionszeiten. Die Basisannahme ist, dass sich der Grad an allgemeiner Aktiviertheit nach einer kurzen  $VP_{n-1}$  erhöht (bzw. weniger verringert), nach einer langen  $VP_{n-1}$  jedoch stark verringert. Erstere Bedingung resultiert in schnellen, letztere in langsamen Reaktionen. Zur Erklärung des variablen Vorperiodeneffekts wird hierbei auf die klassische Annahme einer strategischen Überwachung (Monitoring) konditionaler Wahrscheinlichkeiten (strategisches Modell) zurückgegriffen. Die charakteristische Asymmetrie des sequenziellen Vorperiodeneffekts entsteht dem Modell gemäß aus der Kombination beider Prozesse.

Das **Ziel der vorliegenden Arbeit** war es, die mit der Dynamik der zeitlichen Handlungsvorbereitung in Zusammenhang stehenden Mechanismen genauer zu beleuchten. In allen 19 Experimenten kam ein variables Vorperiodendesign als Basisdesign zum Einsatz: Die Darbietung eines WS markiert den Beginn der VP, nach deren Verstreichen dann das IS erscheint, auf das eine Einfach- bzw. Wahlreaktion zu erfolgen hat. Ein sich anschließendes Intertrial-Intervall separiert aufeinander folgende Durchgänge voneinander. In **Studie 1** wurde die Rolle des zeitlichen Kontexts (d.h. des zeitlichen Rahmens, der sich durch einen Satz VPs definiert) bei der Handlungsvorbereitung untersucht. Gemäß der Literatur zum klassischen Konditionieren gilt, dass kurze Zeitabstände ( $< 1000$  ms) effektiver gelernt werden als lange Zeitabstände, es ist jedoch bislang unklar, ob sich dies auch auf Reaktionszeitstudien generalisieren lässt. Im Hauptergebnis fand sich ein sequenzieller Vorperiodeneffekt sowohl in einem kurzen Zeitkontext (VPs: 200, 400, 600 ms) als auch in einem langen Zeitkontext (VPs: 1200, 2400, 3600 ms). Im langen Zeitkontext war die asymmetrische Sequenzmodulation jedoch kleiner. Konsistent mit bisherigen Studienergebnissen fand sich diese Sequenzmodulation jedoch nicht mehr, wenn die Abstandsbreite der VPs sehr eng gewählt wurde (VPs: 300, 400, 500 ms). In den **Studien 2 und 3** wurde die Rolle spezifischer Eigenschaften des WS bei der zeitlichen Vorbereitung untersucht. Es ging um die Frage, inwieweit die Initiierung von Vorbereitungsprozessen von Merkmalen des WS abhängt. Gemäß einem strategischen Modell nimmt das WS die Rolle eines symbolischen Startpunkts ein, der einer Person den Beginn der Vorbereitungsphase signalisiert. Aus Sicht des Trace-Conditioning-Modells jedoch agiert das WS als ein Abrufreiz, indem es Gedächtnisinhalte automatisch aktiviert, die im vorherigen Durchgang mit dem WS assoziiert waren. Es zeigte sich, dass ein Wechsel der WS-Modalität über Durchgänge zu einer beeinträchtigten Vorbereitung in Durchgängen mit kurzer  $VP_n$  führt, nicht jedoch bei langer  $VP_n$  (indiziert durch eine spezifische Modulation des sequenziellen Vorperiodeneffekts).

In **Studie 4** wurde der Effekt von kontinuierlicher auditiver Stimulation während des VP-Intervalls untersucht. Grundsätzlich sollte die damit einhergehende Distraction zu einer Beeinträchtigung der Performanz führen. Gemäß des Dual-Process-Modells sollte sich jedoch eine selektive Beeinträchtigung der Performanz in langen  $VP_n$ -Durchgängen zeigen, was auch der Fall war. In der Bedingung mit auditiv gefüllter (verglichen zu ungefüllter) VP kam es zu einer Abflachung des variablen Vorperiodeneffekts. Dies zeigt, dass Vorbereitungsprozesse beeinträchtigt sind, wenn Aufmerksamkeit anderweitig gebunden wird. In **Studie 5** wurde die Reaktionsleistung in kurzen und langen zeitlichen Kontexten und als Funktion mehrerer vorangehender VP-Längen untersucht. Gemäß des Dual-Process-Modells sollte die Effizienz des Überwachungsprozesses abnehmen, je mehr Durchgänge mit langen VPs nacheinander folgen, und dieser Effekt sollte umso stärker ausfallen, je größer der zeitliche Kontext ist. Diese Annahme konnte empirisch bestätigt werden. **Zusammenfassend** sprechen die vorliegenden Ergebnisse gegen die Annahmen des klassischen strategischen Modells. Auch ein weiterentwickeltes Dual-Process-Modell kann nicht alle Ergebnisse hinreichend erklären. Vielmehr stützen die Ergebnisse ein Erklärungsmodell, welches die Bedeutung von zeitpunktspezifischem Lernen betont.

## ABSTRACT

The presentation of a warning signal (WS) usually shortens the reaction time (RT) to a subsequently presented imperative signal (IS), even if the WS is neutral and contains no information about the type of stimuli to be processed or responses to be made. This effect is attributed to a process of (nonspecific) temporal preparation, which enables individuals to synchronize their internal state of optimal readiness with the moment of IS presentation. There is evidence that a state of optimal preparedness can dynamically be adjusted from trial to trial. For example, if the interval between WS and IS, termed foreperiod (FP), is varied randomly across trials, then RT is a decreasing function of FP length. This is known as the *variable-FP effect*. According to a traditional view (strategic-preparation model), the effect arises because the conditional probability that the IS occurs at a certain moment increases monotonously across trials. It is assumed that individuals are capable to strategically monitor this objective probability increase and to adjust response readiness accordingly. The exact mechanism underlying such monitoring, however, is still a matter of debate.

The strategic-preparation model, however, cannot explain the sequential effects of FP length, which also occur in the variable-FP paradigm. In particular, responses in the variable-FP situation have been observed to not only depend on current FP ( $FP_n$ ) length but also on the FP length of the preceding trial ( $FP_{n-1}$ ): Typically, 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. This is known as the sequential foreperiod (FP) effect. Two models are currently debated concerning the mechanisms underlying the sequential FP effect. According to a trace-conditioning model, the effect arises from a process of associative learning of temporal events. The basic assumption is that the temporal relationship between WS and IS is adjusted from trial to trial. According to the dual-process model, however, the effect arises from the combined contribution of strategic preparation (conditional-probability monitoring) and trial-to-trial changes in (motoric) arousal, resulting from temporal spacing of responses in preceding trials. 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 (detrimental) after-effects of deliberate preparation during the previous trial. On long- $FP_n$  trials, responses are assumed to be 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.

**The aim of the present work** was to examine the mechanisms underlying dynamic temporal preparation in more detail. To this end, 19 experiments were conducted. In all these experiments, the following standard variable-FP design was employed: A WS announced the beginning of the preparatory interval (FP), after which the IS was presented (to which participants had to make a speeded response). The task was either a simple-RT or choice-RT task. Trials were separated by an intertrial interval.



In **study 1**, temporal preparation was examined as a function of the temporal context (i.e., defined as the uncertainty imposed by a particular set of variable FPs). According to the literature on trace conditioning, short intervals can be learned more effectively than long ones. It was unclear, however, whether this effect could be generalized to a variable-FP situation. As a result, an asymmetric sequential FP effect was observed in both short (FPs: 200, 400, 600 ms) and long (FPs: 1200, 2400, 3600 ms) temporal contexts. However, the asymmetry of the effect was smaller in the short than in the long context, and even disappeared when a very dense FP-set was used (FPs: 400, 500, 600 ms). In the **studies 2 and 3**, the effective role of the WS in the process of preparation was examined. It was asked whether the initiation of preparatory activity depends on surface features of the WS. According to a strategic-preparation view, the WS acts as a symbolic cue that announces the beginning of the FP interval. According to a learning-based view, however, the WS acts as a retrieval cue that unintentionally activates stored memories that became specifically associated with the given WS on the previous trial. Consistent with the latter view, it was shown that a shift (compared to a repetition) of WS modality across trials hampered the efficiency of temporal preparation, particularly on short-FP trials. This effect was observed also when the shift was within the auditory modality, even when intensity was held equal.

In **study 4**, the effect of continuous auditory stimulation during the FP interval on RT performance in a variable-FP task was examined. According to a dual-process model, irrelevant sound should distract individuals from preparatory processing, which should yield a performance decrement particularly on long-FP trials. The trace-conditioning model does not explicitly incorporate sensory-stimulation effects during the FP. One could, however, argue that if preparatory processing is fairly automatic, it should not be affected by irrelevant sound. Across all experiments, a filled FP (compared to a blank FP) selectively yielded an RT decrement on long-FP trials, consistent with the dual-process model. In **study 5**, performance was examined in a short versus long FP context and additionally as a function of the amount of preceding long-FP trials (higher-order sequential FP effects). According to the dual-process model, the efficiency of the strategic monitoring process should decrease with increasing FP context, and this effect should additionally be affected by the amount of preceding long-FP trials. The results confirmed this assumption, in line with the predictions of the dual-process model. Taken together, the present results of five studies (including 19 experiments) strongly argue against the assumption of the classic strategic-preparation model of variable-FP phenomena. The results can partly be accounted for by the dual-process model (which expands the assumption of the classic model), but also this model cannot sufficiently explain the effect of WS modality shifts on performance. Overall, the results may support a theoretical view that emphasizes the role of time-point specific learning (reinforcement) as source of sequential-FP phenomena.

## CONTENTS

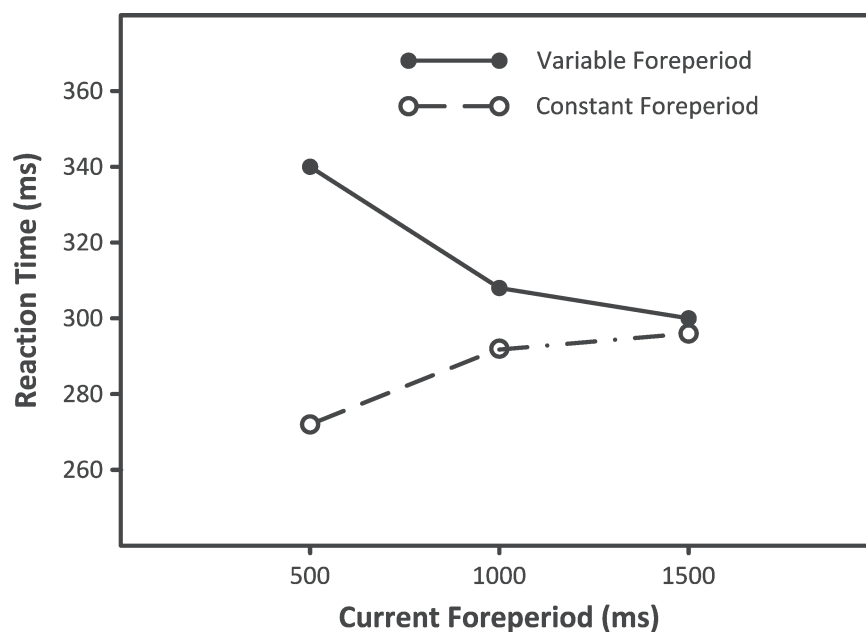
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## 1 INTRODUCTION

Speeded actions are especially effective if they can be prepared in advance. For that reason, processes related to response preparation are particularly important for several kinds of sport. A 100-m sprinter, for example, has to anticipate the starting signal to be optimally prepared at the time when it actually occurs. So the athlete has to orient to the auditory modality in order to optimally process the starting signal. Moreover, he or she has to activate cognitive rules and behavioral programs related to the starting signal. Finally, the athlete has to raise muscle tension in order to get out of the starting block with maximal power. Hence, preparatory activity contains several aspects such as a tuning of the input systems, an increase of overt attention, as well as a mobilization of muscular activity, with the precise contribution of each of these processes depending on the particular kinds of demand. The literature on preparatory processes often distinguishes between processes related to non-specific (temporal) and specific (event) preparation. While the former concept refers to a rather global “energization” of mental and bodily processes, the latter refers more to the fragmented activation of specific modules or functions that are directly related to the task at hand. The present case is an instance of non-specific preparation of a speeded action, since the athlete knows exactly which actions are to be performed, and only the optimal synchronization of the optimal state of readiness with the starting signal is critical for performance (Buckolz & Vigars, 1987).

How people manage to prepare for upcoming events has been subject to laboratory research since the beginning of the 20th century. It has, for example, long been known that a warning signal (WS) speeds up responding to an imperative signal (IS), compared to a condition where no WS is given in advance. The WS may be of auditory or visual modality and the IS may require a simple or a choice decision. The beneficial effect of a WS on performance occurs even when the WS is neutral and does not inform about kinds of stimuli or responses but only about the moment of IS occurrence (usually termed the *imperative moment*). The interval between WS and IS onsets is often termed the foreperiod (FP), which enables individuals to establish an internal state of increased readiness at the moment where the IS is expected to occur. The beneficial effects of a WS are observed even when the imperative moment is not (or only partly) predictable, that is, when there is uncertainty about the exact moment of IS occurrence. When the FP interval is constant across trials, temporal uncertainty is primarily related to the time-estimation process (i.e., the precision by which the IS can be anticipated). When the FP interval is variable across trials, however, individuals are mainly left uncertain about the exact moment at which the IS will occur after the WS in a current trial. Klemmer (1956; 1957) referred to the former case (constant-FP paradigm) as type I temporal uncertainty and to the latter case (variable-FP paradigm) as type II temporal uncertainty.

Woodrow (1914) had already observed that reaction time (RT) varied systematically with the length of the FP interval, with the direction of this relationship being dependent on the specific experimental condition. In his study, an auditory WS preceded an auditory IS to which participants had to respond, and RT was measured as index of performance. When the FP interval was constant within a block of trials (and varied only between blocks of trials), responses were faster with short FPs compared to a condition with long FPs. When the FP was variable within blocks of trials, however, the relationship reversed, since responses were slow in short-FP trials but fast in long-FP trials. These findings – an upward-sloping FP–RT function in the constant-FP paradigm and a downward-sloping FP–RT function in the variable-FP paradigm (see Figure 1) – have repeatedly been shown and differentiated by many researchers (cf. Niemi & Näätänen, 1981). It is generally assumed that RT reflects the degree of readiness at specific time points, which can experimentally be varied by manipulating FP length and variability as well as stimulus features of the WS and the IS (i.e., stimulus modality, intensity, duration, etc.).



**Figure 1:** A typical pattern of results: Reaction time as a function of foreperiod (FP) length, separately displayed for a constant-foreperiod (FP) condition and for a variable-foreperiod (FP) condition.

## 2 THE CONCEPT OF TEMPORAL PREPARATION

The efficiency of speeded action does not only depend on features of currently occurring events (e.g., stimulus properties, such as salience, intensity, etc.) but also on the opportunity to anticipate the moment of occurrence of these events in advance. In general, it is widely agreed that individuals prepare responses based on predictions, expectations, and beliefs about future events. These expectations are either established internally (based on learned predictive relationships in the environment) or externally provided by appropriate cues that deliver advance information about properties of impending events. In general, any possibility to prepare in advance for future events is of great advantage because the actual execution of relevant components of an action is facilitated by advance preparation. The concept of temporal preparation has many facets and can further be differentiated (Niemi & Näätänen, 1981). First, researchers distinguish between the intensity and the selectivity of preparatory processes. The aspect of intensity describes the strength of a general energization of cognitive processes, construed as a global enhancement of alertness and responsiveness due to a neutral WS. The aspect of selectivity describes processes of anticipatory modulation of specific mental representations. The individual contribution of either the intensity or selectivity of a preparatory state depend on various experimental conditions such as the properties of the task, the degree of advance knowledge provided, as well as established expectations due to previous experience.

In a pioneering study, Posner and Boies (1971) have examined the relationship between the intensity and selectivity of preparation in the forewarned letter-matching task. In the simplest version of this task, a warning announced the beginning of a particular trial (i.e., it started the FP interval) and two letters (e.g., AA, AB, etc.) were visually presented as the IS. The participants had to decide whether the stimuli were identical (yes-response) or not (no-response). The critical manipulation was the length of the FP interval as well as the information about IS properties that was provided by the WS at the beginning of each trial. Both temporal preparation (induced by a WS at short vs. long FP) and selective preparation (induced by advance knowledge about IS identity) improved RT performance – but in rather different ways. Temporal preparation without advance knowledge improved RT performance for both matching and non-matching letter pairs (the fastest responses were observed at 500 ms). Selective preparation, however, resulted in improved performance only when the cue validly indicated the IS, compared to a condition where the cue provided invalid information about the IS. Interestingly, the disadvantageous effects of an invalid cue were (under some circumstances) larger with low than with high temporal uncertainty. These findings indicate that a high degree of non-specific (temporal) preparation at the moment of IS occurrence usually facilitates performance, but this relationship can be reversed by experimental manipulations that induce wrong expectations about IS properties, or when attention is misdirected from processing task-relevant features.

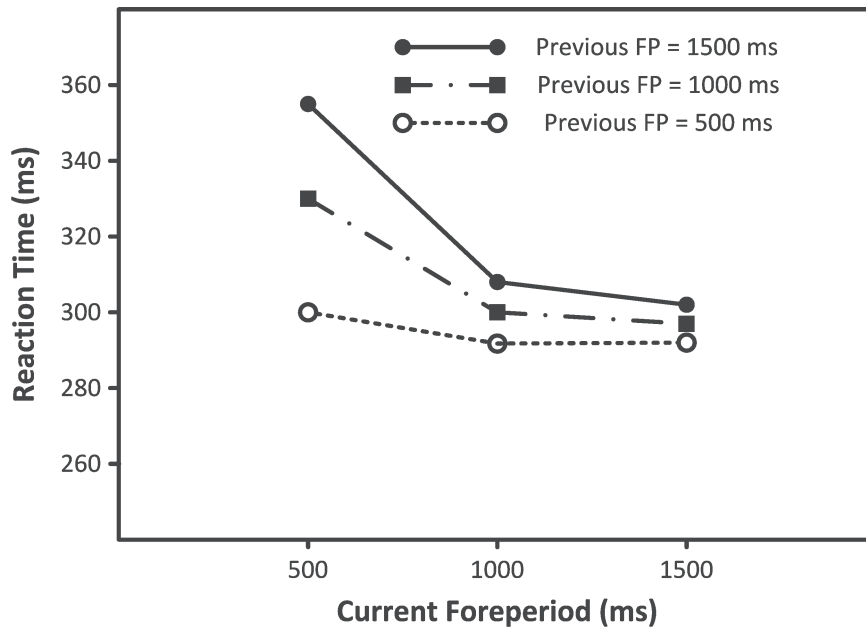
A special case of temporal preparation may be the selective orienting of attention to certain time points (i.e., FP durations) after the WS, often referred to as temporal orienting of attention (Coull & Nobre, 1998; Nobre, 2004). Several studies have provided evidence that attention can also be exclusively directed to the endpoints of certain FP durations, without providing information about IS or response features. In a highly regarded study, Miniussi et al. (1999) have asked their participants to make a speeded response (simple-RT task) to a visually presented IS that occurred randomly across trials at either a short (600 ms) or long (1400 ms) FP duration. A temporal cue, given before each trial, informed the participants that the current trial will either be a short-FP trial or a long-FP trial. In 80% of the trials, the cue indicated the current FP length validly, while in 10% of the trials, the cue provided invalid information about FP length. The remaining 10% of the trials were catch trials (i.e., trials where no IS occurred after the response). On short-FP trials, participants were faster when the cue indicated the current FP length validly, compared to when it delivered invalid information. On long-FP trials, however, there was no such effect, since participants were always fast in both valid- and invalid-cue conditions. In other words, a valid cue facilitated performance on short-FP trials while it had no additional effects on performance on long-FP trials. An invalid cue, on the other hand, hampered performance only on short-FP trials while it had no negative influence on long-FP trials. It should be mentioned here that Correa et al. (2006) further demonstrated that cue validity can also affect performance on long-FP trials if the percentage of catch trials was considerably increased (relative to the other trials).

This asymmetric cue validity effect on performance in short-FP trials (compared to long-FP trials) has often been explained by assuming that individuals make use of the objective increase in the conditional probability of IS occurrence over time, which occurs in situations with randomly varying FP length. More precisely, it has been argued that the downward-sloping FP-RT function arises because individuals transform the objective increase in conditional probability (*hazard rate*) into a subjective expectation that guides their preparation from the beginning to the end of the FP interval in a current trial. That is, the more time has already passed during the FP without IS occurrence, the greater the objective probability of IS presentation at any later imperative moment (Näätänen, 1970; Requin & Granjon, 1969). To illustrate this point, imagine a situation (a simple- or choice-RT experiment) where the IS will be presented with equal a-priori probability at three imperative moments, say 1000, 2000, or 3000 ms after the WS. At the first imperative moment (i.e., 1000 ms after the WS), the probability of IS occurrence is 33% (and 66% that it will be presented later). In trials where the first imperative moment is bypassed, the probability that the IS will occur at the next one (i.e., 2000 ms after the WS) increases to 50%. When this moment is also bypassed, participants can be entirely certain that the IS will be presented at the latest imperative moment (i.e., 3000 ms after the WS). The typical pattern observed in this situation is a decrease of RT with increasing FP length.

### 3 DYNAMIC ADJUSTMENT OF TEMPORAL PREPARATION

The robust finding of a downward-sloping FP–RT function in the variable-FP paradigm has been taken as evidence that individuals are capable to establish an internal prediction model based on a process of conditional-probability monitoring during the FP interval, and to prepare responses based on expectancies that are derived from this model (Näätänen, 1970; Nickerson, 1967; Rabbitt & Vyas, 1980; Requin & Granjon, 1969). According to this traditional view, individuals strategically track the objective increase in the conditional probability of IS occurrence and transform the objective values into a subjective representation. This process is assumed to require attentional resources and is subjectively experienced as effortful (Stuss et al., 2005; Vallesi & Shallice, 2007; Vallesi, Shallice, & Walsh, 2007). For example, when resources are reduced for some reason (e.g., by means of cognitive load, distraction, etc.), the monitoring process is assumed to run less efficiently, and a flattening of the FP–RT function is predicted in such conditions. A related process is described by Coull and Nobre (1998), who proposed that individuals are able to intentionally orient attention to expected imperative moments after the WS in variable-FP settings, based on information provided by a temporal cue. In contrast to the conditional-probability monitoring process, where individuals have to establish expectancies by exploiting implicit information, the temporal-orienting view is based on explicit information given in advance of a trial.

Although the mechanism proposed by the classic strategic-preparation model is widely employed to explain the downward-sloping FP–RT function, it has a fundamental weakness since the strategic-preparation account remains rather silent regarding another phenomenon that also occurs in the variable-FP paradigm. In fact, it has been shown that the slope of the FP–RT function arises – at least to some degree – from sequential effects of FP length (Alegria & Delhaye-Rembaux, 1975; Los & Agter, 2005). In a pioneering study, Mowrer (1940) had his participants respond as fast as possible (simple-RT task) to an IS that occurred randomly between intervals of up to 12 s. He observed faster responses in trials where the IS occurred earlier in time than in the preceding trial, compared to trials where the IS in the current trial occurred later than in the preceding trial. He argued, therefore, that individuals' expectations about the moment of IS occurrence might be subject to a dynamic interplay between stable and variable expectancies that may arise from processes of associative learning of temporal intervals experienced during the experiment. Indeed, subsequent studies actually found that RT does not only depend on FP length in the current trial (i.e.,  $FP_n$ ) but also on FP length in the preceding trial (i.e.,  $FP_{n-1}$ ). This so-called *sequential FP effect* refers to the fact that responses on short-FP trials are slower when preceded by a long  $FP_{n-1}$  than when preceded by an equally long or shorter one. The effect is asymmetric, since responses only vary on short- $FP_n$  trials but are virtually unaffected by  $FP_{n-1}$  length on long- $FP_n$  trials (see Figure 5).



**Figure 2:** A typical pattern of results in the variable-foreperiod (FP) paradigm: Reaction time as a function of current FP length, separately displayed for short (500 ms), medium (1000 ms), and long (1500 ms) FPs.

Although several post-hoc explanations have been offered to explain the sequential FP effect (Niemi & Näätänen, 1981, S. 141-146), its nature and underlying mechanisms are only poorly understood up to present. Considering this backlog, Los and colleagues (Los, Knol, & Boers, 2001; Los & Van den Heuvel, 2001) have proposed an alternative model based on dynamic associative learning of temporal intervals (trace conditioning) to account for the asymmetric sequential FP effects in variable-FP settings. The authors contradict the assumption of an intentionally guided strategic-monitoring process but explain the empirical findings by means of the rather unintentional process of trace conditioning. Precisely, it is assumed that the respective behavioral effects result from a dynamic learning (and re-learning) of the time interval between the WS and the IS (i.e., FP length). The model makes assumptions about the underlying representation of discrete time during the FP and assumptions about associative-learning rules. Regarding the latter aspect, the model builds on previous theorizing in the context of variable-interval trace-conditioning research in domains such as eye-blink conditioning. According to the trace-conditioning model of temporal preparation, the time during the FP interval is represented as a sequence of time-tagged events, and the WS is considered a conditioned stimulus (CS) that becomes associated (through the sequence) with the moment of IS occurrence (the imperative moment), or with stimulus/response features that previously occurred at this moment. The WS is assumed to act as a retrieval cue that activates the time-tagged event sequence that ends with the presentation of the IS. For example, if the WS starts the sequence and the IS occurs at a particular time point, an associative connection is established between WS, time, and the imperative moment, facilitating activation at this moment in subsequent trials.



According to Los and colleagues, the principles that guide behavior in the variable-FP paradigm are equivalent to those in the context of eye-blink conditioning research. In classic trace-conditioning research, a CS is usually presented at the start of a trial, followed by a time interval (the “trace”) after which the unconditioned stimulus (US) is presented. The subject of learning is the time interval between CS and US. To illustrate this point, consider the classic study of Kehoe, Graham-Clarke und Schreurs (1989): There, rabbits were conditioned to blink in response to a tone (CS) that signaled an air puff to the sclera of the eye (US). The interval between CS and US (i.e., the time from tone onset to air puff occurrence) was randomly varied within a block of trials (400 vs. 900 ms). As a result, the rabbits learned to blink twice, once at 400 ms and once at 900 ms. In such experiments, the distribution of responses around an imperative moment is usually taken to index performance. In studies on temporal preparation where human participants are used, the speed of responses is measured as index of performance, which requires skeletal activation that is much more costly to the organism.

Los and van den Heuvel (2001) argued that temporal preparation (considered a trace-conditioning process) does not result in a reflex-like activation of responses in the variable-FP paradigm, but only facilitates responses via an anticipatory (sub-threshold) activation of the motor system. Hence, the model presumes that individuals follow the experimenter’s instruction to respond to the IS as fast as possible. In other words, although dynamic temporal preparation is considered an unintentional process, the model presumes a general intention (willingness) of the participants to respond with maximum efficiency. Sufficient general task motivation of the participants provided, the main predictions of the model are derived from three conditioning rules: Response strength (i.e., preparedness) at a particular moment (1) increases when the IS occurs at that moment, due to excitatory reinforcement, (2) remains unchanged when the IS occurs earlier, and (3) decreases when the IS occurs at a later moment, due to extinction. Additionally, the model assumes that temporal precision decreases with FP length, which means that response activation is sharp-peaked at a short FP but rather round-peaked at a long FP. Based on these rules, the model predicts fast responses on short-FP repetition trials, since response strength was reinforced at the same critical moment on the previous trial. Fast responses are also predicted to occur on short–long FP sequences, since the critical moment was not bypassed on the previous trial (and, thus, its previously acquired response strength was not reduced). Conversely, in long–short FP sequences, slow responses are predicted by the model, since all critical moments except the latest one were bypassed on the previous trial.

An alternative model of dynamic temporal preparation was recently proposed by Vallesi and colleagues (Vallesi & Shallice, 2007; Vallesi, Shallice et al., 2007). The authors took a different view of variable-FP phenomena and developed the classic strategic model into a dual-process account, 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 trial-to-trial fluctuations in (motoric) arousal. Note that the term arousal here is viewed as the general readiness to respond, which is often termed “alertness” in other contexts (Langner et al., 2012). On short-FP<sub>n</sub> trials, responses are assumed to be facilitated when following a short-FP<sub>n-1</sub> trial, relative to a long-FP<sub>n-1</sub> 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<sub>n</sub> trials, however, responses are fast irrespective of previous FP length, because the decrement in arousal following long-FP<sub>n-1</sub> trials is compensated for by active preparation based on conditional-probability monitoring. Critical to the response slowing in long–short FP sequences, therefore, is the time spent in a state of response preparation on trial<sub>n-1</sub>.

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<sub>n</sub> trials (Vallesi & Shallice, 2007, S. 1385-1387). According to the dual-process model, the two processes combine to produce the standard RT pattern, although they can be dissociated from each other. Under the assumption that no deliberate preparation takes place during the FP (either because no resources are available or because participants do not engage in the preparatory process), a symmetrical effect of previous FP length should occur. This assumption is supported by several empirical findings. For example, Vallesi and Shallice (2007) presented children of different age with a simple-RT task in a variable-FP setting. The authors demonstrated that very young children (4-5 years) exhibited a symmetrical sequential FP–RT effect, while somewhat older children (6-7, 8-9, 10-11 years) exhibited the typical (asymmetric) pattern. This was explained by assuming that very young children have not yet developed mechanisms of supervisory control required for conditional-probability monitoring. As a consequence, the authors argue, the behaviour of very young children in the context of a variable-FP setting is solely determined by trial-to-trial variations in arousal (i.e., motoric responsiveness), yielding a symmetrical sequential FP effect in this group of individuals.

In a further study, Vallesi et al. (2007) corroborated their view by applying transcranial magnetic stimulation (TMS) over the right dorsolateral prefrontal cortex (rDLPFC). By means of this method, the activity of this brain region can be transiently inhibited, and the corresponding effects on overt performance can thus be attributed to the functioning of this region. Conducting a variable-FP experiment, Vallesi et al. demonstrated that the FP<sub>n</sub>–RT slope but not the sequential FP effect is reduced after inhibiting rDLPFC with TMS, suggesting that strategic processes putatively subserved by prefrontal cortex are not necessary for the emergence of the sequential FP effect. According to Vallesi et al. (2007), im-

paired rDLPFC functioning following TMS is equivalent to a reduction of exactly those attentional resources that are required during the monitoring of time during FPs. 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, Mussoni et al., 2007).

Regarding the strategic-preparation process, the dual-process model assumes that individuals attentively monitor the conditional IS probability during FP, which they use to intentionally enhance preparatory state. As mentioned earlier, a preceding long FP<sub>n-1</sub> should result in a decrease of arousal (resulting in slower responses) in the current trial. According to the dual-process model, this decrease can be compensated for by deliberate strategic preparation (i.e., based on conditional IS probability) in long-FP<sub>n</sub> trials but not so in short-FP<sub>n</sub> ones. In these short-FP<sub>n</sub> trials, it is assumed that there simply is no possibility to predict the IS (beyond the a-priori IS probability), because no increase in the conditional IS probability (beyond a-priori levels) has taken place at the shortest imperative moment. Responses after a short FP<sub>n</sub> are therefore particularly slow in long–short FP sequences, since deliberate preparation in long-FP<sub>n-1</sub> trials is assumed to result in short-term exhaustion of supervisory-control processes (Vallesi & Shallice, 2007, S. 1386). For that reason, the typical asymmetric sequential FP effect is predicted to result under standard conditions, where normal individuals are employed that are capable to implement cognitive control for conditional-probability monitoring and intentional preparation.

Due to the aforementioned reasons, both the dual-process model and the trace-conditioning model predict a similar outcome pattern under standard experimental conditions, which makes it difficult to discriminate between both models. However, they provide different experimental manipulations as a means for testing the validity of their assumptions. One particular feature of the dual-process model is that it considers resources a critical variable (though it does not specify particular kinds of resources). If resources are reduced for some reasons, for example, due to additional cognitive load, this should hamper the efficiency of the monitoring process. Moreover, if individuals that are presupposed to lack cognitive-control abilities, such as young children or highly impulsive individuals, this should also impair efficient conditional-probability monitoring. Correspondingly, a flattened FP–RT function and a symmetrical sequential FP effect should result under these conditions. The finding that very young children (compared to older ones) exhibit a symmetrical sequential FP effect has been taken as supporting this assumption. On the other hand, a flattened FP–RT function has often been observed that was accompanied by a typical (asymmetric) sequential FP effect, indicating that theory and empirical findings are not definitely clear yet (z.B. Correa, Trivino, Perez-Duenas, Acosta, & Lupiáñez, 2010; Trivino, Correa, Arnedo, & Lupiáñez, 2010; Vallesi, McIntosh, & Stuss, 2009).

#### 4 SUMMARY AND RESEARCH QUESTIONS

As discussed above, variable-FP phenomena have been explained by three independent mechanisms: associative learning of temporal intervals (trace conditioning), strategic preparation (conditional-probability monitoring), and sequential variations in motor excitability (termed “arousal”, according to the dual-process model). According to the trace-conditioning model, the FP–RT function arises from trial-to-trial associative learning of WS–IS temporal relationships. The basic assumption is that peak preparation at previously reinforced critical moments is automatically attained and dynamically adjusted. According to the dual-process model, individuals engage in a strategic process of monitoring the increase in the conditional probability of IS occurrence over the FP interval, which results in the downward-sloping FP–RT function. A second (non-strategic) process is assumed to arise from variations in motor excitability due to the time spent in a state of preparation that is held responsible for the arousal decrement. Arousal is assumed to be higher after a short  $FP_{n-1}$  (which benefits performance in this situation) than after a long  $FP_{n-1}$ , and is thus assumed to vary sequentially when FP is randomly varied across trials. According to this model, the asymmetry of the sequential FP effects arises from the combined effects of both component processes.

Both the trace-conditioning model (Los et al., 2001; Los & Van den Heuvel, 2001) and the dual-process model (Vallesi & Shallice, 2007; Vallesi, Shallice et al., 2007) aim to account for variable-FP phenomena. Although both models are based on entirely different mechanisms, it has been difficult to discriminate between both models so far. The latter model provides entirely different possibilities to theorize about variable-FP phenomena, and delivers distinct experimental manipulations to test assumptions about resources and arousal. The goal of the present study was to examine the mechanisms supposed to be responsible for the emergence of variable-FP phenomena in more detail. To this end, a variable-FP design was employed that contained the following basic components: A WS opened the preparatory interval (FP) after which the IS was presented. The task was either a simple-RT task or a choice-RT task, and individuals were required to respond as fast as possible to the IS. Trials were separated by a constant intertrial-interval. The basic design was then varied to answer several questions that were the subject of study in the five papers that constitute the present work.

In study 1, it was asked whether and how the temporal context moderates the RT pattern in variable-FP experiments, comparing performance in a short and a rather long temporal context. In study 2 and 3, it was asked whether WS stimuli act as symbolic starting point for probability monitoring (as suggested by strategic-preparation models), or alternatively, act as retrieval cues that automatically trigger preparatory activity (as suggested by the learning-based model of temporal preparation). In study 4, it was asked whether continuous auditory stimulation (believed to distract resources) selectively impairs temporal

preparation at late critical moments, yielding a flattening of the FP–RT function (as suggested by the dual-process model). In study 5, performance was examined in a wide versus narrow FP context and, additionally, as a function of the amount of preceding long-FP trials (higher-order sequential FP effects). According to the dual-process model, the efficiency of the strategic monitoring process should decrease with increasing FP context, and this effect should additionally be affected by the amount of preceding long-FP trials. Of particular interest was the question of whether responses are faster in the short–short–long FP sequence compared to the long–long–long FP sequence. This finding is predicted from a dual-process model, but should not occur from the perspective of the trace-conditioning model (since FP repetitions should speed up rather than slow down responses, due to reinforcement).

## 5 EMPIRICAL STUDIES

### 5.1 Study 1 – Role of Temporal Context on Foreperiod Effects

The literature on classical trace-conditioning suggests that learning of temporal intervals should be better in a short (< 1000 ms) than in a longer temporal context. This is explained by assuming that temporal precision is higher at short intervals, which results in a better episodic encoding and retrieval of stimulus–response connections (Mauk & Buonomano, 2004, S. 308-311). It is unclear, however, whether these assumptions can easily be transferred to RT studies, and how a change in temporal context influences the RT pattern in variable-FP settings. The few studies that devoted attention to this issue even found an abnormal sequential FP effect that is difficult to interpret (Alegria, 1975; Karlin, 1959). In study 1 (Steinborn, Rolke, Bratzke, & Ulrich, 2008), we therefore compared sequential FP effects in a short and long temporal context. If learning of temporal intervals is more effective in a short (than a long) temporal context, then the asymmetry of the sequential FP effect should be more pronounced in a short than a long temporal context. At least, the typical asymmetric sequential FP effect should also be observed in a short temporal context, which has not been observed in a previous study by Karlin (1959), who found a reversed sequential FP effect in an extremely short temporal context (FPs: 400, 500, 600 ms). Hence, study 1 was also devoted to investigate the reason for the deviant RT pattern that was previously observed in the studies of Karlin (1959) and Alegria (1975).

Broadly, it was aimed to investigate whether the RT pattern that is predicted by the trace-conditioning model of temporal preparation also occurs in a rather short temporal context, as well as to investigate boundary conditions that potentially moderate this RT pattern. It should be noted here that the three experiments follow a rather complex analytical strategy (for details, see Steinborn et al., 2008). In Experiment 1, sequential FP effects

were examined in a short (FPs: 200, 400, 600 ms) and a long (FPs: 1200, 2400, 3600 ms) temporal context, using a choice-RT task. The results revealed the typical sequential FP effect in both short and long FP contexts; however, the asymmetry of the effect was more pronounced in the long FP context, compared to the short one. In Experiment 2, sequential FP effects were examined in a short FP context (FPs: 200, 400, 600 ms) and compared between conditions without catch trials and with 25% catch trials (to prevent premature responding), using a simple-RT task. Two previous findings had revealed an abnormal RT pattern within this short context, and the reasons for this deviant pattern were to be examined. In particular, Alegria (1975) found a symmetric sequential modulation in a choice-RT task (FPs: 600, 700, 800 ms), and Karlin (1959) even found a reversed asymmetric sequential FP effect using a simple-RT task. The results revealed an asymmetric sequential FP effect in both conditions, but the RT pattern in the condition with 25% catch trials was additively shifted upwards. In Experiment 3, it was then examined whether the FP-range (i.e., the temporal density of FPs within a block of trials) is responsible for the abnormal RT pattern found previously. Sequential FP effects were examined in a situation where FPs were extremely dense (FPs: 400, 500, 600 ms) as in Karlin's study, using both a simple-RT and a choice-RT task. In the simple-RT condition, Karlin's finding of a reversed sequential FP effect was replicated, while in the choice-RT condition, there was a (normal) downward-sloping FP-RT function but no sequential modulation.

Taken together, these results show that an asymmetric sequential FP effect also occurs in a very short temporal context, but the RT pattern is moderated by several ancillary variables such as response mode (simple vs. choice decision), the amount of catch trials, as well as the temporal density of FPs. The results are basically consistent with the trace-conditioning model, although it has some difficulties to explain the greater asymmetry of the sequential FP effect in a long FP context, as compared with a short FP context. Nonetheless, this finding can be accounted for by considering other moderator variables such as the fact that a rather long temporal context affects an individual's general (i.e., not specific to critical moments) motor responsiveness. In terms of the dual-process model, the global RT increase in the long-FP condition could be explained by means of the postulated arousal mechanism (although Vallesi et al. use the term more specifically for the case of sequential variations within one particular time context, not between time contexts). However, the dual-process model can also not easily explain why the FP-RT slope became steeper (not flatter) in the long (vs. the short) FP context in Experiment 1.

## 5.2 Study 2 – Shift (vs. Repetition) of Warning Signal Modality

In study 2 (Steinborn, Rolke, Bratzke, & Ulrich, 2009), the role of the warning signal in the process of temporal preparation was examined. According to a widely accepted strategic-preparation view, the WS in variable-FP experiments acts as a symbolic starting point for preparation, and individuals then are assumed to intentionally enhance preparatory state

during the FP. In other words, this view implies that the WS is informative with regard to the beginning of the FP interval, and individuals make use of this information in a voluntary way. According to a learning-based view of temporal preparation, however, the WS (seen as conditioned stimulus, CS) would be considered a retrieval cue that automatically triggers preparatory activity. More precisely, contemporary models of classical conditioning assume that CS–US occurrences are encoded in episodic memory, so that the entire temporal episode can later be re-activated by an identical (or very similar) CS stimulus. To test this assumption, a standard variable-FP design was adapted so that the modality of the WS randomly varied across trials. By means of this design, it was possible to compare the RT patterns between the cases of cross-trial shifts versus repetitions of WS modality. According to a learning-based view of temporal preparation, a shift of WS modality should hamper efficient retrieval of previously stored memories and thus should result in less efficient preparation at critical moments. The three experiments of the Steinborn et al. (2009) study were conducted to directly test a learning-based view of temporal preparation, considering ancillary conditions such as particular WS-modality pairings as critical variable.

In Experiment 1, the effect of a repetition versus a shift of WS modality on temporal preparation in variable-FP settings was examined. Two FPs were used (FPs: 1200, 3600 ms) in a choice-RT task. The modality of the WS (visual vs. auditory, 50% probability for each condition) was randomly varied across trials, comparing the RT pattern in both conditions. A shift (compared to a repetition) of WS modality yielded a slowing of responses on short-FP repetition trials but did not affect responses on long-FP trials. Visually, this is evidenced by a decrease of the asymmetry of the sequential FP effect. In Experiment 2 (choice-RT task), the effect of repetition versus shift of WS modality was replicated, using another pairing of WS modalities. One modality was auditory (sine tone) and the other one was vibrotactile, and each condition was randomly presented between a block of trials (50% probability for each condition). A shift (compared to a repetition) of WS modality yielded a similar modulation of the sequential FP effect as was observed in Experiment 1, demonstrating that the effect generalizes to other WS-modality pairings. In Experiment 3, the results of the previous experiments were conceptually replicated by using a simple-RT task and three FPs instead of two FPs (resulting in more temporal uncertainty). As a result, the same effect on the RT pattern was observed by a WS-modality shift (i.e., steepening of the FP–RT function, decrease of the asymmetric sequential FP effect). This time, however, the effect was much more pronounced than in the previous experiments, which was obviously due to the increased degree of temporal uncertainty in Experiment 3.

Taken together, the results of all experiments of the Steinborn et al. (2009) study support a learning-based view of temporal preparation in variable-FP settings. Across different task forms and WS-modality pairings, a shift of WS features (compared to a repetition) consistently modulated the pattern of sequential FP effects. This modulation of the FP–RT slope and the sequential effect originated mainly from a response slowing at short–

short FP sequences, while responses on long-FP trials were not affected. From a trace-conditioning view of temporal preparation, as proposed by Los and colleagues, this finding could be interpreted in terms of CS stimulus generalization: In WS-repetition trials, temporal preparation is efficiently triggered by the WS, yielding a retrieval of stored memories about WS–IS temporal relationships that were encoded in the previous trial. In WS-shift trials, the WS may inefficiently trigger preparatory activity. Since WS modality is not identical, re-activation of previously encoded WS–IS relationships may not run down with the same effectiveness in WS-shift trials than in WS-repetition trials. This indicates that performance in variable-FP settings is substantially determined by distinct WS–IS associations, and, further, that a change in stimulus properties may render automatic memory retrieval inefficient. The fact that a WS shift only affected preparation on short-FP trials (but had virtually no influence on long-FP trials) indicates that WS-triggered memory retrieval is only relevant at early critical moments while another mechanism may determine performance at late critical moments. Tentatively suggested, the WS had no influence on temporal preparation on long-FP trials because the increase of the conditional probability of IS occurrence during the FP interval provides sufficient (implicit) knowledge for efficient preparation (and WS-induced preparation is redundant at late critical moments).

### 5.3 Study 3 – Shift (vs. Repetition) of Auditory Warning Signals

In study 3 (Steinborn, Rolke, Bratzke, & Ulrich, 2010), the role of the warning signal in the process of temporal preparation was examined in more detail. Specifically, two issues associated with between-modality shifts were identified that might complicate an interpretation of such WS modality shift effects in terms of episodic retrieval: differences in WS stimulus intensity and attention-to-modality effects. Since WS intensity can hardly be equalized across modalities, we argued that any modulation could be attributed to arousal differences. Additionally, since between-modality shifts may also have caused a failure to attend to the actual WS modality on a particular trial, any modulation cannot unequivocally be interpreted in terms of failed memory retrieval. To explain the attenuation of the sequential FP effect in terms of episodic retrieval, it seemed necessary to demonstrate similar effects of WS shifts in situations where both the intensity and the modality of the WS are controlled for. As mentioned above, this is only possible when WS attributes change within a particular modality. Therefore, four experiments were conducted in which two auditory WS events were randomly varied (50% probability for each event). In addition, we considered different WS combinations, tasks, and levels of temporal uncertainty.

In Experiment 1, the effect of a repetition versus a shift of auditory WS features on temporal preparation in variable-FP settings was examined. Two FPs were used (FPs: 1200, 3600 ms) in a choice-RT task. Two well discriminable auditory stimuli (1000- vs. 1400-Hz sine tones, 70 dB) served as WS (50% probability for each pitch level) and were randomly varied across trials. There was no effect of a shift (vs. repetition) of WS features on the RT



pattern. Since the sine tones were easily discriminable for all participants, this finding cannot be attributed to insufficient frequency difference between the low and the high sine tone. In Experiment 2, therefore, two equiprobable auditory WSs were chosen that were more different in their physical stimulus features (sine tone vs. white noise, 70 dB). All other design features were equal to Experiment 1 (choice-RT task, FPs: 1200 vs. 3600 ms). A shift (compared to a repetition) of WS features yielded a slowing of responses on short-FP repetition trials but did not affect responses on long-FP trials. Visually, this is evidenced by a decrease of the asymmetry of the sequential FP effect. In Experiment 3, the WSs were again a sine tone (1000 Hz) versus white noise (as in Experiment 2), but temporal uncertainty was increased (FPs: 1000, 2500, 4000 ms) and a simple-RT task was used. A shift (compared to a repetition) of auditory WS features yielded a similar but more pronounced modulation of the sequential FP effect as was observed in Experiment 1. In Experiment 4, the WS stimuli were again a low (1000 Hz) versus high (1400 Hz) sine tone, but temporal uncertainty was increased (FPs: 1000, 2500, 4000 ms) and a simple-RT task was used. As in Experiment 1, there was no effect of a shift (vs. repetition) of auditory WS features on the sequential FP effect.

The results of the Steinborn et al. (2010) study demonstrate that even a shift of equally intense auditory WS events can attenuate the sequential FP effect (Experiment 2 and 3: when a sine tone vs. noise were used as WS stimuli), with effect sizes similar to the findings observed between modalities (Steinborn et al., 2009). The present results thus provide a strong argument against an encoding-failure explanation of the WS-shift effect, that is, against the possibility that WS attributes may not sufficiently be attended in WS-shift trials (as compared to WS-repetition trials), since the two WS stimuli were always presented in the auditory modality and were of equal intensity. Instead, the results support a retrieval-failure explanation, which implies that stored memories about previously encountered WS–IS relationships are not efficiently retrieved in WS shift trials. The results of Steinborn et al. (2010) therefore corroborate and extend the Steinborn et al. (2009) study, showing that temporal preparation in variable-FP tasks is more efficient when WS attributes are repeated across trials, as compared to when they change across trials. This supports a learning-based view of temporal preparation but contradicts a strategic-preparation view, which considers the WS a symbolic marker that is intentionally used by the participants to start preparatory activity on the current trial. The contribution of the Steinborn et al. (2010) study was to rule out two alternative explanations, namely that any performance decrement in WS-shift trials may be due to difficulties to shift attention to the current modality and to differences in WS-induced arousal (assuming that auditory stimuli are more arousing than visual ones).

#### **5.4 Study 4 – Distraction by Irrelevant Sound during Foreperiods**

As mentioned previously, the dual-process model (Vallesi & Shallice, 2007) points to the importance of attentional capacity for tracking time and probability information during the

FP interval. Hence follows that any manipulation that effectively reduces capacity during the FP should impair preparatory processing, which should manifest itself in a specific RT increase on long-FP<sub>n</sub> trials. Empirical support for this prediction is mainly derived from studies comparing group-related individual differences in cognitive-control functions, but there is also evidence from the inhibition of rDLPFC functions via TMS. According to Vallesi et al., decreasing rDLPFC functioning via TMS is equivalent to a reduction of those kinds of attentional resources that are required for monitoring time and probability information. Further, irrelevant sensory stimulation during preparatory processing has been shown to interfere with RT performance in FP experiments, although the precise effect that sound during the FP has on performance is far from clear. Study 4 (Steinborn & Langner, 2011), therefore, aimed to examine the effect of an auditorily filled FP interval on RT performance in more detail by disentangling alternative explanations.

More specifically, the so-called *auditory filled-FP effect* was examined, which refers to a performance decrement in trials where the FP interval is filled with irrelevant auditory stimulation compared to a condition without additional stimulation. According to one account, irrelevant stimulation distracts individuals from processing time and probability information during the FP (distraction-during-FP hypothesis). This should predominantly affect long-FP trials. Alternatively, the filled-FP effect may arise from a failure to shift attention from FP modality to IS modality (attention-to-modality hypothesis). The first hypothesis focuses on preparatory processing, predicting a selective RT increase on long-FP trials, whereas the second hypothesis focuses on target processing, only predicting a global RT increase irrespective of FP length. Across four experiments that were varied with respect to several ancillary conditions, a filled-FP (compared to a blank-FP) condition consistently yielded a selective RT increase in long-FP trials, irrespective of the FP–IS modality pairing. This pattern of results contradicts the attention-to-modality hypothesis but corroborates the distraction-during-FP hypothesis of the filled-FP effect. More generally, the data of the Steinborn and Langner (2011) study have theoretical implications by supporting a multi-process view of temporal preparation under time uncertainty.

According to a strategic view, supervisory monitoring during FP depends on the availability of attentional resources, and manipulations that reduce applicable resources are predicted to impair monitoring efficiency. Given that irrelevant sound captures attention and draws off resources by tapping rDLPFC functions, the observed decrease of the FP<sub>n</sub>–RT function in the filled-FP condition may arise from distraction-impaired attentional monitoring. This, in turn, would lead to a failure to compensate arousal decreases following long-FP trials, consistent with the dual-process view. On the other hand, it cannot be excluded that non-strategic mechanisms are affected as well, albeit via a different mechanism. For example, the trace-conditioning model assumes that time is tracked pre-attentively along a chained event sequence, which does not require attentional resources, but may still be susceptible to structural interference effects. To the degree to which irrelevant sound

during the FP produces structural interference (e.g., by masking internal signals around critical moments), the conditioning process itself could be affected. Hence, while the present results provide active support for the dual-process model (which assumes that offloading or distracting resources should hamper efficient conditional-probability monitoring, they do not necessarily rule out the learning-based account of temporal preparation. On the other hand, the present findings are not directly predicted by the trace-conditioning model as proposed by Los and colleagues, and hence may favor the dual-process model somewhat more than the trace-conditioning model. A detailed discussion of remaining issues and potential experiments to resolve them is provided in the discussion of the manuscript.

### 5.5 Study 5 – Effects of Higher-order Foreperiod Sequences

In study 5, it was aimed to examine the notion of “arousal” (as defined by Vallesi et al.) as a contributing mechanism to variable-FP phenomena in more detail. According to the dual-process model, arousal decreases during time-in-readiness but such reductions can be compensated for by active strategic preparation (conditional-probability monitoring), particularly on long-FP trials. For that reason, responses are always fast on long-FP trials, irrespective of previous FP length. Hence, no difference in RT between short–long and long–long FP sequences should be observed. If such an RT difference is obtained indeed, as argued by Vallesi and Shallice (2007, p. 1386), this may indicate that the strategic-preparation process did not fully compensate the arousal decrement after a long  $FP_{n-1}$  trial, leaving a sign of decreased arousal on RT performance. In fact, there is electrophysiological evidence that Vallesi and Shallice viewed as a covert signature of arousal (Los & Heslenfeld, 2005), and behavioral studies also (sometimes) indicate that responses are slower in long–long than in short–long FP sequences. Such a pattern is not predicted from the learning-based view of variable-FP phenomena, since FP repetitions should speed up, rather than slow down, responses (due to reinforcement). In five experiments, higher-order sequential FP effects on RT performance were examined, 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 context (i.e., average FP length), and reaction mode (simple vs. choice reaction).

To test assumptions about arousal variations from the perspective of a dual-process model, it seemed reasonable to employ a variable response–stimulus interval (RSI) instead of a variable-FP interval. This paradigm is equivalent to the variable-FP design, except that no intertrial-interval separates subsequent trials (such that the response–response interval more directly corresponds to the length of the preparatory interval, see Steinborn & Langner, 2012). The order of the five experiments corresponds to the increasing 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 the results of Experiment 3 (high temporal uncertainty) to situations differing in the number of critical moments and the presence (Exps. 3 & 4) versus absence (Exp. 5) of response uncertainty (choice-RT vs. simple-RT task).

The results confirmed the predictions of the dual-process model but revealed the importance of contextual temporal uncertainty as critical variable: Slower responses in long–long–long (compared with short–short–long) FP sequences were not found within a short-FP context (Experiments 1–2) but clearly emerged within a long-FP context (Experiments 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. Importantly, the results revealed that the effect is additionally moderated by temporal context (i.e., average length of a particular FP set), being larger under high (compared to low) temporal uncertainty. This clearly indicates that it is more difficult and exhausting to prepare during long (compared to relatively short) FP intervals. This finding may thus provide further support for arousal (motoric responsiveness) 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.

## 6 GENERAL DISCUSSION

The work presented here aimed to examine the dynamic aspects of temporal preparation in simple-RT and choice-RT experiments with randomly varied FP intervals. In this situation, RT usually varies across trials because individuals are left uncertain about the exact moment of IS occurrence on a given trial. Two basic effects have been established in this situation: responses become faster with increasing FP length (FP–RT slope) and vary asymmetrically as a function of preceding FP length (sequential FP effect). According to the trace-conditioning model of temporal preparation, these phenomena arise from learning temporal WS–IS associations that are dynamically adjusted from trial to trial. According to the dual-process model, the variable-FP phenomena originate from two independent processes: A strategic process of conditional-probability monitoring is considered responsible for the downward-sloping FP–RT function, while trial-to-trial changes in an individual's general responsiveness (motoric arousal) are considered to produce sequential variations in RT performance. Both processes are assumed to jointly produce the pattern of asymmetric sequential FP effects. Both models claim to explain (by means of different mechanisms) the same variable-FP phenomena in standard situations, and a challenge for current research is to differentiate between both models. In the present work, several hy-

potheses were empirically tested in a series of experiments, which were derived either from the trace-conditioning model or the dual-process model, respectively.

The results of study 1 (Steinborn et al., 2008) show that a typical asymmetric pattern of sequential FP effects occurs similarly in both short and long FP contexts, consistent with the trace-conditioning model. The fact that the asymmetry of the sequential FP effect was more pronounced in the long (vs. the short) FP context, however, is difficult to explain from a trace-conditioning perspective. That is, although the trace-conditioning model does not make a specific prediction about changes in the RT patterning with increasing temporal context, it seems reasonable to predict from this model that the higher temporal precision should yield a more pronounced sequential FP effect in the short than in the long temporal context (since time-related reinforcement is more sharply peaked in a short than a long temporal context). From the perspective of a dual-process model, only the effects of temporal context on global RT performance can be explained elegantly. The finding that the FP–RT function became steeper (not flatter) with increasing temporal context could be explained by assuming that individuals in a long (vs. short) temporal context became more exhausted (i.e., refractory, in terms of Vallesi et al.) during a long-FP trial particularly when the subsequent trial was a short-FP trial (i.e., in long–short FP sequences). Note, however, that the latter explanation leaves room for alternative interpretations, obviously because the dual-process model at present is not specific about when exactly individuals should exhibit preparatory deficits in variable-FP experiments (see Steinborn et al., 2008, 2009, and 2010, for discussions of this issue). It should further be noted that one remaining questions regarding temporal context could be answered in study 5 (Steinborn & Langner, 2012).

While the main goal of the Steinborn et al. (2008) study was to examine sequential modulations of FP length as a function of temporal context, it was also aimed to clarify why Karlin (1959) observed an abnormal RT pattern (reversed sequential FP effect) using three very dense FPs (400, 500, 600 ms) in a simple-RT task. Two candidate variables were examined in a replication experiment, namely the inclusion of catch trials (vs. no catch trials; Experiment 2) and a variation of task mode (simple-RT vs. choice-RT task; Experiment 3). The results of Experiment 3 are especially relevant here: An FP set of similar density (as in Karlin's study) was used comparably in a simple-RT and a choice-RT task. Whereas the sequential FP effect was reversed in the simple-RT condition (replicating Karlin's results), it was virtually absent in the choice-RT condition. One possibility is that when the FP-range is very dense, individuals may not represent three distinct imperative moments but a single relatively noisy one to which they attain preparation. The results 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 on short-FP<sub>n</sub> trials. The observation of a reversed sequential effect, however, shows that the moment of peak preparation was still influenced by the preceding trial. Overall this finding suggests that, although participants adjusted their moment of peak

preparation in a trial-by-trial manner, they did probably not adjust between three distinct imperative moments (as they would in situations with a broader FP-range) but in a rather analogous fashion, by rescheduling a single moment of peak expectation (a representation arising from a fusion of three distinct moments). A more detailed description of this mechanism is provided in the Steinborn et al. (2008) study.

Studies 2 and 3 (Steinborn et al., 2009, 2010) aimed to examine the role of the WS in temporal-preparation experiments, with particular emphasis on predictions derived from a learning-based view of temporal preparation. From the perspective of a strategic-preparation model, the WS is considered to symbolically indicate the beginning of the preparatory interval, whereby there is no reason to assume a modulation of performance due to a cross-trial shift of WS attributes. From the perspective of models based on associative learning, however, the WS acts as a retrieval cue that re-activates previously encoded trial episodes and by this means triggers preparatory activity rather automatically. Given the empirical evidence on the encoding-specificity principle (which states that memory is operating most effectively when information available at encoding is also present at retrieval), one would assume that temporal preparation is more effective when the WS is repeated across trials, as compared to when the WS is shifted. Greater effectiveness of WS-induced retrieval should be reflected in improved performance especially in short–short FP sequences (because the WS has direct effects only at short FPs, while at long FPs, performance is also affected by the conditional-probability monitoring process). This exactly was demonstrated in study 2 (Steinborn et al., 2009), since a shift (vs. repetition) of WS modality across trials hampered the efficiency of temporal preparation, particularly in short–short FP sequences. In study 3 (Steinborn et al., 2010), this effect was also observed when the shift occurred within the auditory modality, even when intensity was held equal. Across all experiments of the studies 2 and 3, the effect of a shift (vs. repetition) of WS attributes was also larger when temporal uncertainty was high than when it was low.

In general, the results of studies 2 and 3 (Steinborn et al., 2009, 2010) may be taken to support the trace-conditioning model of temporal preparation, which assumes that the WS (acting as a CS) unintentionally triggers preparatory activity in advance of an impending IS (equivalent to an US) on a given trial. At a more detailed level, the results provide new insights into the precise mechanism that produce the variable-FP phenomena. In particular, a shift of the WS was most detrimental when a short  $FP_n$  was preceded by an equally short  $FP_{n-1}$ , while there was virtually no effect on long- $FP_n$  trials, irrespective of whether the preceding  $FP_{n-1}$  was short or long. By this means, the variable-FP parameters were substantially affected by a WS shift. While a repetition of WS modality across subsequent trials revealed the typical downward-sloping FP–RT function and the typical asymmetric sequential FP effect, a shift of WS modality attenuated the sequential FP effect by about 40% (see Steinborn et al., 2009, Figures 1, 2, and 3). In short, a shift of WS modality reduced the beneficial effect of a short FP repetition on RT. By contrast, when a long- $FP_{n-1}$  trial pre-

ceded a short-FP<sub>n</sub> trial, RT did not depend on the sequence of WS modality. Moreover, the attenuation of the sequential FP effect due to a shift of WS modality was reliably observed with different cross-modal WS pairings (auditory-visual; auditory-tactile), different task forms (simple-RT and choice-RT task) and different levels of temporal uncertainty. This demonstrates the generality of the present results of both studies 2 and 3.

The observation that a shift of WS modality produced an attenuation of the asymmetric sequential FP effect (via the aforementioned mechanism) cannot be explained by the strategic-preparation model but is fairly consistent with the trace-conditioning model. In study 3 (Steinborn et al., 2010), two issues associated with between-modality shifts (as examined in study 2) were identified that might complicate an interpretation of such WS-modality shift effects in terms of episodic retrieval: differences in WS intensity and attention-to-modality effects. Since WS intensity can hardly be equalized across modalities, any modulation by a WS shift could be attributed to arousal differences (e.g., auditory stimuli may be more arousing than visual ones, etc.). Additionally, since between-modality shifts may also have caused a failure to attend to the actual WS modality in a particular trial, any modulation cannot unequivocally be interpreted in terms of failed memory retrieval. To explain the attenuation of the sequential FP effect in terms of episodic retrieval, it seemed necessary to demonstrate similar effects of WS shifts in situations where both the intensity and the modality of the WS are controlled for. In study 3, therefore, two distinct WS events within a single (auditory) modality were randomly varied across trials. In addition, different WS combinations, task forms, and levels of temporal uncertainty were considered. The results demonstrate that even a shift of equally intense auditory WSs can affect preparatory efficiency (Experiment 2 and 3, sine tone vs. white noise) with effect sizes similar to the findings observed between modalities.

Taken together, the results of studies 2 and 3 provide evidence in support of the view that the WS acts as retrieval cue that automatically initiates preparatory activity in variable-FP settings. This conclusion is derived from the fact that a cross-trial shift of WS features (as compared to a repetition) diminished preparatory efficiency. At a more detailed level, the present results revealed that WS-triggered preparatory activity is important in short-FP trials (particularly in short-short FP sequences), while it does not affect preparatory activity at late critical moments (irrespective of the particular FP sequence). This demonstrates that another mechanism must be responsible for (variable-FP) temporal preparation on long-FP trials, which is independent of WS attributes. From the perspective of a strategic-preparation model, one could identify this process as related to processing the conditional probability of IS occurrence, which should (for aforementioned reasons) not depend on “surface” features (i.e. WS attributes). Though, this finding can well be explained from a trace-conditioning view if one accepts the additional assumption that certain stimulus attributes (particularly irrelevant perceptual features) of the WS decay over time (during long-FP intervals). A more detailed differentiation of potential mechanisms within

a trace-conditioning view as well as a differentiation between alternative trace-conditioning model subtypes is provided in the discussion sections of Steinborn et al. (2009, 2010).

In study 4 (Steinborn & Langner, 2011), the effect of continuous irrelevant sound during the FP interval on performance was examined in a series of four experiments. It was aimed to explore the mechanism underlying the filled-FP effect and to reveal several ancillary conditions that may be responsible for divergent findings in the literature. In addition, it was aimed to test a direct prediction of the dual-process model of temporal preparation, namely that irrelevant sound during the FP should hamper attentional resources required for monitoring conditional probabilities and establishing associated preparatory states. The results of these experiments revealed a global performance decrement in trials where the FP interval is filled with irrelevant auditory stimulation, as compared to conditions without additional stimulation, replicating previous findings. This performance decrement in the filled-FP condition was especially pronounced in long-FP trials but less so in short-FP trials, yielding a flattening of the FP–RT function. Importantly, this effect was even larger when the filled FP and the IS were presented in the same modality than when they were presented in different modalities. By this means, prior hypotheses could be ruled out assuming that the performance decrement due to a filled-FP originates from difficulties to shift attention between modalities. More generally, the data of the Steinborn and Langner (2011) study have theoretical implications by supporting a multi-process view of temporal preparation under time uncertainty. According to strategic-preparation views (including the dual-process view), preparation during the FP depends on the availability of resources. Given the evidence that irrelevant sound captures attention and draws off resources, the observed flattening of the  $FP_n$ –RT function in the filled-FP condition may be interpreted as resulting from distraction-impaired attentional monitoring during the FP interval.

The results of study 4 are hence consistent with the dual-process model of temporal preparation, since this model makes the explicit prediction that any manipulation that hampers attentional resources during the FP interval should impair the efficiency of conditional-probability monitoring (as indicated by a flattening of the  $FP_n$ –RT function). Given that most of the prior studies on that issue used a between-subject design (demonstrating that individuals known as “being impaired in attentional efficiency” exhibit a flattened  $FP_n$ –RT function), the present work contributes to current theorizing on how individuals prepare responses under conditions of time uncertainty. While the trace-conditioning model does not make explicit predictions about resource availability affecting preparatory efficiency during the FP interval, the dual-process model actually does make such a prediction. Hence, one could argue that the dual-process model is the to-be-favored model in explaining the results of study 4. On the other hand, researchers in the field of classical-conditioning research often equate resource availability with the efficiency of encoding and retrieval mechanisms. Hence, any experimental variable capable to interfere with encoding/retrieval processes may, by this means, effectively decrease capabilities that are concep-



tualized as resources (from the dual-process model). To the degree to which irrelevant sound during FP produces structural interference (by masking internal signals around critical moments), elementary processes of associative learning itself could be affected.

In study 5, the contribution of arousal (as conceptualized by Vallesi & Shallice, 2007) was systematically investigated at different levels of contextual temporal uncertainty. According to the dual-process model, arousal is viewed as global responsiveness of an individual to an IS. According to Vallesi and Shallice (2007), arousal varies sequentially, being increased after a short  $FP_{n-1}$  but decreased after a long  $FP_{n-1}$  (see Introduction for a detailed explanation). This assumption leads to the prediction that responses should be slower in long–long than in short–long FP sequences. This difference should be even more pronounced for responses in long–long–long versus short–short–long FP sequences. This prediction was not confirmed within a short-FP context (Experiments 1–2) but clearly confirmed within a long-FP context (Experiments 3–5). Hence, the data support the notion that transient arousal changes contribute to sequential performance effects in variable-FP tasks but also indicate that this effect depends on temporal-preparation demands (being larger under high compared to low temporal uncertainty). The findings of study 5 are thus in line with the predictions derived from the dual-process account, since they clearly indicate that it is more difficult and exhausting to prepare during a sequence of long (compared to relatively short) FP intervals.

The trace-conditioning account, on the other hand, does not predict slower responses in long–long–long compared to short–short–long FP sequences, since FP repetitions should speed up (rather than slow down) responses due to reinforcement. From this perspective it is predicted that response strength at any critical moment is increased after reinforcement, which should result in faster responses when a particular FP length is repeated as compared to when FP length is alternated (i.e. non-reinforced) across two subsequent trials. While this prediction was confirmed within a narrow FP context, it was not confirmed in a wider FP context. This indicates that the mechanism of trial-to-trial reinforcement (as proposed by the trace-conditioning model) dominates performance within a short temporal context, while sequential fluctuations in general motor responsiveness (as proposed by the dual-process model) affect performance especially within a long temporal context. Hence, the present study revealed that the predictions of both theoretical models of temporal preparation are partially valid, depending on the particular experimental situation: The trace-conditioning model is valid in situations where contextual temporal uncertainty is low to moderate, while the dual-process model (particularly the arousal component of this model) is valid in situations where contextual temporal uncertainty is especially high. By this means, the present study contributes to current theorizing about the mechanism underlying variable-FP phenomena, by demonstrating the differential validity of both models, providing further evidence for a multi-component view of temporal preparation phenomena in variable-FP settings

At this point, one could ask whether the arousal component of the dual-process model should be regarded as being inconsistent with the trace-conditioning model. For example, although the trace-conditioning model does not incorporate arousal as 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 (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 the "true" associative strength, but some authors even argued 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. The results of study 5 (Steinborn & Langner, 2012) may thus not be interpreted as being inconsistent with a learning-based view of temporal preparation. Rather, they might suggest that the general responsiveness of an individual has a modulating influence on learning-based performance.

## 7 FINAL CONCLUSION

The results of the present work demonstrate that the beneficial effect of a warning signal on the subsequent speeded response to an imperative signal critically depends on previously established associative connections. If the associative connection between a particular WS and subsequent elements (time, IS, response) of a trial is not established, the beneficial effect of a WS may be reduced. The present work therefore demonstrated that a neutral WS does not solely facilitate performance by alerting individuals (i.e., by energizing cognitive processes), but by memory retrieval of previously encountered trial episodes (i.e., by re-instantiating mental representations of event sequences associated with the WS). By means of such a process, individuals are able to synchronize a transient state of optimal preparedness with the moment of IS occurrence. These results are more consistent with a trace-conditioning model than with a strategic-preparation model of temporal preparation, since according to the latter view, the WS is mainly viewed as a symbolic instruction to start preparation. According to the trace-conditioning view, on the other hand, the WS automatically triggers preparatory activity so that peak readiness is attained at the exact moment that was imperative on the previous trial. Importantly, the results of studies 2 and 3 (Steinborn et al., 2009, 2010) are not only consistent with the trace-conditioning model but provide new insights into the mechanism by which individuals attain and maintain a state of preparation (as well as to adjust implicit temporal expectancies) in situations where the IS occurs unpredictably after the WS.

Specifically, these studies have shown that the WS directly affects RT performance only at the first (of several) critical moments, while performance at later ones is obviously independent of the WS event (cf. Steinborn et al., 2009, 2010). This is evidenced by the fact that a shift (compared to a repetition) of WS modality across two subsequent trials hampered performance only on short-FP<sub>n</sub> trials (that were preceded by a short-FP<sub>n-1</sub> trial), while performance on long-FP<sub>n</sub> trials was always optimal irrespective of the WS. In other words, the present data indicate that the WS does not directly trigger preparatory activity at later (than the first) critical moment. If it did, there should be a performance benefit in trials where both FP length and WS modality is repeated (compared to a shift of both or one of them). It is possible that the sensory representation of a WS decreases rapidly. Thus it might be sufficiently available only at short critical moments, whereas the conceptual attributes (i.e., the symbolic meaning) have a stronger persistency. Such a decrease might be caused by interference due to competing mental representations arising from activations around critical moments before the latest critical moment. The exact mechanism by which interference possibly occurs cannot be determined based on the present data but future experimental approaches are outlined in the discussion sections of studies 2 and 3 (Steinborn et al., 2009, 2010).

On a broader level, the results of the present work demonstrate that the effect of neutral (i.e., nonspecific) WSs on performance is somewhat more complex than previously assumed. The WS may have at least three different roles in RT experiments: First, it informs about the beginning of a current trial (i.e., it opens the preparatory interval) and thereby serves as symbolic marker that can be strategically used to prepare for the IS. Second, it may cause an alerting response, energizing cognitive processes. Alerting by external sensory stimulation is often viewed as a non-strategic process, but it may actually interact with strategies adopted and intentions implemented by individuals. For example, a greater alertness response may be observed under conditions of high task motivation (i.e., the intention to perform well). Third, the WS may act as retrieval cue able to activate previously experienced trial episodes (including temporal relationships between WS and IS) from memory. Such a mechanism was strongly suggested by study 2 (Steinborn et al., 2009), and some of its potential boundary conditions were examined in study 3 (Steinborn et al., 2010). The degree to which one of these three core functions (of the WS) dominates performance in a particular task paradigm appears to depend on the specific situation and experimental context. For example, an experimentally induced state of high task motivation may probably counteract cross-trial effects of WS modality on RT performance (Falkenstein, Hoormann, Hohnsbein, & Kleinsorge, 2003), and a variation of WS intensity may also influence this relationship, probably by affecting the general energetic state of an individual in a particular experimental situation.

For the aforementioned reasons, it seems plausible to assume that the mechanisms that are postulated to produce the variable-FP phenomena (trace-conditioning model vs. dual-process model) are not entirely exclusive but may exist in parallel, depending on the

specific experimental situation. Therefore, a promising research strategy for revealing one of these mechanisms among the other is to use experimental manipulations that selectively affect one of the presumed mechanisms. In the present five studies (Steinborn et al., 2008, 2009, 2010; Steinborn & Langner, 2011, 2012), it was shown that WS effects on performance critically depend on features of the WS and hence are not simply due to its alerting properties, as previously suggested. This clearly supports a learning-based perspective of temporal preparation as suggested by Los and colleagues. Moreover, it was demonstrated that additional stimulation during the FP results in performance deficits that are specific to temporal-preparation processes. These effects can be elegantly explained by the dual-process model. Finally, a limitation of a pure learning-based perspective was revealed, namely that responses are (under some circumstances) faster in short–long FP sequences than in long–long FP sequences. From a strictly defined conditioning view, one could argue that responses on long-FP<sub>n</sub> trials should always be faster after reinforcement (after a long-FP<sub>n-1</sub> trial) than after non-reinforcement (after a short-FP<sub>n-1</sub> trial). In a situation with low contextual temporal uncertainty, this was actually observed (consistent with a learning-based view), while under high contextual uncertainty, the detrimental effects of maintaining arousal during long FPs obviously counteracted the beneficial effects of reinforcement (consistent with a dual-process view).

Taken together, the present results argue against the assumptions of the classic strategic-preparation model of variable-FP effects. First of all, the classic view considers that an individual's temporal expectation continuously increases with the length of the FP interval (which explains the negatively sloped FP–RT function), while the effect of a sequential variation of FP length is not incorporated. More specifically, the present results contradict the widely accepted strategic-preparation view that people use the WS only symbolically to endogenously initiate preparatory activity. Precisely, the classic view cannot explain the effect of a shift of WS modality on RT performance as was demonstrated here. Rather, the present findings support a learning-based interpretation of WS effects, namely that a WS triggers memory retrieval of previously stored trial episodes and, thereby, automatically activates preparatory activity. In addition, the classic strategic-preparation model has no answer available regarding the effect of contextual temporal uncertainty (i.e., the scaling/spacing of a certain set of FPs) on the RT pattern in variable-FP experiments. Here it is at least necessary to implement an energetic mechanism that taps on the difficulty to maintain a certain level of response readiness over longer time periods. Vallesi and colleagues considered this problem and transformed the classic strategic-preparation model into a dual-process model. This present work presents the first systematic evaluation of the potential influence of temporal context on preparatory efficiency, and the results can be elegantly explained by the dual-process model. Finally, the currently debated theoretical accounts (trace-conditioning model vs. dual-process model) could be distinguished regarding their range of validity.

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In sum, the present work allows specifying conditions under which either conditioning processes or mechanisms described by the dual-process model predominantly govern temporal preparation for speeded action under time uncertainty. It can thus be concluded that the mechanisms put forth in both models are not mutually exclusive but rather competitive or even complementary. Ultimately, both theoretical accounts appear to be essential for explaining the full range of variable-FP phenomena, supporting the notion of non-specific preparation being a multi-component process.

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## **11 APPENDIX**

Papers 1, 2, 3, 4, und 5



## 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 sharp-edged 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/m<sup>2</sup>) at the center of a grey (38.4 cd/m<sup>2</sup>) 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  $\eta^2$ ; 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,  $F(2,42) = 8.3$ ,

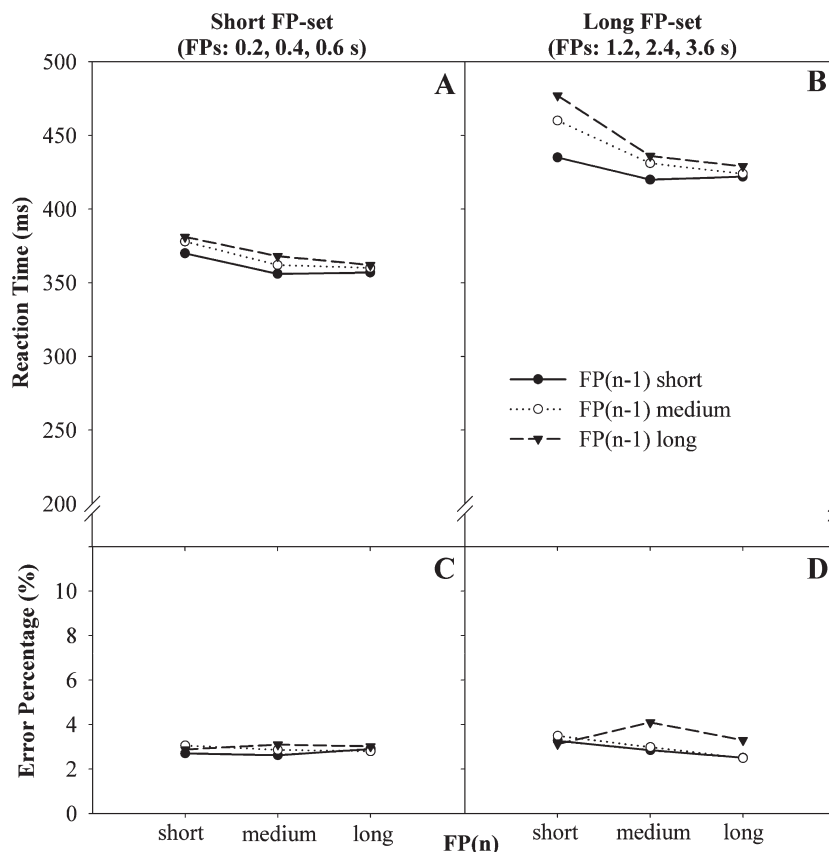


Fig. 1. Reaction time (panel A, B) and error percentage (panel C, D) as a function of the preceding foreperiod ( $FP_{n-1}$ ) and the current foreperiod ( $FP_n$ ) in Experiment 1. Data are separately displayed for the short FP-set (left panel, FPs: 0.2, 0.4, 0.6 s) and the long FP-set (right panel,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

partial  $\eta^2 = .28$ ,  $p < .01$ , and also a significant  $FP\text{-set} \times FP_{n-1}$  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  $FP\text{-set} \times FP_{n-1} \times FP_n$  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.

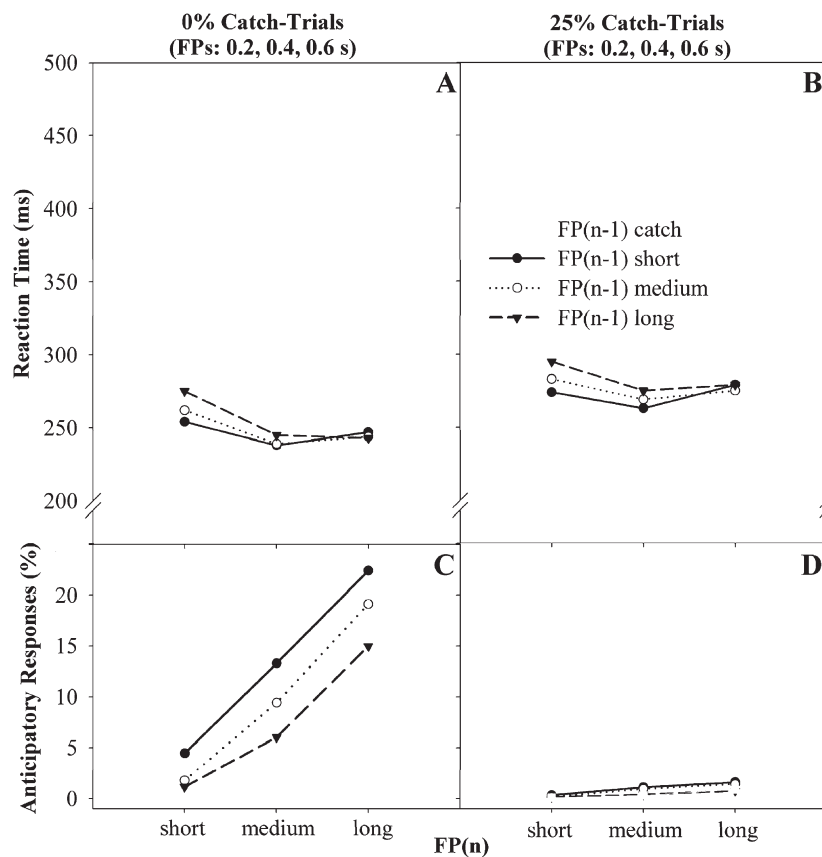
### 3.2. Results and discussion

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.

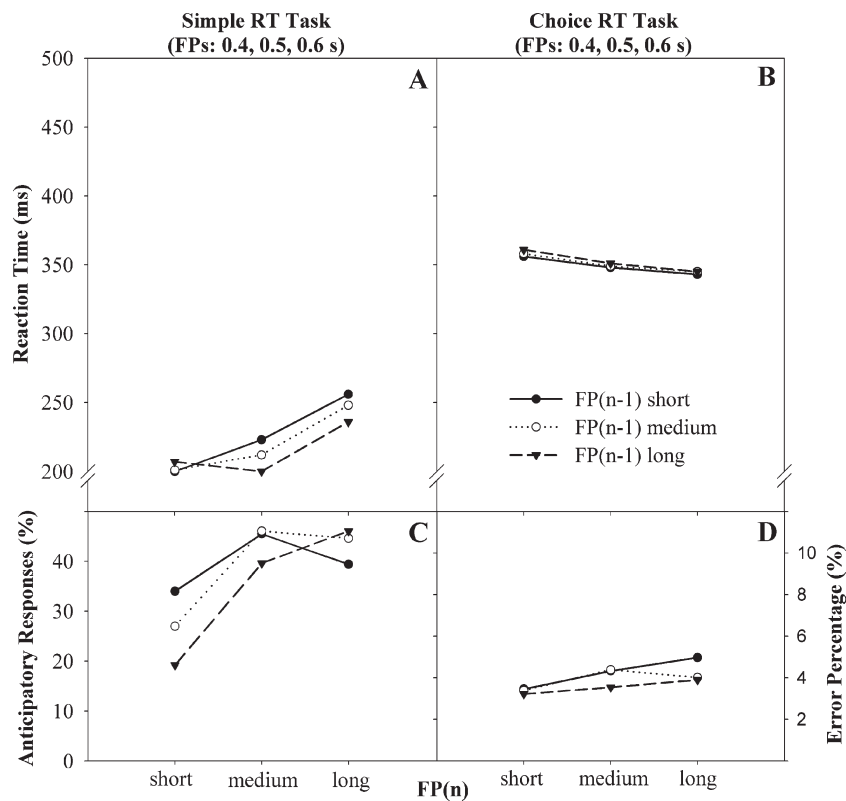
**Stimuli and apparatus.** All stimuli were identical to Experiments 1 and 2.

**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-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)<sup>1</sup>.

## 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

<sup>1</sup> 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 0.4, 0.5, 0.6 0.8, 1.0, 1.2 1.6, 2.0, 2.4 2.8, 3.5, 4.2	4.25 0.5 1.0 2.0 3.5	Simple RT
Drazin (1961)	Experiment 1 0.5–2.5 1.0–2.0 1.25–1.75 Experiment 2 0.125–1.125 0.25–1.25 0.5–1.5 1.0–2.0 2.0–3.0	1.5 1.5 1.5 0.625 0.75 1.0 1.5 2.5	Simple RT
Zahn and Rosenthal (1966)	1, 3 3, 10	2.0 8.0	Simple RT
Baumeister and Joubert (1969)	2, 4, 8, 16	7.5	Simple RT
Näätänen (1970)	2.5, 3.0, 3.5 2, 3, 4 1, 3, 5	3 3 3	Simple RT
Schupp and Schlier (1972)	0.8–5.8 0.8–7.4 0.8–12.4	2.5 3.3 5.8	Simple RT
Stilitz (1972)	1, 3, 5	3.0	Simple RT
Possamai, Granjon, Requin, and Reynard (1973)	1, 2, 3, 4, 5, 6 2, 4, 6, 8, 10, 12 4, 8, 12, 16, 20, 24	3 3 3	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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## Dynamic adjustment of temporal preparation: Shifting warning signal modality attenuates the sequential foreperiod effect

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### ABSTRACT

We examined sequential effects in the variable foreperiod (FP) paradigm, which refer to the finding that responses to an imperative signal (IS) are fast when a short FP trial is repeated but slow when it is preceded by a long FP trial. The effect has been attributed to a trace-conditioning mechanism in which individuals learn the temporal relationship between a warning signal (WS) and the IS in a trial-by-trial manner. An important assumption is that the WS in a current trial (i.e., trial  $FP_n$ ) acts as a conditioned stimulus, such that it automatically triggers the conditioned response at the exact critical moment that was imperative in the previous trial (i.e., trial  $FP_{n-1}$ ). According to this assumption, a shift from one WS modality in trial  $FP_{n-1}$  to another modality in trial  $FP_n$  is expected to eliminate or at least reduce the sequential FP effect. This prediction was tested in three experiments that included a random variation of WS modality and FP length within blocks of trials. In agreement with the prediction, a shift in WS modality attenuated the asymmetry of the sequential FP effect.

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### 1. Introduction

The present study examines the role of warning signals (WS) in temporal preparation experiments. In such experiments, a WS precedes the imperative signal (IS) by a certain duration (referred to as foreperiod, FP), which enables non-specific preparation to the IS (Hackley & Valle-Inclan, 2003; Los & Schut, 2008). Reaction times (RTs) are especially short when the length of the FP interval is predictable and individuals can synchronize peak readiness with the imperative moment (i.e., the moment of IS presentation). But even when FP randomly varies across subsequent trials and the imperative moment cannot exactly be predicted (i.e., variable FP paradigm), the time flow after the WS event provides information that can be exploited to enhance their preparatory state. Since the conditional probability that the IS occurs at a particular moment increases with time, slow responses are observed in short FP trials but especially fast responses in long FP trials. That is to

say, RT is a downward-sloping function of FP in the variable FP paradigm (e.g., Drazin, 1961; Klemmer, 1956).

A traditional strategic account attributes this FP-RT function to a process of conditional probability monitoring during the FP interval. In fact, the characteristic downward-sloping of RT with the length of FP is taken as evidence that the individual somehow converts the objective increase of the conditional probability of IS occurrence into a subjective expectation (Niemi & Näätänen, 1981, p. 137). An important theoretical assumption of this account is that the individual actively tracks the time flow after the WS and enhances preparation accordingly (Näätänen & Merisalo, 1977). The empirical fact that the FP-RT function changes in slope when different FP-distributions are used that correspond to different conditional probabilities is usually taken as support for this view. For example, when a FP distribution is used that equalizes the conditional probabilities for each imperative moment, termed a non-aging FP distribution, it is shown that the FP-RT function typically becomes flat (e.g., Baumeister & Joubert, 1969; Näätänen, 1971; Zahn & Rosenthal, 1966).

A trace conditioning account introduced by Los and colleagues (Los & Agter, 2005; Los & Heslenfeld, 2005; Los, Knol, & Boers, 2001; Los & Van den Heuvel, 2001) suggests an alternative

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explanation according to which the FP-RT function is shaped by an unintentional process of associative learning (cf. Machado, 1997; Moore, Choi, & Brunzell, 1998). Specifically, it is assumed that the individuals learn the temporal relationship between WS and IS in a trial-by-trial manner. Accordingly, the downward-sloping FP-RT function is considered to arise largely from sequential effects (Alegria & Delhaye-Rembaux, 1975; Los & Agter, 2005), which refers to the fact that RT in a current trial not only depends on the current FP (i.e.,  $FP_n$ ) but also on FP of the immediately preceding trial (i.e.,  $FP_{n-1}$ ). Specifically, responses in a short  $FP_n$  trial are slower when preceded by a long  $FP_{n-1}$  than when preceded by an equally long or shorter  $FP_{n-1}$  trial (e.g., Karlin, 1959; Klemmer, 1956; Steinborn, Rolke, Bratzke, & Ulrich, 2008; Vallesi et al., 2007; Vallesi & Shallice, 2007; Van der Lubbe, Los, Jaskowski, & Verleger, 2004; Van Koningsbruggen & Rafal, 2009). Thus, the sequential FP effect is asymmetric since it is restricted to short  $FP_n$  trials whereas long  $FP_n$  trials are not subject to a sequential modulation.

Los et al.'s model relies on the following assumptions (cf. Los & Van den Heuvel, 2001, p. 373). First, the conditioned strength at a critical moment (i.e., one of the three possible imperative moments) is reinforced when the IS occurs at this moment. Second, the conditioned strength at a critical moment remains unchanged when the IS occurs at an earlier critical moment, and third, the conditioned strength at a critical moment decreases when the critical moment is bypassed because the IS occurs at a later critical moment. The model makes specific predictions about possible FP sequences in the variable FP condition. When a short FP length is repeated, fast responses are predicted because response strength was reinforced at the same imperative moment in the preceding trial. When FP alters from long to short, especially slow responses are predicted because the imperative moment was bypassed in the preceding trial, resulting in a decrease of conditioned response strength at short  $FP_n$ . Finally, when FP alters from short to long, fast responses are predicted because later imperative moments are less frequently bypassed (e.g., Los & Agter, 2005) and thus less frequently associated with non-responding (e.g., Mattes, Ulrich, & Miller, 1997; Miller, 1998; Reynolds & Miller, 2007, for a discussion in a related domain).

A further yet important assumption of the trace conditioning model concerns the role of the WS in the process of preparation. Since conditioning processes are usually characterized as being unintentional, Los and Van den Heuvel (2001, p. 373) stated that the WS is not solely considered a starting point to intentionally enhance preparation, as would be implied by the strategic view. Instead, it acts as a conditioned stimulus (i.e., a retrieval cue) that unintentionally triggers response activation at previously reinforced critical moments during the FP interval. Like in other trace conditioning models (e.g., Grossberg & Merrill, 1992; Machado, 1997; Moore et al., 1998), the trace is represented as an ordered sequence of time-tagged components. It is assumed that specific features of the WS event initiate an activation cascade such that one component excites the next, and when the IS occurs during this cascade, a time-tagged associative link is established between the sensory representation of the WS and the IS (Los et al., 2001, p. 128). Thus, when a WS event occurs at the beginning of trial  $FP_n$ , which resembles  $FP_{n-1}$ , this event re-activates sensorimotor couplings that were acquired in trial  $FP_{n-1}$ . Consequently, response activation in trial  $FP_n$  is then achieved at the exact critical moment that was imperative in trial  $FP_{n-1}$  (see also Harris, 2006; Logan, 1990; Moore et al., 1998).

A conditioning view of variable FP phenomena implies that response activation at recently reinforced critical moments should be item-specific rather than concept-based since it involves an unintentional translation of sensory inputs into motor outputs. Given a specific set of stimulus features as components of the WS, even goal-directed action can be triggered directly by environmental

stimuli without the need for intentional involvement (e.g., Bargh & Gollwitzer, 1994; Koch, 2001; Miller & Trevena, 2002; Verbruggen & Logan, 2008, for a similar view in related domains). Under the assumption that a successful retrieval of the previously encountered trial episode depends on the similarity between stimuli in the encoding and the test situation (Hommel, Müssele, Aschersleben, & Prinz, 2001; Rescorla, 1976; Tulving & Thompson, 1973), the pattern of sequential effects in the variable FP paradigm should depend on whether elementary attributes of the WS, for example, its sensory modality, are similar or different from those of the previous trial.

Three experiments were conducted in which WS modality was randomly varied within blocks of trials in a variable FP paradigm, considering different WS modality pairings and levels of temporal uncertainty. If temporal preparation depends on mechanisms of elemental associative learning, as proposed by the trace conditioning account of temporal preparation (Los et al., 2001; Los & Van den Heuvel, 2001), a shift in WS modality should eliminate or at least reduce the typical asymmetric sequential FP effect that is typically found in WS modality repetition trials.

## 2. Experiment 1

In Experiment 1 (choice RT task), a variable FP paradigm (FPs: 1200 and 3600 ms) was employed in which WS modality (auditory and visual) randomly varied within blocks of trials. As stated before, if the WS triggers the conditioned response rather automatically, the typical asymmetric sequential FP effect should be observed in WS modality repetition trials but should be reduced in WS modality shift trials.

### 2.1. Method

*Participants.* Twenty-four (9 males and 15 females) volunteers (mean age = 26.2 years,  $SD = 6.4$ ) took part in this experiment. All participants but one were right-handed and all of them had normal or corrected-to-normal vision.

*Stimuli and apparatus.* The experiment was run in a dim and noise-shielded room; it was controlled by an IBM computer with color display (19", 150 Hz refresh rate) and programmed in MATLAB™ using the Psychophysics Toolbox extensions (Brainard, 1997). Participants were seated 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 WS was either auditory or visual and appeared for 200 ms. The auditory WS (1000 Hz frequency; 70 dB SPL) was presented binaurally via headphones and the visual WS (a white star;  $100 \text{ cd/m}^2$ ;  $2.4^\circ \times 2.4^\circ$  angle of vision) was presented in the centre of a grey ( $38.4 \text{ cd/m}^2$ ) computer screen. The letter "L" or "R" ( $1.14^\circ \times 0.86^\circ$  angle of vision) served as the IS and was displayed in blue ( $7.1 \text{ cd/m}^2$ ) at the centre of the computer screen.

*Design and procedure.* Participants performed a two-choice response task and were required to respond with either the left shift-key (left index finger, if "L" was presented) or the right shift-key (right index finger, if "R" was presented). We used a three-factorial within-subject design, with factors WS-modality sequence (WS-SEQ: repetition of WS modality vs. shift of WS modality), previous FP length ( $FP_{n-1}$ : short vs. long) and current FP length ( $FP_n$ : short vs. long).

A trial started with the presentation of the WS, followed by a blank FP interval after which the IS occurred. The IS was terminated either by the participant's response or when the response interval expired after 2000 ms. A constant intertrial interval of 1500 ms separated subsequent trials. 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 word “falsch” (wrong) was presented for 300 ms, whereas in case of response interval expiration, the phrase “zu langsam” (too slow) was presented for 300 ms. Participants performed 48 practice trials and 1040 experimental trials; a short break was given after each block of 150 trials.

## 2.2. Results and discussion

RTs shorter than 100 ms or longer than 1000 ms were considered outliers and corresponding trials were discarded from the analysis (0.5%). Wrong responses (i.e., pressing the wrong response key) were classified as response errors and corresponding trials were also discarded from RT analysis. A three-factorial within-subject analysis of variance (ANOVA) was performed, with WS-modality sequence (WS-SEQ: repetition of WS modality vs. shift of WS modality), previous FP length ( $FP_{n-1}$ : short vs. long) and current FP length ( $FP_n$ : short vs. long) as factors and RT as the main dependent variable. Both main effects and interaction effects are listed in Appendix A and only the most important effects will be subsequently reported. Fig. 1 displays RT and error percentage for the case when WS modality was repeated (Panels A and C) and the case when WS modality was shifted (Panels B and D).

Consistent with the conditioning account, a significant WS-SEQ  $\times$   $FP_{n-1} \times FP_n$  interaction effect was observed [ $F(1, 23) = 13.6$ ; partial  $\eta^2 = 0.37$ ;  $p < 0.001$ ], indicating that the size of the asymmetric sequential FP effect was larger when WS modality was repeated compared to when WS modality was shifted (see Fig. 1). When WS modality was repeated, the sequential effect at short

$FP_n$  (i.e., RT after a long- $FP_{n-1}$  minus RT after a short  $FP_{n-1}$ ) was 31 ms. This effect decreased to 18 ms when WS modality was shifted. Thus, a shift of WS modality attenuated the sequential FP effect at short  $FP_n$  by 42%. Also note that error rate varied only in a small range (Fig. 1) and there were no statistical effects on error rate (Table 1). This clearly indicates that the results are not confounded by a speed-accuracy tradeoff.

Our main ANOVA collapsed the data across WS modalities allowing a direct assessment of a modality shift on the sequential FP effect. However, in order to examine whether the obtained modality shift effect is furthermore modulated by the specific WS modalities, we performed an additional ANOVA. This analysis included the factors (a) sensory WS modality in trial  $n - 1$  (auditory vs. visual), (b) sensory WS modality in trial  $n$  (auditory vs. visual), (c) foreperiod length in trial  $n - 1$  ( $FP_{n-1}$ : short vs. long), and (d) foreperiod length in trial  $n$  ( $FP_n$ : short vs. long). This additional analysis revealed significant effects of WS modality. Importantly, however, the inclusion of WS modality did not meaningfully change the pattern of switch vs. repetition effects assessed with the simpler ANOVA design as aforementioned. Specifically, the attenuation of the sequential effect after a switch appeared in both modality switch sequences (i.e., visual–auditory or auditory–visual). Nevertheless, a significant four-way interaction emerged indicating a modulation of the attenuation effect by WS modality [ $F(1, 23) = 13.7$ ,  $p < 0.01$ , partial  $\eta^2 = 0.37$ ]. The attenuation effect was 34% comparing visual–visual with visual–auditory WS sequences and 46% comparing auditory–auditory with auditory–visual WS sequences. That is, a shift from auditory to visual WS modality produced a stronger attenuation of the sequential FP effect than a shift from visual to auditory WS modality.

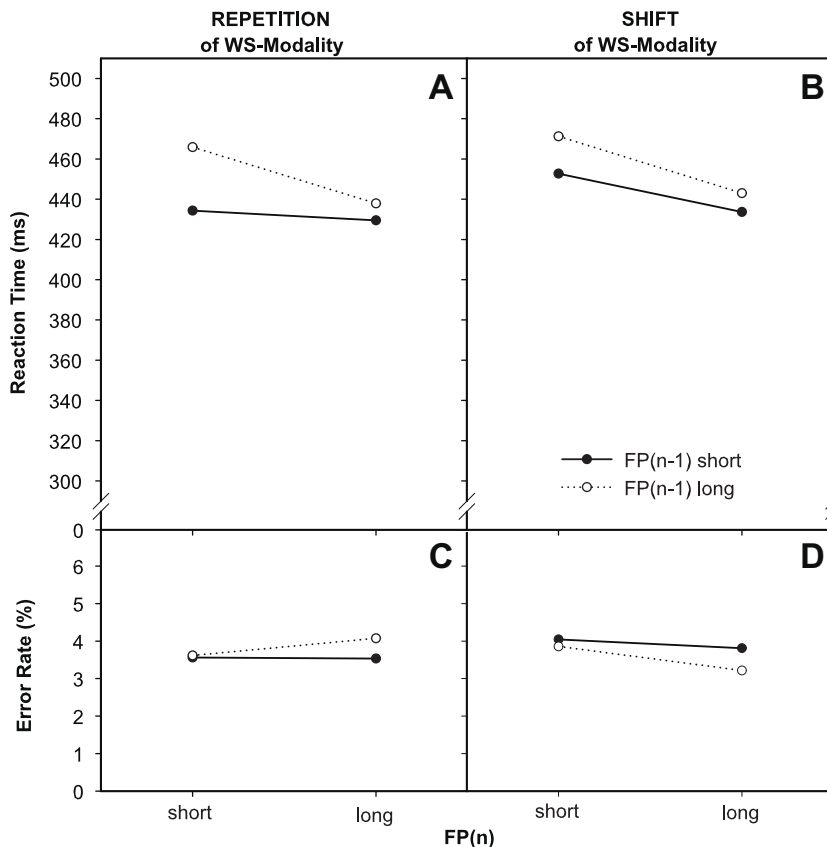


Fig. 1. Mean reaction time and error percentage as a function of the preceding foreperiod ( $FP_{n-1}$ ) and the current foreperiod ( $FP_n$ ) in Experiment 1. Data are separately displayed for WS modality repetition trials (Panels A and C) and WS modality shift trials (Panels B and D).

In sum, the present results revealed a clear-cut influence of a WS modality shift vs. repetition on the individuals' temporal preparation. Although a shift of WS modality from trial  $FP_{n-1}$  to  $FP_n$  did not eliminate the sequential FP effect, it clearly attenuated its asymmetry by reducing the repetition benefit on RT in short  $FP_n$  trials. This dependence on stimulus features indicates that automatic preparatory activity due to specific WS features substantially contributes to temporal preparation in the variable FP paradigm, as is expected from the perspective of a trace conditioning account. In addition, responses were always fast in long  $FP_n$  trials, irrespective of the length of  $FP_{n-1}$  and irrespective of whether WS modality was repeated or shifted. This indicates that the WS triggers the conditioned response only in short  $FP_n$  trials but has virtually no influence in long  $FP_n$  trials.<sup>1</sup>

### 3. Experiment 2

Experiment 2 (FPs: 1200 and 3600 ms; choice RT) was conducted to examine whether the result of Experiment 1 is rather specific to the WS modality pairing used in Experiment 1 (i.e., auditory and visual), or whether it generalizes to other WS modality pairings. Hence, in order to examine the robustness and generality of the attenuation of the sequential FP effect due to WS modality changes, Experiment 2 used a different WS modality pairing, that is, an auditory WS and a vibrotactile WS.

#### 3.1. Method

**Participants.** Thirty (12 males, 18 females) volunteers (mean age = 26.0 years,  $SD = 6.7$ ) took part in the experimental session. All participants but four were right-handed and all of them had normal or corrected-to-normal vision.

**Stimuli and apparatus.** The experimental setting was the same as in Experiment 1 and only the WS modality pairing was different (i.e., using an auditory WS and a vibrotactile WS). The auditory WS (1000 Hz frequency; 70 dB SPL) was binaurally presented via headphones and the vibrotactile WS (a vibrotactile stimulation via TheraTapper™) was fixed at the inside of the participants' lower legs.

**Task, design and procedure.** The task, the design and the procedure were the same as in Experiment 1.

#### 3.2. Results and discussion

RTs shorter than 100 ms or longer than 1000 ms were considered outliers and corresponding trials were discarded from the analysis (0.5%); wrong responses were used to compute the percentage of errors. Fig. 2 summarizes the results and depicts RT and error percentage as a function of  $FP_{n-1}$  and  $FP_n$ , separately

<sup>1</sup> One reviewer suggested that if the state of conditioning is modulated by the sequence of WS-modalities, there may also be higher-order sequential effects on RT with regard to WS triple sequences. Accordingly, we analysed the four possible WS triple sequence patterns: auditory–auditory–auditory/visual–visual–visual (AAA), auditory–auditory–visual/visual–auditory–auditory (AAB), auditory–visual–auditory/visual–auditory–visual (ABA), and auditory–visual–visual/visual–auditory–auditory (ABB). If there is any influence of trial  $n - 2$ , this should be indicated by a four-way interaction of the factors WS sequence pattern (AAA, AAB, ABA, ABB),  $FP_{n-2}$  (short vs. long),  $FP_{n-1}$  (short vs. long), and  $FP_n$  (short vs. long). The main effect of  $FP_{n-2}$  on RT [ $F(1, 23) = 11.5$  partial  $\eta^2 = 0.33$ ;  $p < 0.01$ ] indicates the presence of higher-order sequential effects. The overall RT pattern was increased (7 ms) when  $FP_{n-2}$  was long compared to that when it was short. There was also an interaction between  $FP_{n-2}$  and  $FP_{n-1}$  [ $F(1, 23) = 5.2$ ; partial  $\eta^2 = 0.18$ ;  $p < 0.05$ ] but no three-way interaction between  $FP_{n-2}$ ,  $FP_{n-1}$ , and  $FP_n$  ( $F < 1$ ) on RT. Notably, the factor WS sequence pattern did not significantly interact with  $FP_{n-2}$ ,  $FP_{n-1}$ , and  $FP_n$  ( $F < 1$ ). In sum, besides the main effect of  $FP_{n-2}$ , (e.g., Los et al., 2001; Possamai, Granjon, Reynard, & Requin, 1975) there was no evidence for higher-order sequential effects related to WS modality sequence.

for the two levels of the factor WS-SEQ: repetition of WS modality (Panels A and C) and shift of WS modality (Panels B and D). Appendix A contains all specific ANOVA results.

The WS-SEQ  $\times$   $FP_{n-1} \times FP_n$  interaction effect was again significant [ $F(1, 29) = 4.5$ ; partial  $\eta^2 = 0.13$ ;  $p < 0.05$ ]. As in Experiment 1, a shift of WS modality from trial  $FP_{n-1}$  to  $FP_n$  attenuated the asymmetry of the sequential FP effect by reducing the beneficial effect of a short FP repetition on RT. When WS modality was repeated, the sequential effect at short  $FP_n$  (i.e., RT after a long- $FP_{n-1}$  minus RT after a short  $FP_{n-1}$ ) was 28 ms. This effect decreased to 17 ms when WS modality was shifted. Thus, a shift of WS modality attenuated the sequential FP effect by 39%. As expected, responses were consistently fast in long  $FP_n$  trials, irrespective of  $FP_{n-1}$  and irrespective of whether WS modality was repeated or shifted. As in Experiment 1, error rate varied only in a small range (Fig. 2) and there were no statistically reliable effects on error rate (Table 1). The similarity of the RT pattern in Experiments 1 and 2 demonstrates the generality of the effect across different cross-modal WS modality pairings.

Similar as in Experiment 1, we performed an additional four-way ANOVA including the factors WS modality in trial  $n - 1$ , WS modality in trial  $n$ ,  $FP_{n-1}$ , and  $FP_n$ . As before, this ANOVA revealed a significant four-way interaction [ $F(1, 29) = 4.9$ ,  $p < 0.05$ , partial  $\eta^2 = 0.14$ ]. The attenuation effect was 50% comparing tactile–tactile with tactile–auditory WS sequences, and 32% comparing auditory–auditory with auditory–tactile WS sequences. That is, a shift from the vibrotactile to the auditory WS modality produced a stronger attenuation of the sequential FP effect than a shift from the auditory to the vibrotactile WS modality.

### 4. Experiment 3

Since the modulating influence of the factor WS-SEQ on the sequential FP effect in Experiments 1 and 2 was small, one could argue that the relative contribution of automatic response activation is only marginal. However, such an interpretation may be premature since the actual size of the attenuation effect induced by the WS factor may depend on the degree of temporal uncertainty that is imposed by the experimental design (Klemmer, 1956; Niemi & Näätänen, 1981, p. 137). Moreover, the use of a choice RT task instead of a simple RT task may have resulted in a decrease of the sequential FP effect because parts of the effect could be absorbed during central processing in the choice RT task (Correa, Lupiáñez, Milliken, & Tudela, 2004; Steinborn et al., 2008). In order to increase temporal uncertainty in Experiment 3, we used three (FPs: 1000, 2500, and 4000 ms) instead of two FPs and a broader FP-range. In addition, we used a simple instead of a choice RT task. Experiment 3 thus aimed at replicating Experiment 1 (auditory and visual WS modality) under conditions of higher temporal uncertainty that has been shown to produce a larger sequential FP effect and with a simple instead of a choice RT task. By this means, this should also provide a greater opportunity to obtain a modulation of the sequential FP effect by the factor WS modality sequence.

#### 4.1. Method

**Participants.** The data of 30 (9 males, 21 females) volunteers (mean age = 23.7 years,  $SD = 5.1$ ) were entered into the analysis of the experimental data (one of 31 participants was excluded because of technical problems). All participants but three were right-handed and all of them had normal or corrected-to-normal vision.

**Stimuli and apparatus.** The experimental setting in Experiment 3 was identical to Experiment 1 except that three FPs (1000, 2500, and 4000 ms) instead of two FPs were used, with an auditory–visual cross-modal WS modality pairing.

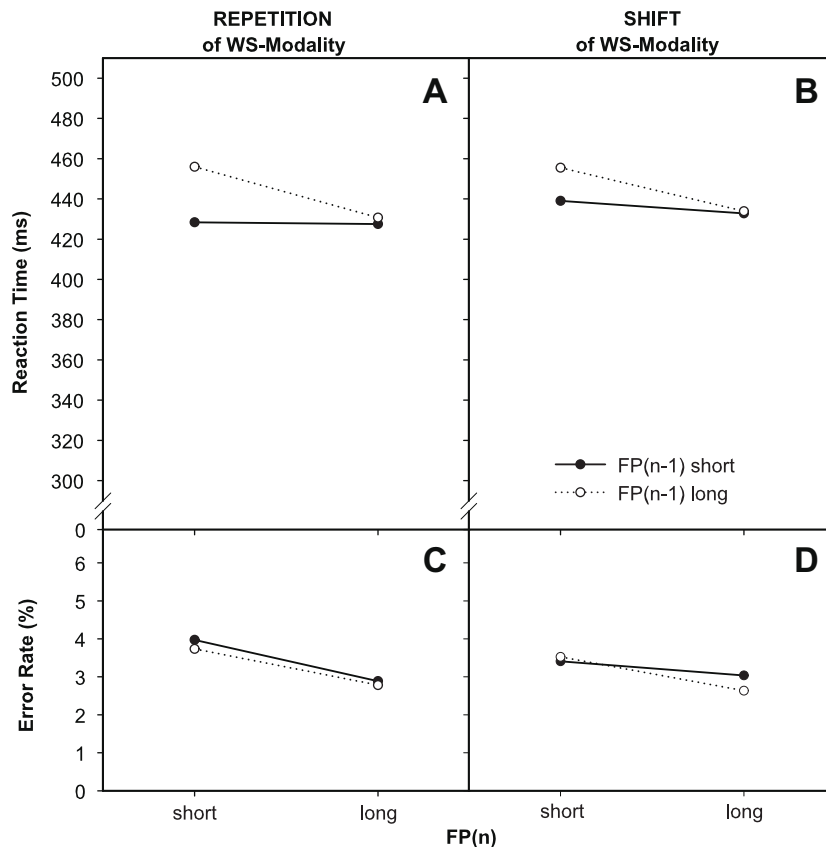


Fig. 2. Mean reaction time and error percentage as a function of the preceding foreperiod ( $FP_{n-1}$ ) and the current foreperiod ( $FP_n$ ) in Experiment 2. Data are separately displayed for WS modality repetition trials (Panels A and C) and WS modality shift trials (Panels B and D).

**Task, design and procedure.** The task, the design, and the procedure were identical to the previous two experiments, except that a simple RT task (instead of a choice RT task) was used. Participants had to respond always with the right index finger irrespective of whether the stimulus was “L” or “R”.

#### 4.2. Results and discussion

Trials with RTs shorter than 100 ms or longer than 1000 ms were discarded from the analysis (0.5%). Premature responses and trials with RTs shorter than 100 ms were defined as anticipatory responses. Fig. 3 summarizes the results and depicts RT as a function of  $FP_{n-1}$  and  $FP_n$ , separately for each level of WS-SEQ: repetition of WS modality (Panel A) and shift of WS modality (Panel B). All main and interaction effects are listed in Appendix A and only the relevant effects are subsequently referred to.

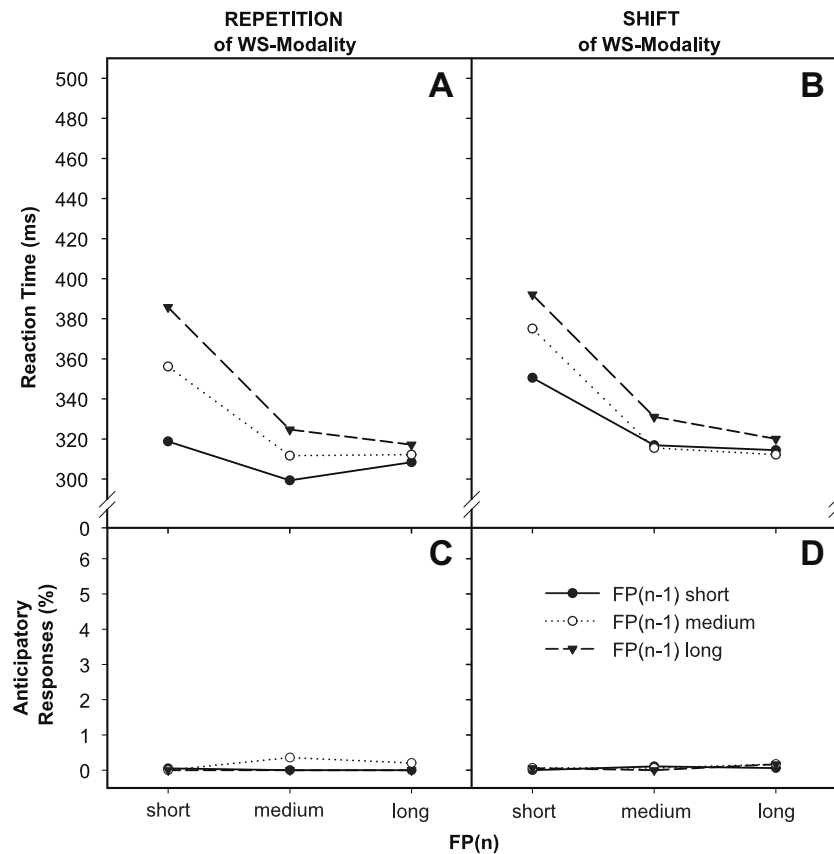
The WS-SEQ  $\times$   $FP_{n-1} \times$   $FP_n$  interaction effect [ $F(4, 116) = 4.7$ ; partial  $\eta^2 = 0.14$ ;  $p < 0.01$ ] replicated the results of Experiments 1 and 2, indicating a modulating influence of the factor WS-SEQ on the sequential FP effect. Shifting WS modality from trial  $FP_{n-1}$  to  $FP_n$  attenuated the asymmetry of the sequential FP effect. When WS modality was repeated, the sequential effect at short  $FP_n$  (i.e., RT after a long- $FP_{n-1}$  minus RT after a short  $FP_{n-1}$ ) was 67 ms. Thus, in accordance with our expectations, the sequential FP effect in Experiment 3 was larger than those observed in Experiment 1 (31 ms) and Experiment 2 (28 ms). This effect decreased to 41 ms when WS modality was shifted. Thus, a shift of WS modality attenuated the sequential FP effect at short  $FP_n$  by 39%. Accordingly, the relative attenuation of the asymmetry of the sequential FP effect at short  $FP_n$  was very similar to those of Experiment 1 (41%) and Experiment 2 (39%). In addition, the factor WS-SEQ had a strong

influence on RT in short  $FP_n$  trials but affected RT minimally in medium  $FP_n$  trials and not at all in long  $FP_n$  trials (Fig. 3). There was only a small percentage of anticipatory responses (Fig. 3). However, the WS-SEQ  $\times$   $FP_{n-1} \times$   $FP_n$  interaction effect shows that not only RT but also anticipatory responding is reduced by a WS modality shift [ $F(4, 116) = 3.0$ ; partial  $\eta^2 = 0.09$ ;  $p < 0.05$ ].

It should be noted that, as in the two preceding experiments, the additional four-way ANOVA again revealed a significant four-way interaction [ $F(4, 116) = 4.2$ ,  $p < 0.01$ , partial  $\eta^2 = 0.13$ ]. The attenuation effect was 34% comparing auditory–auditory with auditory–visual WS sequences and 40% comparing visual–visual with visual–auditory WS sequences. That is, a shift from the auditory to the visual WS modality produced a smaller attenuation of the sequential FP effect than a shift from the visual to the auditory WS modality. This is in contrast to Experiment 1, in which a larger attenuation effect was found for auditory–visual WS modality shifts, compared to visual–auditory WS modality shifts.

#### 5. General discussion

In three experiments, we examined whether a shift of WS modality across subsequent trials (i.e., from  $FP_{n-1}$  to  $FP_n$ ) modulates the sequential FP effect in the variable FP paradigm. The present results can be summarized as follows: First, a repetition of WS modality across subsequent trials revealed the typical downward-sloping FP-RT effect and the typical asymmetric sequential FP effect. A shift of WS modality attenuated the sequential FP effect by about 40%. In short, a shift of WS modality reduced the beneficial effect of a short FP repetition on RT. By contrast, when a long  $FP_{n-1}$  trial preceded a short  $FP_n$  trial, RT did not depend on the sequence of WS modality. Second, the attenuation of the sequential



**Fig. 3.** Mean reaction time and percentage of anticipatory responses as a function of the preceding foreperiod ( $FP_{n-1}$ ) and the current foreperiod ( $FP_n$ ) in Experiment 3. Data are separately displayed for WS modality repetition trials (Panels A and C) and WS modality shift trials (Panels B and D).

FP effect due to a shift of WS modality was reliably observed with different cross-modal WS pairings (i.e., auditory–visual; auditory–vibrotactile), different task forms (i.e., simple and choice RT) and different levels of temporal uncertainty.

The present findings are consistent with other studies that examined effects of acquisition-to-test or trial-to-trial shifts of stimulus modality in experiments on procedural learning and repetition priming. These studies showed that the beneficial effect of previous stimulus exposure on RT is attenuated by a shift of stimulus modality from the training to the test period, or from the previous to the current trial, respectively (e.g., Dennis & Schmidt, 2003; Gondan, Lange, Rösler, & Röder, 2004; Kirsner, Milech, & Standen, 1983; Quinlan & Hill, 1999; Roediger & Blaxton, 1987). Here we extended the aforementioned findings to the temporal domain, demonstrating modality-specific repetition effects of FP length in the variable FP paradigm. To our knowledge, this is the first study that examined the effects of WS modality sequence on the individuals' temporal preparation in the variable FP paradigm. It should be noted, however, that our interest was not on the specific effects of either auditory or visual WS modality (e.g., Rodway, 2005), but on the effects of changes of elementary WS attributes across trials on the sequential FP effect. Nevertheless, the sequential FP effect was differentially modulated by the specific WS modality sequence. In Experiment 1, a shift from auditory to visual WS modality produced a stronger attenuation of the sequential FP effect than a shift from visual to auditory WS modality. In Experiment 3, however, the effect was in the opposite direction. Therefore, it seems that the specific WS modality sequence effects are influenced by task demands (simple RT vs. choice RT) and thus are difficult to interpret at the moment. More research is needed to clarify the role of specific WS modalities on sequential FP effects.

We examined an important property of the trace conditioning model. In particular, we tested the assumption that at critical moments in a current trial, response activation is time-locked to the WS as it was temporally associated with the IS in the previous trial. Consistent with this assumption, models of classical conditioning in related domains likewise assume that a conditioned stimulus acts as a retrieval cue that automatically activates sensorimotor representations of previously encountered trial episodes (e.g., Harris, 2006; Moore et al., 1998; Rescorla, 1976; Tulving & Thompson, 1973). The results obtained in the present experiments generally agree with this assumption, showing that response activation in a current trial is stronger (and responses are faster) when WS modality is repeated compared to the condition when WS modality is shifted. In terms of the trace conditioning account, individuals cannot benefit from previous reinforcement in short FP repetition trials after a shift of WS modality. Interestingly, however, when a short  $FP_n$  is preceded by a long  $FP_{n-1}$ , a shift of WS modality has virtually no effect on RT. This suggests that a shift of WS modality affects performance only at previously reinforced imperative moments but not at previously bypassed imperative moments.

The attenuation of the sequential FP effect due to a shift of WS modality was asymmetric since it appeared predominantly in short  $FP_n$  trials but to a much lesser degree in medium and long  $FP_n$  trials. This observation is not particularly surprising since the typical characteristic of the sequential FP effect is its asymmetry. Therefore, any variable that affects the sequential FP effect is expected to exert its influence only at those critical moments that are subject to a sequential variation. Nevertheless, the asymmetry of the modality sequence effect indicates that response activation in short FP repetition trials is substantially triggered by elementary WS attributes, whereas response activation in longer  $FP_n$  trials is

relatively independent of WS identity. From a trace conditioning view, responses at late imperative moments may already be maximally fast because they are less frequently extinguished and therefore may not benefit additionally from specific WS-triggered temporal preparation (Los et al., 2001; Los & Van den Heuvel, 2001). From a strategic view, however, the especially fast responses at long  $FP_n$  trials may arise from a process of conditional probability monitoring that dominates response preparation at late imperative moments (e.g., Näätänen & Merisalo, 1977; Vallesi & Shallice, 2007; Zahn, Kruesi, & Rapoport, 1991).

Our results thus are also consistent with dual-process views of variable FP phenomena (e.g., Vallesi & Shallice, 2007; Zahn et al., 1991). According to this view, temporal preparation is achieved by a combination of an unintentional process and an intentional process. The unintentional process is similar to the trace conditioning mechanism as proposed by Los and colleagues (Los & Agter, 2005; Los & Heslenfeld, 2005; Los et al., 2001; Los & Van den Heuvel, 2001) and considered to produce the sequential FP effect in short  $FP_n$  trials. The intentional process is sensitive to an increase in the conditional probability of IS presentation and assumed to produce the especially fast responses in long  $FP_n$  trials. Thus, the dual-process model can also account for the asymmetric influence of a shift of WS modality, if one assumes that a shift of WS modality affects only the unintentional component.

Although all three experiments revealed a clear attenuation of the sequential FP effect due to a shift of WS modality, there was still a substantial residual sequential FP effect even when WS

modality was shifted. This finding suggests that temporal preparation is not exclusively triggered by specific sensory WS features, but in some cases (or to some degree) may also be triggered by unspecific stimulation, such as arousal that is evoked by any WS event (Hackley et al., 2009). For example, it has been argued that the salience of a WS, in particular its capability to evoke unspecific orienting, can also become the subject of trial-to-trial trace conditioning (Moore et al., 1998, pp. 5–7). Given that this feature is shared by both auditory and visual WS events (or auditory and tactile, respectively), this may explain the occurrence of the residual sequential FP effect. In other words, the residual sequential FP effect may reflect that, even in WS modality shift trials, successful retrieval of previously encountered trial episodes occurs in some trials, because it is based on the degree of feature commonality between the cross-modal WS events (Rescorla, 1976; Tulving & Thompson, 1973).

Taken together, the present results indicate that RT variations in short  $FP_n$  trials (i.e., learning and re-learning due to sequential FP variability) are influenced by associative learning of sensorimotor connections between WS, time, and IS. The present data therefore suggest that temporal preparation in short  $FP_n$  trials is substantially driven by elementary WS features that, even though task-irrelevant, guide the individuals' preparation at critical moments in the variable FP paradigm. In long  $FP_n$  trials, however, the individuals' preparation does not depend on WS attributes but is already optimal (and thus may be less sensitive to WS modality sequence effects). In conclusion, the present results largely agree with the

**Table 1**  
ANOVA results for Experiments 1 and 2.

	Source	Reaction time				Error percentage		
		dfs	F	p	$\eta^2$	F	p	$\eta^2$
<i>Experiment 1 (auditory and visual WS)</i>								
1	WS-SEQ	1,23	43.7	0.000	0.66	0.2	0.895	0.01
2	$FP_{n-1}$	1,23	67.3	0.000	0.75	0.3	0.895	0.01
3	$FP_n$	1,23	31.9	0.000	0.58	0.1	0.733	0.05
4	$WS-SEQ \times FP_{n-1}$	1,23	8.6	0.007	0.27	2.8	0.109	0.11
5	$WS-SEQ \times FP_n$	1,23	9.1	0.006	0.28	1.6	0.218	0.65
6	$FP_{n-1} \times FP_n$	1,23	30.0	0.000	0.57	0.0	0.927	0.00
7	$WS-SEQ \times FP_{n-1} \times FP_n$	1,23	13.6	0.001	0.37	0.94	0.342	0.04
<i>Experiment 2 (auditory and visual WS)</i>								
1	WS-SEQ	1,29	22.3	0.000	0.44	0.7	0.410	0.24
2	$FP_{n-1}$	1,29	99.2	0.000	0.77	0.5	0.500	0.02
3	$FP_n$	1,29	32.6	0.000	0.53	19.3	0.000	0.40
4	$WS-SEQ \times FP_{n-1}$	1,29	9.4	0.005	0.24	0.0	0.923	0.00
5	$WS-SEQ \times FP_n$	1,29	0.2	0.688	0.01	1.1	0.304	0.04
6	$FP_{n-1} \times FP_n$	1,29	50.3	0.000	0.64	0.2	0.637	0.01
7	$WS-SEQ \times FP_{n-1} \times FP_n$	1,29	4.5	0.044	0.13	1.3	0.255	0.04

Note: Effect size: partial  $\eta^2$ ; FPs: 1200 and 3600 ms, Factors: WS-modality sequence (WS-SEQ: repetition of WS modality vs. shift of WS modality), previous foreperiod ( $FP_{n-1}$ : short vs. long), current foreperiod ( $FP_n$ : short vs. long).

**Table 2**  
ANOVA results for Experiment 3.

	Source	Reaction time				Anticipatory responses		
		dfs	F	p	$\eta^2$	F	p	$\eta^2$
<i>Experiment 3 (auditory and visual WS)</i>								
1	WS-SEQ	1,29	36.2	0.000	0.56	0.1	0.778	0.00
2	$FP_{n-1}$	2,58	190.6	0.000	0.87	4.0	0.039	0.12
3	$FP_n$	2,58	179.7	0.000	0.86	1.3	0.273	0.04
4	$WS-SEQ \times FP_{n-1}$	2,58	15.3	0.000	0.35	2.6	0.084	0.08
5	$WS-SEQ \times FP_n$	2,58	19.7	0.000	0.41	1.7	0.198	0.06
6	$FP_{n-1} \times FP_n$	4,116	62.3	0.000	0.68	1.2	0.318	0.04
7	$WS-SEQ \times FP_{n-1} \times FP_n$	4,116	4.7	0.003	0.14	3.0	0.039	0.09

Note: Effect size: partial  $\eta^2$ ; FPs: 1000, 2500, and 4000 ms; Factors: WS-modality sequence (WS-SEQ: repetition of WS modality vs. shift of WS modality), previous foreperiod ( $FP_{n-1}$ : short vs. medium vs. long), current foreperiod ( $FP_n$ : short vs. medium vs. long).

assumptions of conditioning models (Los & Van den Heuvel, 2001; Moore et al., 1998; Rescorla, 1976) arguing that specific features of the WS event elicit response-related activation at previously reinforced short critical moments without (or only with little) intentional involvement.

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## Appendix A

See Tables 1 and 2.

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## The effect of a cross-trial shift of auditory warning signals on the sequential foreperiod effect

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### ABSTRACT

When a warning signal (WS) precedes an imperative signal (IS) by a certain amount of time (the foreperiod, FP), responses are speeded. Moreover, this effect is modulated by the FP length in the previous trial. This sequential FP effect has lately been attributed to a trace-conditioning mechanism according to which individuals learn (and re-learn) temporal relationships between the WS and the IS. Recent evidence suggests that sensory WS attributes are critical to trigger time-related response activation. Specifically, when WS modality is shifted in subsequent trials (e.g., from auditory to visual modality), the sequential FP effect becomes attenuated. This study examined whether the sequential FP effect is reduced only by between-modality shifts or whether this attenuation generalizes to cross-trial shifts of WS attributes within modalities. We compared dimensional (low vs. high tone frequency) and qualitative shifts (pure tone vs. noise) of equal-intense auditory WS events. The results of four experiments revealed that shifts of tone frequency did not, whereas shifts of qualitative tone characteristics did attenuate the sequential FP effect. These results support the view that the WS acts as a trigger cue that unintentionally activates responses at previously reinforced critical moments.

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### 1. Introduction

Warning signals (WS) preceding an imperative response signal (IS) are known to speed-up responses via both top-down guided (i.e., intentional) and bottom-up triggered (i.e., unintentional) processes (Hackley, 2009; Los & Schut, 2008). In a typical experiment, the IS follows the WS by a certain duration (referred to as foreperiod, FP), enabling individuals to establish a state of nonspecific preparation at the moment of IS occurrence (referred to as the imperative moment). In a constant FP paradigm, the IS occurs regularly on time after the WS and so individuals are enabled to synchronize peak readiness with the imperative moment. In a variable FP paradigm, the IS occurs irregularly after the WS and thus individuals have little reliable information to time their preparation. Consequently, reaction times (RTs) to the IS are longer in the variable FP condition than in the constant FP condition. Moreover, in the variable FP condition, responses are usually slow in short FP trials but fast in long FP trials, yielding a downward-sloping FP-RT function (Niemi & Näätänen, 1981, pp. 137–141). This variable

FP effect is usually interpreted such that the elapsing time after the WS contains information about IS occurrence, since the probability of IS occurrence increases as the FP interval becomes longer (Baumeister & Joubert, 1969; Karlin, 1959; Klemmer, 1957).

From a strategic point-of-view, the WS event is considered a meaningful signal that reminds individuals to intentionally start preparation according to task rules and instructions (Gottsdanker, 1980; Näätänen & Merisalo, 1977). Notably, even when no explicit WS is given (as is the case in serial choice reaction time tasks), individuals may strategically use kinaesthetic feedback of their previous response as a warning to start preparation for the next IS (Rabbitt & Vyas, 1980). This strategic view implies that the individuals engage in a rather abstract cognitive process of attaining preparation, using the WS event symbolically by means of rule-utilization (Bourne, 1966, pp. 19–21), that is without referencing to a particular WS exemplar or to specific sensory attributes of particular exemplars. A further important assumption of this view is that individuals actively track the time flow after the WS and enhance preparation accordingly (Näätänen, 1971; Rabbitt & Vyas, 1980; Requin & Granjon, 1969). This process of monitoring the conditional probability of IS occurrence during the FP interval is considered an intentional process that requires the controlled

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allocation of mental resources and is thus effortful in nature (Näätänen & Merisalo, 1977; Stuss et al., 2005).

According to this strategic view, the downward-sloping of RT with FP length is considered to represent the time course of the individuals' average expectation about IS occurrence (Näätänen & Merisalo, 1977). Changes in the conditional probability of IS occurrence are predicted to cause a change in the FP-RT slope. For example, when a non-aging FP distribution is used that equalizes the conditional probabilities for each critical moment (i.e., a possible moment of IS presentation), the FP-RT function typically becomes flat (e.g., Baumeister & Joubert, 1969; Zahn & Rosenthal, 1966). Furthermore, Coull and Nobre (1998) describe a mechanism similar to the conditional probability monitoring process in the context of explicit cueing studies: Individuals are considered to intentionally exploit any advance information about temporal intervals to orient attention to a time point at which the IS is expected to occur (see also, Correa, Lupiáñez, Milliken, & Tudela, 2004; Lange, Rösler, & Röder, 2003).

In contrast to the strategic view, a trace-conditioning viewpoint (Los & Agter, 2005; Los & Heslenfeld, 2005; Los, Knol, & Boers, 2001; Los & Van den Heuvel, 2001) assumes that the individuals capitalize on previously established associative connections between the WS and the moment of IS occurrence. Specifically, if a connection due to previously encountered temporal relationships is established, the WS event acts as a retrieval cue that automatically triggers response-related activation at critical moments (Los & Van den Heuvel, 2001, pp. 371–373; Los et al., 2001, p. 125). As in other models, the trace is represented as an ordered sequence (i.e., a chain) of time-tagged components. Each component is assumed to act like a conditioned stimulus, capable of triggering the subsequent event. The WS event starts an activation cascade such that one component excites the next until the IS occurs during the cascade. When the IS occurs, an associative link is established between the respective component on the time line and the IS (Los et al., 2001, p. 128). Thus, when the current FP ( $FP_n$ ) resembles the foreperiod of the previous trial ( $FP_{n-1}$ ), it re-activates stored memories acquired in trial  $n-1$  at the exact critical moment that was imperative in the previous trial (cf. Machado, 1997; Moore, Choi, & Brunzell, 1998, for models in related domains).

According to the trace-conditioning view, the downward-sloping FP-RT function is considered to arise from sequential effects due to variable FP length. This sequential FP effect refers to the fact that responses in a short  $FP_n$  trial are slower when preceded by a long  $FP_{n-1}$  than when preceded by an equally long or shorter  $FP_{n-1}$  trial (e.g., Elliot, 1970; Karlin, 1959; Steinborn, Rolke, Bratzke, & Ulrich, 2008; Vallesi, McIntosh, Shallice, & Stuss, 2009; Van der Lubbe, Los, Jaśkowski, & Verleger, 2004). Thus, the sequential FP effect is asymmetric since it is restricted to short  $FP_n$  trials whereas long- $FP_n$  trials are not subject to a sequential modulation. This sequential FP effect is explained by a set of conditioning rules (Los & Van den Heuvel, 2001, p. 372): Conditioned strength at critical moments is reinforced when the IS occurs at this moment, remains unchanged when the IS occurs earlier, but decreases when the IS occurs at a later critical moment. Accordingly, fast responses are predicted in FP-repetition trials because response strength was reinforced in the preceding trial. Fast responses should also occur in short-to-long FP sequences because later critical moments were not bypassed in the preceding trials. However, slow responses are predicted in long-to-short FP sequences because the short critical moment was bypassed previously, resulting in a decrease of conditioned response strength at short  $FP_n$ .

As outlined before, there are two theoretical views of how WS events are recruited for temporal preparation. (a) According to a strategic view, individuals utilize stimuli that are instructed as to symbolize the WS, and intentionally start preparation henceforward. From this perspective, therefore, variations in elementary

WS attributes should not affect preparation. (b) By contrast, the trace-conditioning view assumes that the WS causes retrieval of the previous trial episode, and the preparatory process runs down similarly as in the previous trial (Los & Van den Heuvel, 2001, p. 373). From this perspective, variations in stimulus attributes are likely to affect preparation, such that a change in critical WS attributes impairs the retrieval of episodic memories. This view is supported by other models in the context of classical conditioning, procedural learning, and memory research. For example, Tulving and Thompson (1973) has argued that the probability of successful retrieval of an item stored in memory is an increasing function of the similarity between the item encountered at encoding and those presented at retrieval. This recruitment-by-similarity assumption is common to many instance-theoretic explanations of episodic memory (see also Bouton & Moody, 2004, p. 669; Logan, 1990, p. 6). Importantly, the encoding-specificity model considers retrieval an all-or-none process (retrieval is either successful or not) but evidence for gradual processes have been shown as well (cf. Turatto, Benso, Galfano, & Umiltà, 2002; Töllner, Gramann, Müller, & Eimer, 2009).

The trace-conditioning view suggests transfer effects between stimuli at training and test (here between WS events between  $FP_{n-1}$  and  $FP_n$ , respectively) that should be larger for similar than for dissimilar stimuli, and changes in stimulus attributes are expected to result in less efficient retrieval processes. In fact, recent evidence suggests that preparation is more efficient when WS modality is repeated compared to when it is shifted across subsequent trials – a finding that is in accord with the trace-conditioning view. Steinborn, Rolke, Bratzke, and Ulrich (2009) demonstrated that a repetition of WS modality from  $FP_{n-1}$  to  $FP_n$  exhibited the standard variable FP effect. Shifting WS modality, however, increased the slope of the  $FP_n$ -RT function due to an attenuation of the sequential FP effect. More specifically, a shift of WS modality increased RT in short-to-short FP sequences (when a short  $FP_n$  trial is preceded by a short  $FP_{n-1}$ ), but did not affect RT in long-to-short FP sequences (when a short  $FP_n$  trial is preceded by a long  $FP_{n-1}$ ). Based on these findings, a retrieval failure hypothesis was postulated, which implies that despite WS (in modality-shift trials) being sufficiently attended, successful re-instantiation of the previously encountered trial episode ( $FP_{n-1}$ ) has not taken place. Consequently, stimulus-triggered preparation fails and does not aid individuals when preparing for the impending IS event, resulting in a slowing of responses especially in short  $FP_n$  trials.

Although the attenuation of the sequential FP-effect in modality-shift trials (Steinborn et al., 2009) is in line with the trace-conditioning view, the pattern of results might be interpreted in alternative ways. First, one might assume that those participants failed to attend to the WS in modality-shift trials because attention prevails in the WS modality of the previous trial. According to such an attention-based explanation, a modality shift attenuates the variable FP effect because mental focus was not sufficiently directed to the relevant WS attributes (e.g., Hommel, 2009, pp. 516–518; Spence, Nicholls, & Driver, 2001). If one does not attend to the WS at the time of its occurrence, relevant information cannot be extracted and automatic preparation is likely to fail. In order to establish a retrieval failure interpretation of WS shifts in the variable FP paradigm, it is thus necessary to show that the attenuation of the sequential FP effect occurs even when it is ensured that attention is directed to the actual WS modality (Spence et al., 2001). Second, since intensity can hardly be controlled between modalities, a shift of WS modality might have induced a change in phasic arousal (Hackley, 2009). In particular, a shift from visual to auditory WS modality may artificially speed-up RT because auditory signals are considered intrusive and more arousing than visual ones. A shift from auditory to visual WS modality may also produce artificial effects on RT but in the opposite direction (cf.



Grice, 1968). To strengthen the trace-conditioning account, it is therefore necessary to demonstrate a modulation of the sequential FP-effect in WS-shift trials when WS intensity is kept constant.

The present study aimed to rule out both confounds, attention-to-modality effects (i.e., the WS is not sufficiently attended in WS-shift trials) and intensity-shift effects (i.e., the WS is especially attended when intensity increases across trials but less attended when intensity decreases across trials) by examining the effect of a repetition versus a shift of WS attributes within modalities on the sequential FP effect. The design was similar to the one of Steinborn et al.'s (2009) study. Specifically, two WS events were randomly varied within blocks of trials in a variable FP paradigm. In contrast to the previous study, the shift from one WS event to the next occurred exclusively within the auditory modality. According to our knowledge, no study so far has examined within-modality WS-shift effects in temporal preparation. Thus it seemed natural to employ well-distinguishable pure tones (i.e., 1000 and 1400 Hz). Taking recent developments in related domains into account, we also considered shifts between qualitative tone characteristics (e.g., Schröter, Ulrich, & Miller, 2007), different task conditions (e.g., Correa et al., 2004), and levels of temporal uncertainty (e.g., Karlin, 1959; Steinborn et al., 2009). In all experiments, it was ensured that the WS stimuli were easy to distinguish and of similar sound intensity. If the modality-shift effect reported by Steinborn et al. merely reflects a failure of attending the appropriate sensory modality in modality-shift trials, a within-modality shift of WS features should not modulate the sequential FP effect.

## 2. Experiment 1

In Experiment 1 (two-choice RT task), a variable FP paradigm (FPs: 1200 vs. 3600 ms) was employed in which two well-distinguishable auditory WS (1000 vs. 1400 Hz) were randomly varied within blocks of trials. If a shift between tone frequencies affects trace-conditioning, as has been demonstrated for shifts between modalities (Steinborn et al., 2009), the sequential FP effect should be attenuated. This would be indicated by a significant WS-SEQ  $\times$  FP<sub>n-1</sub>  $\times$  FP<sub>n</sub> interaction effect.

### 2.1. Method

#### 2.1.1. Participants

Thirty-five (8 male, 27 female) volunteers (mean age = 24.7 years, SD = 5.7) took part in the experimental session. All participants but six were right-handed and all of them had normal or corrected-to-normal vision.

#### 2.1.2. 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 programmed in MATLAB™ using the Psychophysics Toolbox extensions (Brainard, 1997). Participants were seated at a distance of about 60 cm in front of the computer screen. A dot sign (0.5°  $\times$  0.5° angle of vision) served as fixation point and therefore was constantly presented throughout the experimental session in the middle of the screen. The auditory WS (either 1000 or 1400 Hz frequency; 70 dB SPL) was binaurally presented via headphones for 200 ms. All participants reported that they could easily judge the difference between the two pure tones. The letters "L" and "R" (1.14°  $\times$  0.86° angle of vision) served as the IS and were presented visually, displayed in blue (7.1 cd/m<sup>2</sup>) at the centre of the screen.

#### 2.1.3. Design and procedure

Participants performed a two-choice response task and were required to respond 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"). We used a three-factorial within-subject design, with the factors WS-SEQ (repetition vs. shift), FP<sub>n-1</sub> (short vs. long), and FP<sub>n</sub> (short vs. long). A trial started with the presentation of the WS, followed by a blank FP interval after which the IS was presented. The IS was terminated either by the participants' response or by response interval expiration (i.e., after 2000 ms). A constant intertrial interval of 1500 ms separated subsequent trials. Participants were instructed to respond quickly and accurately to the IS. 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 300 ms, whereas in case of response interval expiration, the words "zu langsam" (too slow) were presented for 300 ms. The participants performed 48 practice trials and 1040 experimental trials during the session, with a short break given after a block of 150 trials. The overall session lasted about 90 min.

## 2.2. Results and discussion

Responses faster than 100 ms and slower than 1000 ms were considered outliers and discarded from the analysis (0.5%). Trials following feedback trials (erroneous responses, too slow response) were also excluded. Erroneous responses were scored as index of error percentage. A three-factorial within-subject analysis of variance (ANOVA) was performed, with WS-SEQ (repetition vs. shift), FP<sub>n-1</sub> (short vs. long), and FP<sub>n</sub> (short vs. long) as factors and RT as the main dependent variable. All main and interaction effects are listed in Appendix 1 and only the theoretically relevant effects are subsequently reported in more detail. Fig. 1 displays RT and error percentage for WS repetition (Panel A and C) and WS-shift trials (Panel B and D).

Although the present experiment produced a clear sequential FP effect as indicated by the highly significant FP<sub>n-1</sub>  $\times$  FP<sub>n</sub> interaction, this effect was not significantly modulated by a cross-trial shift of WS tone frequency (from low-to-high, or high-to-low) as shown by the non-significant WS-SEQ  $\times$  FP<sub>n-1</sub>  $\times$  FP<sub>n</sub> interaction ( $F < 1$ ). This suggests that changes in WS tone frequency enabled a full cross-trial transfer of response activation. However, there was a significant WS-SEQ  $\times$  FP<sub>n-1</sub> interaction on RT [ $F(1,34) = 18.6$ ; partial  $\eta^2 = 0.35$ ;  $p < 0.001$ ]; the WS-shift had a detrimental effect on RT performance after a short FP<sub>n-1</sub> trial but not after a long FP<sub>n-1</sub> trial. The results of Experiment 1 therefore show that even shifts of tone frequencies had a moderate effect on performance. Importantly, since there was no three-way interaction on RT, the results of Experiment 1 do not allow the conclusion that a shift of WS tone frequency affects the asymmetry of the sequential FP effect.

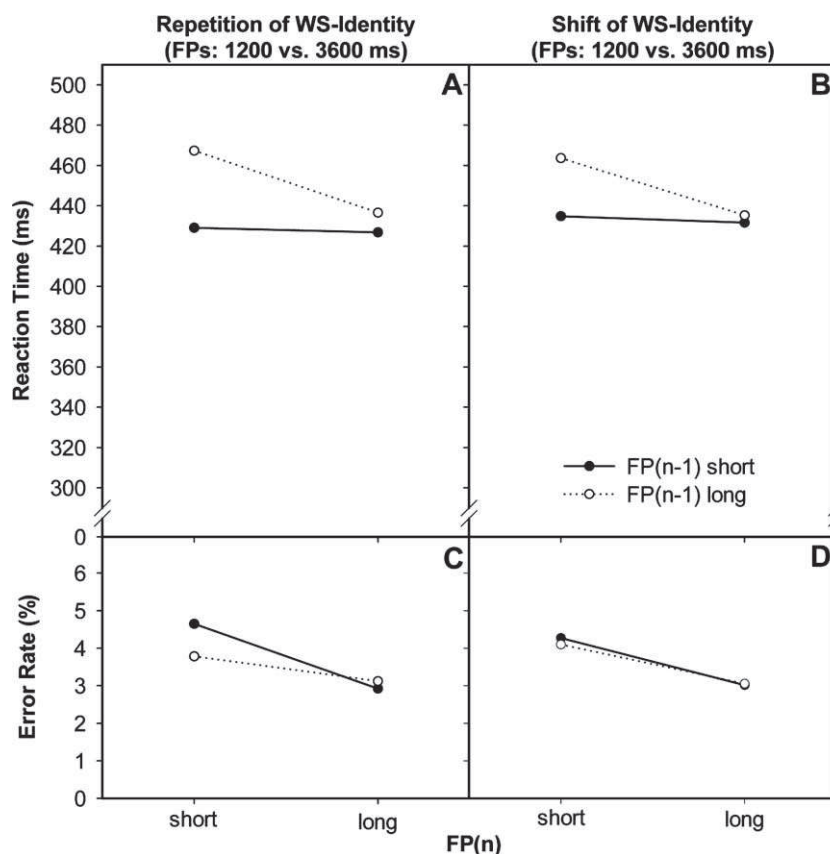
## 3. Experiment 2

Experiment 2 (FPs: 1200 and 3600 ms; choice RT) was conducted to examine whether the sequential FP effect is modulated when the auditory WS stimuli differ in a qualitative way, rather along a single physical dimension. Accordingly, we used a pure tone (1000 Hz frequency) and broadband noise (white noise) as WS in Experiment 2. If a cross-trial shift of WS identity attenuates the sequential FP effect, this should be indicated by a significant WS-SEQ  $\times$  FP<sub>n-1</sub>  $\times$  FP<sub>n</sub> interaction effect on RT.

### 3.1. Method

#### 3.1.1. Participants

Thirty-five (8 male, 27 female) volunteers (mean age = 22.1 years, SD = 2.1) took part in the experimental session. All



**Fig. 1.** Effect of a repetition versus a shift of WS identity (low vs. high tone frequency) on sequential FP effects in Experiment 1. Reaction time and error percentage displayed as a function of the preceding foreperiod ( $FP_{n-1}$ ) and the current foreperiod ( $FP_n$ ), separately for WS repetition trials (panel A and C) and WS-shift trials (panel B and D).

participants but three were right-handed and all of them had normal or corrected-to-normal vision.

### 3.1.2. Stimuli and apparatus

The experimental setting was exactly the same as in Experiment 1 and only the WS pairing was different. The auditory WS (pure tone of 1000 Hz vs. white noise; 70 dB SPL) was binaurally presented via headphones for 200 ms.

### 3.1.3. Task, design and procedure

The task, the design and the procedure were the same as in Experiment 1, except that a different WS pairing (i.e., pure tone vs. white noise) was used. We used a three-factorial within-subject design, with the factors WS-SEQ (repetition vs. shift),  $FP_{n-1}$  (short vs. long) and  $FP_n$  (short vs. long), and RT as the main dependent measure.

## 3.2. Results and discussion

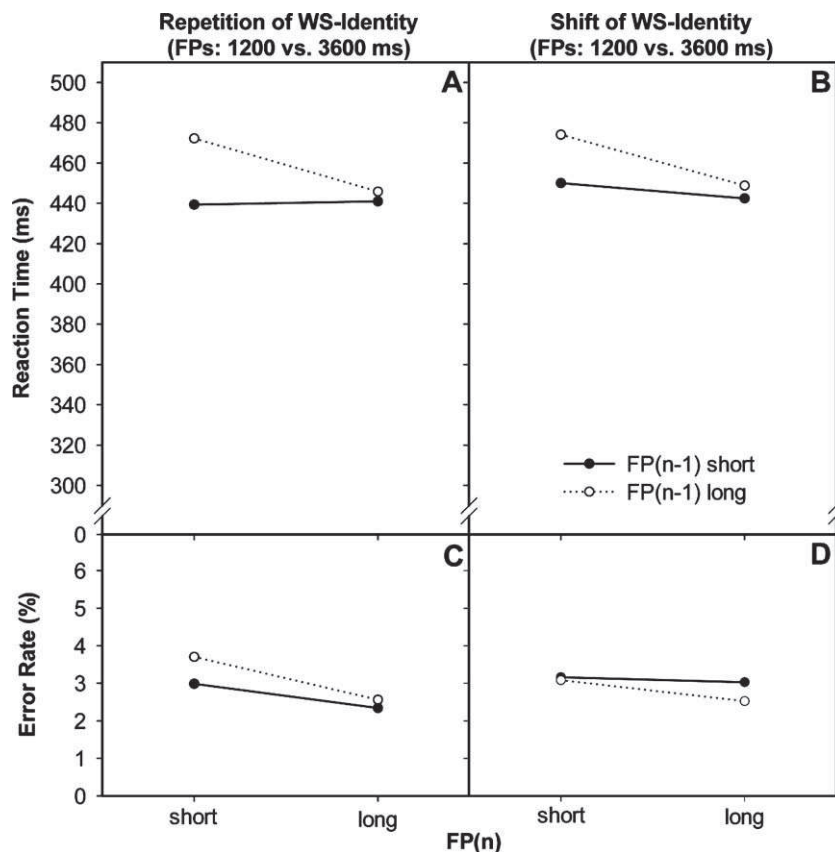
Responses faster than 100 ms or slower than 1000 ms were considered outliers and their corresponding trials (0.5%) were discarded from the analysis. Trials following feedback trials (erroneous responses, too slow response) were also excluded. Erroneous responses were used to compute the percentage of errors. A three-factorial within-subject analysis of variance (ANOVA) was performed, with WS-SEQ (repetition vs. shift of WS identity),  $FP_{n-1}$  (short vs. long) and  $FP_n$  (short vs. long) as factors and RT as the main dependent variable. Fig. 2 summarizes the results and depicts RT and error percentage as a function of  $FP_{n-1}$  and  $FP_n$ , separately for WS repetition (Panel A and C) and WS-shift trials (Panel B and

D). All main and interaction effects are listed in Appendix 1 with the relevant effects discussed subsequently.

A significant WS-SEQ  $\times$   $FP_{n-1} \times$   $FP_n$  interaction effect was observed [ $1,34 = 8.9$ ; partial  $\eta^2 = 0.21$ ;  $p < 0.01$ ] indicating that the size of the asymmetric sequential FP effect was larger when WS identity was repeated compared to when it was shifted (see Fig. 2). When WS identity repeated, the sequential effect at short  $FP_n$  (i.e., RT after a long- $FP_{n-1}$  minus RT after a short  $FP_{n-1}$ ) was 33 ms. This effect decreased to 24 ms when WS modality shifted. Thus, a shift of WS modality attenuated the sequential modulation at short  $FP_n$  by 18%. Consistent with previous findings (Steinborn et al., 2009), responses were always fast in long- $FP_n$  trials, irrespective of the length of  $FP_{n-1}$  and irrespective of whether WS modality was repeated or shifted. This indicates that the WS triggers the conditioned response mainly in short  $FP_n$  trials but has virtually no influence in long- $FP_n$  trials. Also note that error rate varied only in a small range (Fig. 2) and that there were no statistical effects on error rate (Table 1). This clearly indicates that the results are not confounded by a speed-accuracy tradeoff (Table 2).

## 4. Experiments 3

In Experiment 2, we were able to demonstrate that a modulation of the sequential FP effect can even occur when WS is shifted within modalities, using tones and noise as WS stimuli. Since effect size was small, we asked whether a more pronounced modulation could be revealed with a greater degree of time and occurrence uncertainty. It has been demonstrated that an increase in time uncertainty results in a stronger modulation of the sequential FP effect due to a shift of WS modality (Steinborn et al., 2009). Experiment 3 therefore was conducted to replicate the results obtained in Experiment 2,



**Fig. 2.** Effect of a repetition versus a shift of WS identity (pure tone vs. white noise) on sequential FP effects in Experiment 2. Reaction time and error percentage displayed as a function of the preceding foreperiod ( $FP_{n-1}$ ) and the current foreperiod ( $FP_n$ ), separately for WS repetition trials (panel A and C) and WS-shift trials (panel B and C).

similarly using a pure tone and white noise as WS stimuli. In addition, we used three instead of only two FPs, and a broader FP-range (FPs: 1000, 2500, and 4000 ms). Since sequential effects are larger when a simple RT task is used, as has been empirically verified in several studies (e.g., Correa et al., 2004; Steinborn et al., 2008), we employed a simple RT task instead of a choice RT task.

#### 4.1. Method

##### 4.1.1. Participants

Thirty-one (11 male, 20 female) volunteers (mean age = 23.0 years, SD = 3.0) took part on the experimental session. All participants but two were right-handed and all of them had normal or corrected-to-normal vision.

##### 4.1.2. Stimuli and apparatus

The experimental setting in Experiment 3 was identical to the previous experiments except that we used three FPs (1000, 2500, and 4000 ms), and two auditory WS events (pure tone vs. broadband noise).

##### 4.1.3. Task, design and procedure

The task, the design and the procedure were identical to those of Experiments 1 and 2 with the exception that participants always had to respond with the right index finger irrespective of whether the letter “L” or “R” was presented as the IS. The within-subject design was three-factorial with the factors WS-SEQ (repetition vs. shift),  $FP_{n-1}$  (short vs. medium vs. long) and  $FP_n$  (short vs. medium vs. long), and with RT as the main dependent measure.

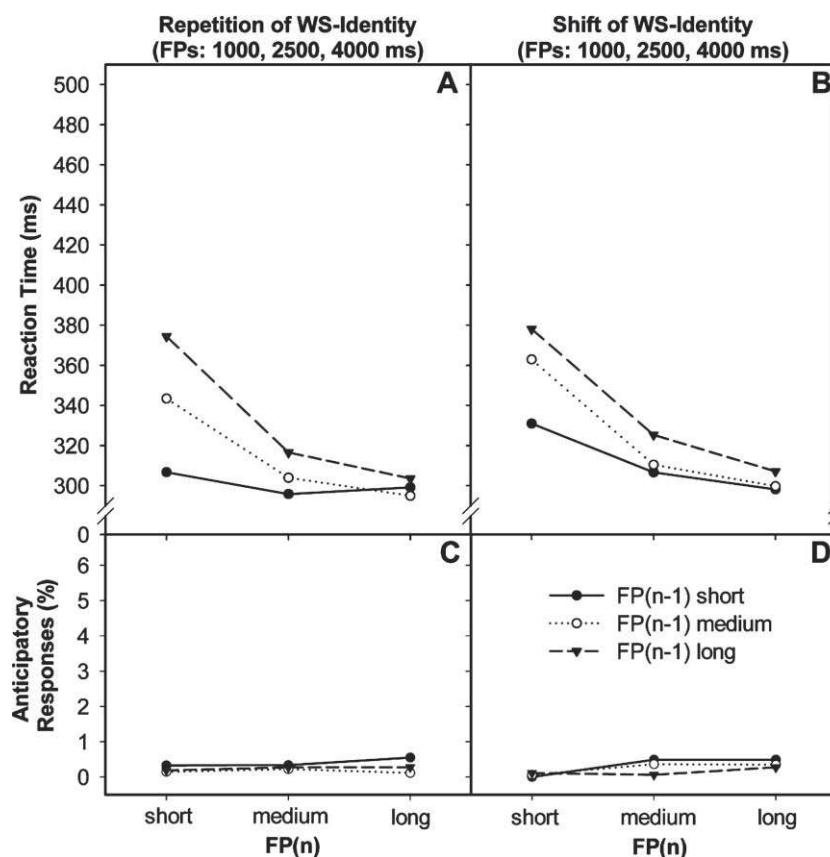
#### 4.2. Results and discussion

Trials with RTs shorter than 100 ms or longer than 1000 ms were discarded from RT analysis (0.5%). Premature responses and trials with RTs shorter than 100 ms were defined as anticipatory responses. Fig. 3 summarizes the results and depicts RT as a function of  $FP_{n-1}$  and  $FP_n$ , separately for each level of WS-SEQ: repetition of WS identity (Panel A) and shift of WS identity (Panel B). All main and interaction effects are listed in Appendix 1 and only the theoretically relevant effects are subsequently referred to.

The WS-SEQ  $\times$   $FP_{n-1}$   $\times$   $FP_n$  interaction effect [(4,120) = 6.2; partial  $\eta^2 = 0.17$ ;  $p < 0.001$ ] replicated the results of Experiment 2, indicating a modulating influence of the factor WS-SEQ on the sequential FP effect. Again, shifting WS identity from trial  $n-1$  to trial  $n$  attenuated the asymmetry of the sequential FP effect. When WS identity repeated, the sequential effect at short  $FP_n$  (i.e., RT after a long- $FP_{n-1}$  minus RT after a short  $FP_{n-1}$ ) was 68 ms. In agreement with our expectations, the sequential FP effect in Experiment 3 was larger than that observed in Experiment 2 (compare Figs. 2 and 3). This effect decreased to 47 ms when WS modality shifted. Thus, a shift of WS modality attenuated the sequential modulation at short  $FP_n$  by 31%. Accordingly, the relative attenuation of the sequential FP effect at short  $FP_n$  was larger than in Experiment 2 (18%). In addition, the factor WS-SEQ had a strong influence on RT in short  $FP_n$  trials but affected RT only minimally in medium  $FP_n$  trials and not at all in long- $FP_n$  trials (Fig. 3). In each of the two WS-SEQ conditions, there were only a small percentage of anticipatory responses.

#### 5. Experiment 4

In both Experiments 2 and 3 (WS = tone vs. noise), we were able to demonstrate a modulation of the sequential FP effect due to a



**Fig. 3.** Effect of a repetition versus a shift of WS identity (pure tone vs. white noise) on sequential FP effects in Experiment 3. Reaction time and percentage of anticipatory responses displayed as a function of the preceding foreperiod ( $FP_{n-1}$ ) and the current foreperiod ( $FP_n$ ), separately for WS repetition trials (panel A and C) and WS-shift trials (panel B and C).

shift between WS attributes within modalities. In addition, the attenuation of the sequential FP effect was larger with greater time uncertainty. In contrast, Experiment 1 (WS = low vs. high tone) did not yield a modulation of the sequential FP effect. In Experiment 4 (WS = low vs. high tone), therefore, we aimed to check whether a greater degree of time uncertainty would actually yield a modulation of the sequential FP effect due to a shift between WS tone frequencies. As in Experiment 3, we used three FPs, a broad FP-range (FPs: 1000, 2500, 4000 ms), and a simple RT task. By means of this more sensitive manipulation, we asked whether it is possible to demonstrate an attenuation of the sequential FP effect even with tone–tone shifts of WS identity.

## 5.1. Method

### 5.1.1. Participants

Thirty-two (8 male, 24 female) volunteers (mean age = 24.4 years,  $SD = 4.3$ ) took part in the experiment which took place at different experimental sessions. All participants but one were right-handed and all of them had normal or corrected-to-normal vision.

### 5.1.2. Stimuli and apparatus

The experimental setting in Experiment 4 was identical to the previous experiments. Here, three FPs (1000, 2500, 4000 ms) and a simple RT task were used.

### 5.1.3. Task, design, procedure

Design and procedure were identical to the previous experiments.

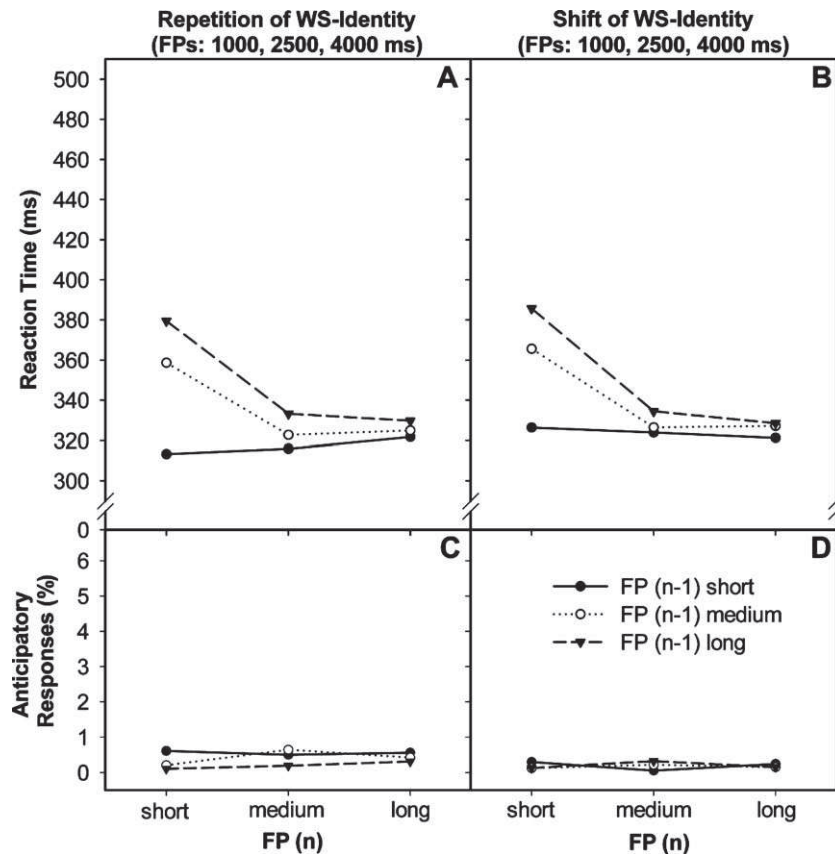
## 5.2. Results and discussion

Trials with RTs shorter than 100 ms or longer than 1000 ms were discarded from the analysis (0.5%). Premature responses and trials with RTs shorter than 100 ms were defined as anticipatory responses. Fig. 4 depicts RT as a function of  $FP_{n-1}$  and  $FP_n$ , separately for each level of WS-SEQ: repetition of WS identity (Panel A) and shift of WS identity (Panel B). All main and interaction effects are listed in Appendix 1.

Similar as in Experiment 1, there was again a significant WS-SEQ  $\times$   $FP_{n-1}$  interaction on RT [ $F(2,62) = 3.4$ ; partial  $\eta^2 = 0.09$ ;  $p < 0.05$ ]: the WS-shift had a detrimental effect on RT after a short  $FP_{n-1}$  trial but not after a long  $FP_{n-1}$  trial. Thus, Experiment 4 shows again some moderate effect of a shift of WS tone frequency on RT performance. Most importantly, Experiment 4 did not reveal the critical WS-SEQ  $\times$   $FP_{n-1} \times$   $FP_n$  interaction effect ( $F < 1$ ). Thus, shifts between tone frequencies did not attenuate the asymmetric sequential FP effect, replicating the result of Experiment 1 (see Table 1, Fig. 1). Since all the participants were capable of easily judging the difference between the tones, the results may not be interpreted such that the tone frequencies used (1000 vs. 1400 Hz) were not sufficiently different to reveal a modulation of the sequential FP effect.

## 6. General discussion

According to a trace-conditioning view of temporal preparation, WS events have the capability to retrieve previously encountered trial episodes, and by this means automatically trigger response activation to an impending IS (Los & Van den Heuvel, 2001, p.



**Fig. 4.** Effect of a repetition versus a shift of WS identity (low vs. high tone frequency) on sequential FP effects in Experiment 4. Reaction time and percentage of anticipatory responses displayed as a function of the preceding foreperiod ( $FP_{n-1}$ ) and the current foreperiod ( $FP_n$ ), separately for WS repetition trials (panel A and C) and WS-shift trials (panel B and D).

371). This is indicated by the sequential FP effect, considered to reflect trial-to-trial temporal learning in the variable FP paradigm. Consistent with this view, it has been shown that when WS modality shifts across trials, the sequential FP effect is attenuated (Steinborn et al., 2009). Here we identified two issues associated with between-modality shifts, that might complicate an interpretation of such WS modality-shift effects in terms of episodic retrieval: differences in WS stimulus intensity (Hackley, 2009), and attention-to-modality effects (Spence et al., 2001). Since WS intensity can hardly be equalized across modalities, we argued in the introduction that any modulation could be attributed to arousal differences. Additionally, since between-modality shifts may also have caused a failure of attending to the actual WS modality in a particular trial, any modulation cannot unequivocally be interpreted in terms of failed memory retrieval.

To explain the attenuation of the sequential FP effect in terms of episodic retrieval, it seemed necessary to demonstrate similar effects of WS shifts in situations where both the intensity and the modality of the WS are controlled for. As mentioned above, this is only possible when WS attributes change within a particular modality. Therefore, we conducted four experiments in which two auditory WS events were randomly varied. In addition, we considered different WS combinations, task forms and levels of temporal uncertainty. The results demonstrate that even a shift of equally intense auditory WS events can attenuate the sequential FP effect (Experiment 2 and 3: tone vs. noise), with effect sizes similar to the findings observed between modalities (Steinborn et al., 2009). We argue that the present results provide a strong argument against an encoding-failure explanation of the WS-shift effect, which implies that WS attributes are not sufficiently

attended in WS-shift trials. Instead, the results support a retrieval-failure explanation, which implies that episodic memories are not, or at least less efficiently, retrieved in WS-shift trials.

#### 6.1. Role of the warning signal in temporal preparation

The present results indicate that the WS in variable-FP experiments triggers time-point specific response activation automatically. According to the trace-conditioning model of temporal preparation (e.g., Los & Van den Heuvel, 2001, p. 373; Los et al., 2001, p. 128), the WS event initiates a cascade of sensory events. In this sense, each event is sequentially bound on a time-line and after the WS event, activation wanders through this sequence as a train of sensation (Moore et al., 1998; Smallwood, Nind, & O'Connor, 2009). When an overt response is made to the IS at a particular critical moment on this time line, the response then becomes connected with those sensory elements in the chain that are activated at this trial. Since previously encountered trial episodes are stored in episodic memory, an identical WS event is capable of directly activating stored memories and by this means triggers preparatory activity in subsequent trials (see also, Machado, 1997; Moore et al., 1998). If, however, a WS event is presented which sufficiently differs from that one presented previously, episodic memories will not (or less likely) be retrieved and automatic (stimulus-triggered) preparation will fail in this particular trial (Tulving & Thompson, 1973).

The present study extends previous results on between-modality shifts (Steinborn et al., 2009) by demonstrating that the sequential FP effect can also be modulated by shifts within WS modalities. This was the case for shifts between tones and noise (Experiments

2 and 3). Consistent with the assumptions of the trace-conditioning model (Los & Van den Heuvel, 2001, p. 373; Los et al., 2001, p. 128), response activation in a current trial was stronger (i.e., responses were faster) for WS repetitions (e.g., noise-to-noise; tone-to-tone) than for WS shifts (e.g., noise-to-tone; tone-to-noise). Interestingly, this happened even though both WS modality and intensity were kept constant, suggesting that successful re-instantiation of the  $FP_{n-1}$  trial episode depends crucially on the specific auditory characteristics of the WS. Therefore, we suggest that our participants are less likely to benefit from reinforcement in trial  $FP_n$  after a shift of the WS event, most probably due to a failure of getting access to previously experienced trial episodes and not to a failure of attending to the WS itself at the moment of its occurrence. Although such a retrieval-failure explanation might imply an all-or-none process (retrieval is either successful or not), it should be mentioned that this does not argue against the possibility that inefficient retrieval can also occur in a rather gradual fashion, especially in situation where retrieval cues contain multiple attributes (e.g., Harris, 2006; Rescorla & Wagner, 1972; Wagner, 2008).

Interestingly, the WS in Experiments 2 and 3 exerted its influence exclusively at short critical moments but not at later ones. When a short  $FP_n$  is preceded by a long  $FP_{n-1}$ , a shift from tone to noise (or noise to tone) has virtually no effect on RT. As previously stated (Steinborn et al., 2009), we suggest that the WS triggers response activation only at short critical moments but not at later ones. This interpretation is in line with the trace-conditioning view (Los & Van den Heuvel, 2001, p. 373; Los et al., 2001), which assumes that responses at late imperative moments are consistently fast because they are less frequently extinguished and may not benefit additionally from WS-triggered activation. Furthermore, it is also possible that the sensory attributes of a WS decay rapidly and thus are available only at short critical moments, whereas the conceptual attributes (i.e., the symbolic meaning) have a longer persistency (Glenberg & Swanson, 1986). Therefore, the finding that WS features have no influence in long- $FP_n$  trials is also consistent with a strategic view (Näätänen, 1971; Näätänen & Merisalo, 1977; Rabbitt & Vyas, 1980), according to which fast responses in long- $FP_n$  trials arise from an effortful and intentionally guided process of conditional probability monitoring that dominates response preparation at late imperative moments. However, since the trace-conditioning model also predicts fast responding regardless of whether the last WS is repeated or not, it provides the most parsimonious account for the present findings.

Contrary to a strategic view, however, the trace-conditioning model provides a theoretical basis to address cross-trial WS shifts in variable-FP experiments, since this model considers the WS event a trigger signal that automatically initiates preparatory activity (Los & Van den Heuvel, 2001, p. 373; Los et al., 2001, p. 128). Thus, the present study corroborates the idea that WS events speed-up responses not only via mechanisms of automatic alerting (Hackley, 2009) or strategic preparation (Näätänen, 1971; Näätänen & Merisalo, 1977) but because of their capability to retrieve previously established association between WS, time, and IS. However, saying that a strategic view cannot explain the present findings does not generally argue against strategic models of temporal preparation. It is clear that performance in RT experiments depends critically on the participants' general intention to respond quickly to the IS (cf. Los & Van den Heuvel, 2001, p. 373). Fluctuations in the participants' energetical state or problems in the ability to maintain alertness (Vallesi, McIntosh, & Stuss, 2009; Vallesi & Shallice, 2007; Zahn, Kruesi, & Rapoport, 1991) may be a source of performance effects that is entirely different from temporal associative learning. Thus, the need for a general intention to comply with the task constraints and to energize behavior for speeded responding makes it unlikely that trace-conditioning is the only

mechanism that affects performance in variable foreperiod paradigms.

According to Hebb (1955), every sensory stimulation that comprises a warning signal has two different functions: a cue function and an arousal function. The cue function represents the information associated with the stimulation (here, the previous trial episode) and the arousal function energizes behavior. The trace-conditioning view (Los & Van den Heuvel, 2001) focuses on the cue function but not on the arousal function. However, a recently proposed dual-process view (Vallesi & Shallice, 2007; Vallesi, Shallice, & Walsh, 2007; Vallesi, McIntosh, & Stuss, 2009) takes arousal into account: Responses in short  $FP_n$  trials are assumed to be facilitated after a short  $FP_{n-1}$  (due to a response-generated increase in arousal) but especially slow after a long  $FP_{n-1}$  (due to a decrease in arousal). In long- $FP_n$  trials, however, responses are fast because the arousal decrement can be compensated by a strategic conditional probability monitoring process (see also Näätänen, 1971; Rabbitt & Vyas, 1980). Thus, the dual-process model can also explain the present finding that a WS shift had no effects on RT in long- $FP_n$  trials. Without explicitly considering an associative learning mechanism of WS-IS relationships, however, the dual-process view cannot account for the effect of a shift of WS attributes on the sequential FP effect.

## 6.2. Sources of cross-trial transfer in WS-shift trials

Although a shift of WS identity had a modulating influence on temporal preparation, there was a substantial residual sequential FP effect in WS-shift trials. The effect was similar in size as the one recently observed in between-modality shift trials (Steinborn et al., 2009), and may be explained in terms of stimulus generalization. It has long been recognized that performance on a retrieval task tends to be superior when the test context is similar to that experienced during training, or the previous trial, respectively (Taatgen, Huss, Dickson, & Anderson, 2008; Tulving & Thompson, 1973). Often, performance deteriorates when stimulus modality changes from the training to the test period, or from the previous to the current trial, respectively (e.g., Gondan, Lange, Rösler, & Röder, 2004; Quinlan & Hill, 1999; Roediger & Blaxton, 1987; van Dantzig, Pecher, Zeelenberg, & Barsalou, 2008). Subsequently, we will discuss three possible sources of stimulus generalization which may explain the residual sequential FP effect: (1) feature overlap (the warning signals share common properties: loudness), (2) concept overlap (the same if-then rules, or task instructions, are contingent to the warning), and (3) strategic preparation.

First, our results indicate that cross-trial WS-shift effects on RT depend crucially on the extent to which auditory stimuli differ qualitatively from each other. Whereas shifts of tone frequency enabled cross-trial transfer and thus did not attenuate the asymmetric sequential FP effect (Experiments 1 and 4), shifts between tones and noise (Experiments 2 and 3) seem to differ physically enough as to reveal a modulation of the effect. It should be noted, that Experiments 1 and 4 showed a detrimental effect of a shift of WS tone frequency on RT performance, since RT was somewhat prolonged after a short  $FP_{n-1}$  but not after a long  $FP_{n-1}$ . Since these two experiments, however, did not reveal the critical three-way interaction, it is nevertheless likely that the pure tones, even though differing in frequency, were regarded similar by the cognitive system (i.e., a class of elemental-level events, Harris, 2006). In contrast, the percept of a pure tone may be entirely different from the percept established by broadband noise (cf. Schröter, Frei, Ulrich, & Miller, 2009; Schröter et al., 2007, for a discussion in a related domain). If pure tones are classified into a common perceptual class, it follows that WS-triggered response activation is not restricted to the precise stimulus encountered previously but may generalize to other similar stimuli from the same perceptual

class. Thus, a shift of tone frequency may have yielded the activation of a rather identical cascade of sensory events, whereas a shift from tone to noise (or noise to tone, respectively) did yield the activation of a distinct cascade. It makes sense to assume that the more features the two warning signals differ by, the less likely the identical cascade will be activated and the more the sequential FP effect will be attenuated. From the perspective of a *feature-overlap hypothesis*, therefore, the residual sequential FP effect may indicate the degree to which preparation is not exclusively triggered by specific WS attributes but by unspecific stimulation that is common to all WS events (cf. Hackley et al., 2009).

Second, the residual sequential FP effect could alternatively result due to concept formation that enables a rather symbolic use of WS events for preparation. In conditioning models, such a mechanism is described as involving the learning of a common (or similar) conditioned response to two or more distinguishable conditioned stimuli (cf. Bourne, 1966; Martin, 1968). Here, the commonality is not on the perceptual level (i.e., the degree of feature overlap) but on the conceptual level at which stimuli are mentally represented (i.e., the degree of function overlap). For example, if a child learns that objects as dissimilar as a train, a bicycle, or a car, are all vehicles, it is helped to deal with them in terms of their common properties as a means of transportation (Bourne, 1966). Analogously, if our participants have learned that the auditory WS events are all symbols that signature the start of a trial (even though dissimilar with respect to their perceptual identity), this could have enabled them to engage in rather abstract cognitive processes to accomplish preparation. Concept formation as classification occurs when conditioned stimuli share the same symbolic meaning, irrespective of their perceptual identity. It has been shown that abstraction becomes more dominant when more stimuli are mapped onto the same unconditioned response, known as the encoding-variability principle (Martin, 1968). From a *concept-overlap hypothesis*, the residual sequential FP effect should therefore increase when more different WS events are used in a variable FP paradigm.

Third, the residual sequential FP effect might simply reflect the contribution of strategic preparation. According to a strategic view, individuals employ the WS symbolically and then intentionally start preparation henceforward (Näätänen & Merisalo, 1977). The critical difference to the aforementioned explanations is that the WS does not directly activate preparatory activity but first activates the goal (its mental representation), which then activates

preparatory activity. In the conditioning literature, goals are considered to act like a (compound) conditioned stimulus (cf. de Wit & Dickinson, 2009; Hommel, 2009): with repeated exposure, therefore, even goal representations can acquire the capability to automatically trigger response activation (cf. Bargh & Gollwitzer, 1994; Verbruggen & Logan, 2009; Verguts & Notebaert, 2008, for a related discussion). Thus, the degree to which WS attributes become associated with the representation of goals (or parts of them, e.g., explicit rules, motivational forces, respectively) may determine the size of the residual sequential FP effect. Strategic preparation may also include proactive attentional strategies to optimize the processing of WS information. For example, it has been proposed that participants are capable of statistically learning the probability of which a stimulus occurs in a particular modality, and adjusting their expectations according to this probability (e.g., Turatto et al., 2002; Töllner et al., 2009). According to such an expectancy-weighting account, individuals may also learn to attend to features of stimuli within one modality according to the probability of their occurrence. Since the two WS stimuli occurred with the same frequency (50:50) in our experiments, there is reason to assume that our participants expected both auditory WS events to the same degree and therefore, in a given trial, oriented attention to both possible WS events. Notably, the presented experiments were not conducted to discriminate between possible sources of the residual sequential FP effect. They may nevertheless provide the theoretical basis to derive predictions about WS-identity shifts in variable-FP experiments in the future.

### 6.3. Conclusion

Taken together, the results of the present study provide strong evidence for a retrieval-failure account of WS-shift effects in temporal preparation. We showed that a within-modality shift of equally intense WS events can modulate sequential effects in the variable FP paradigm. By this means, the present study extends previous results on between-modality shifts (cf., Steinborn et al., 2009), ruling out the possibility that the attenuation of the sequential FP effect is due to a failure of attending to the correct WS modality (since the WS events were always in the same modality), or a failure of sufficiently attending to the WS in general (since auditory WS events are naturally intrusive). In line with the trace-conditioning account (Los & Van den Heuvel, 2001; Los et al., 2001), the present study provides further evidence that

**Table 1**  
ANOVA results for Experiments 1 and 2.

Source	dfs	Reaction time			Error percentage			
		F	p	$\eta^2$	F	p	$\eta^2$	
Experiment 1 (WS = low vs. high pure tone)								
1	WS-SEQ	1.34	1.4	0.247	0.04	0.0	0.949	0.00
2	FP <sub>n-1</sub>	1.34	132.0	0.001	0.80	3.1	0.085	0.08
3	FP <sub>n</sub>	1.34	38.6	0.001	0.53	11.2	0.002	0.25
4	WS-SEQ × FP <sub>n-1</sub>	1.34	18.6	0.001	0.35	0.3	0.605	0.01
5	WS-SEQ × FP <sub>n</sub>	1.34	0.0	0.861	0.00	0.0	0.974	0.00
6	FP <sub>n-1</sub> × FP <sub>n</sub>	1.34	102.9	0.001	0.75	1.4	0.252	0.04
7	WS-SEQ × FP <sub>n-1</sub> × FP <sub>n</sub>	1.34	0.6	0.442	0.02	0.53	0.472	0.01
Experiment 2 (WS = pure tone vs. white noise)								
1	WS-SEQ	1.34	10.7	0.002	0.24	0.1	0.749	0.00
2	FP <sub>n-1</sub>	1.34	137.6	0.001	0.80	0.2	0.676	0.01
3	FP <sub>n</sub>	1.34	27.0	0.001	0.44	6.2	0.018	0.16
4	WS-SEQ × FP <sub>n-1</sub>	1.34	3.6	0.068	0.10	3.8	0.060	0.10
5	WS-SEQ × FP <sub>n</sub>	1.34	2.8	0.099	0.08	1.7	0.206	0.05
6	FP <sub>n-1</sub> × FP <sub>n</sub>	1.34	58.6	0.001	0.63	1.6	0.212	0.05
7	WS-SEQ × FP <sub>n-1</sub> × FP <sub>n</sub>	1.34	8.9	0.005	0.21	0.0	0.932	0.00

Note. Effect size: partial  $\eta^2$ ; FPs: 1200 and 3600 ms, factors: WS-sequence (WS-SEQ: repetition of WS identity vs. shift of WS identity), previous foreperiod (FP<sub>n-1</sub>: short vs. long), current foreperiod (FP<sub>n</sub>: short vs. long).

**Table 2**  
ANOVA results for Experiments 3 and 4.

	Source	dfs	Reaction time			Anticipatory responses		
			F	p	$\eta^2$	F	p	$\eta^2$
Experiment 3 (WS = pure tone vs. white noise)								
1	WS-SEQ	1.30	29.2	0.001	0.49	0.2	0.638	0.00
2	FP <sub>n-1</sub>	2.60	110.8	0.001	0.79	4.4	0.017	0.13
3	FP <sub>n</sub>	2.60	106.8	0.001	0.78	2.3	0.123	0.07
4	WS-SEQ × FP <sub>n-1</sub>	2.60	3.1	0.058	0.09	2.2	0.183	0.05
5	WS-SEQ × FP <sub>n</sub>	2.60	10.5	0.001	0.26	1.8	0.333	0.03
6	FP <sub>n-1</sub> × FP <sub>n</sub>	4.120	74.4	0.001	0.71	1.0	0.309	0.04
7	WS-SEQ × FP <sub>n-1</sub> × FP <sub>n</sub>	4.120	6.2	0.001	0.17	0.9	0.443	0.03
Experiment 4 (WS = low vs. high pure tone)								
1	WS-SEQ	1.31	11.5	0.002	0.27	3.7	0.062	0.11
2	FP <sub>n-1</sub>	2.62	152.6	0.001	0.83	2.9	0.067	0.09
3	FP <sub>n</sub>	2.62	24.7	0.001	0.44	0.1	0.812	0.00
4	WS-SEQ × FP <sub>n-1</sub>	2.62	3.4	0.040	0.09	3.1	0.058	0.09
5	WS-SEQ × FP <sub>n</sub>	2.62	5.9	0.007	0.16	0.4	0.592	0.01
6	FP <sub>n-1</sub> × FP <sub>n</sub>	4.124	89.9	0.001	0.74	1.9	0.121	0.06
7	WS-SEQ × FP <sub>n-1</sub> × FP <sub>n</sub>	4.124	0.6	0.636	0.02	0.6	0.594	0.02

Note. Effect size: partial  $\eta^2$ ; FPs: 1000, 2500, 4000 ms; factors: WS-sequence (WS-SEQ: repetition of WS identity vs. shift of WS identity), previous foreperiod (FP<sub>n-1</sub>: short vs. medium vs. long), current foreperiod (FP<sub>n</sub>: short vs. medium vs. long).

preparation in short FP<sub>n</sub> trials is substantially influenced by associative learning of sensorimotor connections between WS and IS, including the time period (i.e., FP) between them.

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### Appendix 1

See Tables 1 and 2.

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## Distraction by irrelevant sound during foreperiods selectively impairs temporal preparation

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### ABSTRACT

When the interval between a warning signal (WS) and an imperative signal (IS), termed the foreperiod (FP), is variable across trials, reaction time (RT) to the IS typically decreases with increasing FP length. Here we examined the auditory filled-FP effect, which refers to a performance decrement after FPs filled with irrelevant auditory stimulation compared to FPs without additional stimulation. According to one account, irrelevant stimulation distracts individuals from processing time and probability information during the FP (distraction-during-FP hypothesis). This should predominantly affect long-FP trials. Alternatively, the filled-FP effect may arise from a failure to shift attention from FP modality to IS modality (attention-to-modality hypothesis). The first hypothesis focuses on preparatory processing, predicting a selective RT increase on long-FP trials, whereas the second hypothesis focuses on target processing, only predicting a global RT increase irrespective of FP length. Across four experiments, a filled-FP (compared to a blank-FP) condition consistently yielded a selective RT increase on long-FP trials, irrespective of FP-IS modality pairing. This pattern of results contradicts the attention-to-modality hypothesis but corroborates the distraction-during-FP hypothesis. More generally, these data have theoretical implications by supporting a multi-process view of temporal preparation under time uncertainty.

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### 1. Introduction

Time given to prepare a speeded response to an imperative signal (IS) generally improves performance in reaction-time (RT) tasks (Hackley, 2009; Rolke & Ulrich, 2010). In experiments on effects of temporal preparation, a warning signal (WS) typically announces the start of a trial, which is followed by a blank interval (i.e., the foreperiod, FP), and the IS (Los & Schut, 2008). Individuals are assumed to establish a state of nonspecific preparation during the FP interval in order to optimally process task-relevant information and respond to the IS at the moment of its occurrence (i.e., at the imperative moment). With constant FPs, individuals can synchronize peak preparation with the imperative moment (i.e., the moment of IS occurrence). When, however, FP varies randomly across trials, deterministic synchronization is impossible. That is, under time uncertainty, probability information needs to be processed in addition to time estimation.

Responses in such variable-FP paradigms are usually slow in short-FP trials but fast in long-FP trials, yielding a downward-sloping FP-RT function, which is explained by assuming that the time elapsed after the WS is informative, since the conditional probability of IS occurrence monotonously increases during the FP interval (Niemi & Näätänen, 1981, pp. 137–141). Researchers agree that individuals must somehow be capable to convert the objective conditional-probability increase into a subjective expectation; yet, the precise mechanism is still being debated (Bueti, Bahrami, Walsh, & Rees, 2010; Los & Van den Heuvel, 2001; Vallesi, Shallice, & Walsh, 2007).

#### 1.1. Theoretical models of temporal preparation

A strategic account assumes that individuals use the WS as a symbolic time marker to begin with focusing on the task, from which they actively monitor the time flow during the FP interval and increase preparatory state according to the time-related increase in the conditional probability of IS occurrence (Näätänen, 1970; Rabbitt & Vyas, 1980). Accordingly, manipulations that change the conditional IS probability (e.g., Los & Agter, 2005; Requin & Granjon, 1969) or explicit information about the impending imperative moment at the

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beginning of a particular trial (e.g., Correa, Cappucci, Nobre, & Lupiáñez, 2010; Coull, Frith, Büchel, & Nobre, 2000; Coull & Nobre, 1998) are predicted to cause a change in the FP–RT slope. Strategic preparation is considered to require cognitive control for monitoring conditional IS probability (Requin & Granjon, 1969; Stilz, 1972), for shielding against distraction (Dreisbach & Haider, 2008, 2009), and for intentionally enhancing preparatory state (Näätänen & Merisalo, 1977). The critical variable thus is the availability of attentional resources, ensuring the normal operation of preparatory processing at any time during the FP interval. A strategic model implies that when resources are reduced for some reason (e.g., due to insufficient attention, high cognitive load, etc.), these processes should operate less efficiently, and performance thus is predicted to decline under these conditions.

This classic account, however, cannot appropriately explain the typical sequential modulation of the FP–RT slope across subsequent trials. In particular, responses on short-FP trials are slower when preceded by a long-FP trial, compared to when preceded by an equally long or shorter one. The effect is asymmetric in that responses only vary on short-FP trials and are unaffected by previous FP length on long-FP trials (e.g., Alegria, 1975a; Karlin, 1959; Langner, Steinborn, Chatterjee, Sturm, & Willmes, 2010; Los, Knol, & Boers, 2001; Los & Van den Heuvel, 2001; Steinborn, Rolke, Bratzke, & Ulrich, 2008, 2009, 2010; Van der Lubbe, Los, Jaskowski, & Verleger, 2004). A further argument that imposes difficulties for the classic view is that the asymmetry of the sequential FP effect decreases when sensory WS features changes across trials (Steinborn et al., 2009, 2010), indicating that the WS is more than a symbolic marker and also acts as a memory retrieval cue.

Vallesi and his collaborators (Vallesi, McIntosh, & Stuss, 2009; Vallesi & Shallice, 2007; Vallesi, Shallice et al., 2007) developed the classic strategic explanation of the variable-FP effect into a dual-process model, which can account for the sequential FP effect. Maintaining the idea of a strategic preparatory process based on conditional-probability monitoring, the sequential FP effect is assumed to arise from a trial-to-trial variation in motor excitation due to the variable spacing (i.e., the temporal distance) of two subsequent responses (Vallesi, Mussoni et al., 2007). That is, responses on short-FP<sub>n</sub> trials are assumed to be facilitated when following a short-FP<sub>n-1</sub> trial, due to an increase in the motor-activation level. In contrast, responses on short-FP<sub>n</sub> trials are slowed when following a long-FP<sub>n-1</sub> trial, due to a decrease in the motor-activation level. On long-FP<sub>n</sub> trials, however, responses are fast, irrespective of FP<sub>n-1</sub>, because the motor-activation decrement following long-FP<sub>n-1</sub> trials is compensated by strategic preparation based on conditional-probability monitoring. According to this view, the asymmetry of the sequential FP arises from the combined impact of two different processes: an originally symmetric sequential effect, resulting from different residual activation levels produced by prior responses, is rendered asymmetric by a selective probability-based preparation process during a long-FP<sub>n</sub> trial.

Recently, strategic accounts were challenged by a trace-conditioning model, developed by Los and colleagues (Los & Heslenfeld, 2005; Los et al., 2001; Los & Van den Heuvel, 2001). This model accounts for the variable-FP effect and its sequential modulation (i.e., the sequential FP effect) by arguing that the former results from the asymmetry inherent in the latter. In particular, states of peak preparation at critical moments are assumed to be attained by dynamic learning and re-learning of temporal intervals. Elapsed time during the FP is represented as a sequence of time-tagged events (Los et al., 2001, p. 128), with each event capable of being associated with features from external stimuli, internal representations, and responses. The model resembles other trace-conditioning models in related domains, which similarly assume that discrete events along a time line activate each other until target occurrence (e.g., Desmond & Moore, 1991; Dickinson, 1980; Machado, 1997; Moore, Choi, & Brunzell, 1998;

Sutton & Barto, 1981). The WS event is considered to act as a retrieval cue that automatically initiates an activation cascade along this sequence until the IS occurs (Steinborn et al., 2009, 2010). When the IS occurs, an associative link is established between the IS and activated components on the event sequence, increasing the so-called response strength associated with that specific moment.

The main predictions of the model are derived from three conditioning rules (Los & Van den Heuvel, 2001, p. 372): Response strength (i.e., preparedness) at a particular moment (1) increases when the IS occurs at that moment, due to excitatory reinforcement, (2) remains unchanged when the IS occurs earlier, and (3) decreases when the IS occurs later, due to extinction. Based on these rules, the model predicts fast responses on short-FP repetition trials, since response strength was reinforced at the same critical moment on the previous trial. Fast responses are also predicted to occur on short-long FP sequences, since the critical moment was not bypassed on the previous trial (and, thus, its previously acquired response strength was not reduced). Conversely, in long-short FP sequences, slow responses are predicted, since the critical moment was bypassed on the previous trial. In sum, the trace-conditioning model explains both the variable-FP effect and its sequential modulation by a set of rules governing associative trial-to-trial learning, which produce asymmetric sequential dependencies that – as a necessary “side-effect” – result in the well-known variable-FP effect.

### 1.2. Effect of irrelevant stimulation during foreperiods on temporal preparation

As mentioned previously, the dual-process model (Vallesi & Shallice, 2007) points to the importance of attentional capacity for tracking time and probability information during the FP. Hence follows that any manipulation that effectively reduces capacity during FP should impair preparatory processing, which should manifest itself in a specific RT increase on long-FP<sub>n</sub> trials. Empirical support for this prediction is mainly derived from studies comparing group-related individual differences in cognitive-control functions. In particular, subgroups of individuals considered less capable to adequately implement and/or sustain cognitive control have been shown to exhibit a selective RT increase on long-FP<sub>n</sub> trials (yielding a flattening of the FP<sub>n</sub>–RT function), compared to matched normal controls. This has been shown for individuals with a variant of attention-deficit disorder (Zahn, Kruesi, & Rapoport, 1991), trait impulsivity (Correa, Trivino, Perez-Duenas, Acosta, & Lupiáñez, 2010), or patients with damage in the right dorsolateral prefrontal cortex (rDLPFC) (Trivino, Correa, Arnedo, & Lupiáñez, 2010). Vallesi, Shallice, and Walsh (2007) provided experimental evidence that the FP<sub>n</sub>–RT slope, but not the sequential FP effect, is reduced after inhibiting the rDLPFC with transcranial magnetic stimulation (TMS). According to Vallesi et al., decreasing rDLPFC functioning via TMS is equivalent to a reduction of attentional resources.

Further, irrelevant stimulation during preparatory processing has been shown to interfere with RT performance in FP experiments. In a pioneering study, Terrell and Ellis (1964) examined temporal preparation in a simple-RT task as a function of concurrent irrelevant stimulation during the FP interval (FP length was 2, 4, 8, or 12 s). In one condition, a visual WS was presented for 1500 ms and followed by a standard (blank) FP until auditory IS presentation. In the other condition, the visual WS remained present after its onset for the entire FP interval. The authors found a global RT increase in the filled-FP compared to the blank-FP condition but no selective RT increase on long-FP<sub>n</sub> trials. Since the study mainly focused on sustained-attention differences between normal and individuals with mental retardation, it should be noted that normal individuals were more severely affected by the filled-FP condition than retarded ones. Baumeister and Wilcox (1969) replicated these results using an almost identical

design. Again, the filled-FP condition yielded an additive RT increase (the filled-FP effect was also larger for normal than for individuals with mental retardation), while there was no interaction with  $FP_n$  length. The filled-FP effect has also been examined in other studies, and mostly, an RT increase was also observed in normal individuals (e.g., Borst & Cohen, 1989; Cassel & Dallenbach, 1918; Hawkins & Baumeister, 1965; Kellas & Baumeister, 1968).

Accounts of the filled-FP effect have argued that stimulation during the FP interval produces a performance impairment by distracting individuals from maintaining the attentional focus on task processing over the FP. The larger RT increase in normal compared to retarded individuals was explained by a floor effect, assuming that retarded individuals are already deficient in maintaining attention so that no resources can be further “drawn off” by additional challenges (e.g., Baumeister & Wilcox, 1969; Terrell & Ellis, 1964). This *distraction-during-FP hypothesis* is further corroborated by research on what is termed the irrelevant-sound effect on delayed-response performance (cf. Beaman, 2005; Jones & Macken, 1993; Macken, Phelps, & Jones, 2009; Poulton, 1977). In particular, it has repeatedly been shown that concurrent auditory stimulation during task processing is highly intrusive (and, thus, obligatorily processed) and competes with cognitive task processing. Attempts to shield against irrelevant stimulation has been linked to an activation of the rDLPFC – a brain area involved in the maintenance of attention (cf. Hadlington, Bridges, & Beaman, 2006; Shallice, Stuss, Alexander, Picton, & Derksen, 2008; Sturm & Willmes, 2001; Vallesi, Shallice et al., 2007).

Given that irrelevant sound challenges right prefrontal maintenance networks (Campbell, 2005), a filled FP should also impair processes related to temporal preparation. From the perspective of the dual-process model (Vallesi & Shallice, 2007; Vallesi, Shallice et al., 2007), it could be argued that concurrent stimulation reduces attentional resources, which may impair individuals to maintain task focus during the FP interval. The degree to which resources are drawn off may depend on the salience of the stimulation (e.g., modality, intensity, or novelty), and it is likely that concurrent stimulation is most effective in the auditory modality (cf. Jones & Macken, 1993). Thus, from a dual-process perspective, an auditory filled-FP condition should effectively induce a selective RT increase on long- $FP_n$  trials, which should resemble the RT pattern obtained by Vallesi et al. (2007) applying TMS over the rDLPFC during temporal preparation. In the trace-conditioning model (Los & Van den Heuvel, 2001), sensory stimulation effects are not explicitly incorporated. One could, however, argue that if preparatory processing is fairly automatic, it should not be affected by irrelevant sound (cf. Langner, Steinborn, et al., 2010; van Lambalgen & Los, 2008).

### 1.3. Present study

The present study examined the effects of an auditorily filled FP on temporal preparation under time uncertainty (i.e., in variable-FP settings). Since applying concurrent stimulation might also be fecund for theorizing about preparation-related phenomena (Clark & Squire, 1999), studying the as-yet poorly understood nature and specific boundary conditions of filled-FP effects becomes even more worthwhile. Moreover, none of the previous studies employing filled FPs sufficiently analyzed sequential effects. To lessen this backlog, we identified critical variables that may account for previous findings and performance differences. As mentioned above, the standard explanation (i.e., the distraction-during-FP hypothesis) argues that irrelevant auditory stimulation during the FP distracts attention from temporal and conditional-probability monitoring (e.g., Terrell & Ellis, 1964). Alternatively, the filled-FP effect may be related to impaired target processing, that is, it could simply arise from a failure to shift attention from the auditory input during FP to the (visual) IS modality. This explanation has also been offered in

previous research, particularly to explain additive RT increases (Kellas & Baumeister, 1968). Indeed, recent research has shown that the need for stimulus-driven shifts of attention between sensory modalities (across subsequent trials) in speeded stimulus detection induces behavioral costs as well as additional brain activity, as compared to no-shift conditions (Langner et al., 2011; Quinlan & Hill, 1999; Spence, Nicholls, & Driver, 2001). We will refer to this hypothesis as *attention-to-modality hypothesis*. Thus, the standard explanation focuses on preparatory processing, predicting a selective RT increase on long-FP trials, whereas the alternative explanation focuses on target processing, predicting a global RT increase. To test our predictions, four experiments were conducted in which a blank-FP and a filled-FP condition were compared between blocks of trials in a variable-FP paradigm. Across experiments, we used a two-choice RT task with three equiprobable FPs (300, 600, and 900 ms).

As alluded to above, according to the dual-process view, supervisory monitoring during FPs depends on attentional resources, and reductions of applicable resources are predicted to affect the  $FP_n$ -RT slope. According to a trace-conditioning view, the time-tagged event sequence is processed preattentively, and the dynamic associative learning (and re-learning) of temporal contingencies occurs unintentionally. Thus, a decrease in the  $FP_n$ -RT slope by irrelevant sound would be consistent with the dual-process view, but would provide a challenge for the trace-conditioning view. However, since we cannot exactly determine whether irrelevant sound during the FP is also capable to impair preattentive processing (cf. Greenwald, 1970; Poulton, 1977), any modulations of the  $FP_n$ -RT slope may not be taken as strong evidence against the trace-conditioning model. Before applying the filled-FP effect to “test” competing models of variable-FP phenomena, we, therefore, have to determine the nature and specific boundary conditions of the filled-FP effect.

## 2. Experiment 1

In Experiment 1 (two-choice RT task; visual IS; FPs: 300, 600, and 900 ms, rectangular FP distribution), we aimed to replicate previous findings with slightly different task parameters (cf., e.g., Baumeister & Wilcox, 1969; Terrell & Ellis, 1964). To this end, we compared a condition with blank FP intervals to a condition with auditorily filled FP intervals. All trials started with an auditory WS (sine tone presented for 100 ms), which either was followed by a silent FP or was prolonged until IS occurrence. From the perspective of the attention-to-modality hypothesis, a global RT increase should be observed in the filled-FP condition, as compared to the blank-FP condition. In contrast, from the perspective of the distraction-during-FP hypothesis, a selective decrease of the FP-RT slope should be observed on filled-FP as compared to blank-FP trials.

### 2.1. Method

#### 2.1.1. Participants

Twenty-five (8 males, 17 females) volunteers (mean age = 25.1 years,  $SD = 5.9$ ) took part in this experiment. All participants but two were right-handed, and all of them had normal or corrected-to-normal vision. The data of one participant were excluded because of technical problems during one of the experimental sessions.

#### 2.1.2. Apparatus and stimuli

The experiment was run in a dim and noise-shielded room; it was controlled by an IBM-compatible computer with color display (19", 150 Hz refresh rate) and programmed in MATLAB™ using the Psychophysics Toolbox extension (Brainard, 1997). Participants sat 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 WS (sine tone, 1000 Hz; 70 dB) was presented binaurally via headphones. The letter “L” or “R” ( $1.14^\circ \times 0.86^\circ$  angle of vision) served as the IS and was displayed in blue ( $7.1 \text{ cd/m}^2$ ) at the center of the screen.

### 2.1.3. Design and procedure

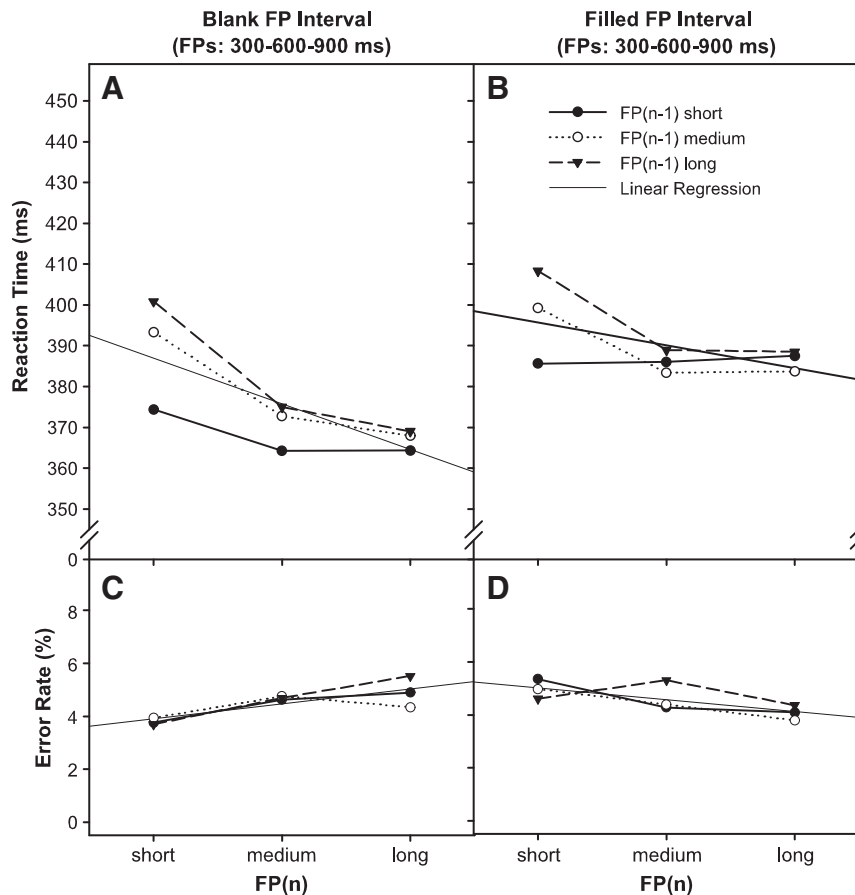
The three-factorial within-subject design contained the factors stimulation during the foreperiod (“Fill”: blank vs. filled FPs), previous foreperiod length (“ $\text{FP}_{n-1}$ ”: 300 vs. 600 vs. 900 ms) and current foreperiod length (“ $\text{FP}_n$ ”: 300 vs. 600 vs. 900 ms). Stimulation was varied across the two halves of the experiment, their order being counterbalanced across participants. A trial in the blank-FP condition started with the auditory WS (presented for 100 ms), followed by a blank FP until the visual IS occurred. A trial in the filled-FP condition started with the same auditory WS, which was prolonged until IS onset. Trials were separated by a 1000-ms intertrial interval. Participants performed a two-choice RT task and were required to respond with either the left shift-key (left index finger, if “L” was presented) or the right shift-key (right index finger, if “R” was presented). The IS was terminated either by response or after expiration of 2000 ms. Participants were instructed to respond quickly and accurately. In case of an erroneous response, the German word “falsch” (wrong) was presented for 300 ms as feedback; in case of response-interval expiration, the phrase “zu langsam” (too slow) was presented. Participants performed 6 warm-up trials and 600 experimental trials in each condition. A large break was given

between the critical (between-block) conditions, and short breaks were 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 were discarded (0.3% on average). Correct responses were used to compute mean RT, while incorrect responses (pressing the wrong response key) were used to compute error percentage (EP). Effects of the factors Fill (blank vs. filled FPs),  $\text{FP}_{n-1}$  (short vs. medium vs. long) and  $\text{FP}_n$  (short vs. medium vs. long) on RT and EP were tested via within-subject analyses of variance (ANOVAs). Complete statistical effects are listed in the Appendix (Table 1); Fig. 1 displays RT and EP separately for blank-FP (panels A and C) and filled-FP (panels B and D) conditions.

As predicted, responses were faster with blank than filled FPs (RTs: 376 vs. 390 ms, RT difference = 4.0%), as indicated by a significant main effect of Fill [ $F(1,23) = 9.1$ ; partial  $\eta^2 = 0.28$ ;  $p < 0.01$ ]. Further, there was a downward-sloping  $\text{FP}_{n-1}$ -RT effect, as indicated by the significant main effect of  $\text{FP}_{n-1}$  [ $F(2,46) = 27.7$ ; partial  $\eta^2 = 0.55$ ;  $p < 0.001$ ]. Critically, the slope of the  $\text{FP}_{n-1}$ -RT function was steeper with blank than filled FPs, as indicated by the significant Fill  $\times$   $\text{FP}_{n-1}$  effect [ $F(2,46) = 4.1$ ; partial  $\eta^2 = 0.15$ ;  $p < 0.05$ ]. Finally, although an asymmetric sequential FP effect emerged within the critical conditions [ $F(4,92) = 12.0$ ; partial  $\eta^2 = 0.34$ ;  $p < 0.001$ ], there was no difference between the conditions (i.e., no three-way interaction on RT emerged:  $F < 0.3$ ). It becomes evident from Fig. 1



**Fig. 1.** Effects of a blank versus an auditorily filled FP interval on the sequential FP effect in Experiment 1. Reaction time and error percentage are displayed as a function of the preceding foreperiod ( $\text{FP}_{n-1}$ ) and the current foreperiod ( $\text{FP}_n$ ), separately for the blank-FP condition (panels A and C) and the filled-FP condition (panels B and D). The linear regression plot (derived from computing a least-square fit to the displayed nine data points) only serves for illustrative purposes.

that the asymmetry of the sequential FP effect did not differ between blank- and filled-FP conditions, since the entire RT pattern in the filled-FP condition was rotated counterclockwise. There were no statistical effects on error rate except for a Fill  $\times$  FP<sub>n</sub> interaction [ $F(2,46) = 4.1$ ; partial  $\eta^2 = 0.15$ ;  $p < 0.05$ ], driven by an EP increase with increasing blank-FP length and an EP decrease with increasing filled-FP length.

In order to assess whether the sequential FP effect on RT was statistically reliable for both the blank-FP and the filled-FP condition, additional ANOVAs were performed separately for either condition. With blank FPs, there was a significant main effect of FP<sub>n</sub> [ $F(2,46) = 26.0$ , partial  $\eta^2 = 0.52$ ,  $p < 0.0001$ ], indicating the downward-sloping FP<sub>n</sub>-RT function, and a significant FP<sub>n-1</sub>  $\times$  FP<sub>n</sub> interaction [ $F(2,92) = 6.5$ , partial  $\eta^2 = 0.21$ ,  $p < 0.001$ ], indicating that the standard situation produced the typical asymmetric sequential FP effect. An analogous analysis also demonstrated these well-established effects for the filled-FP condition, since there was an FP<sub>n</sub> main effect [ $F(2,46) = 9.6$ , partial  $\eta^2 = 0.30$ ,  $p < 0.001$ ] and an FP<sub>n-1</sub>  $\times$  FP<sub>n</sub> interaction [ $F(2,92) = 6.0$ , partial  $\eta^2 = 0.21$ ,  $p < 0.001$ ]. Thus, despite the modulation of the RT pattern by the presence of an auditory FP filling, the asymmetric sequential FP effect was preserved.

### 3. Experiment 2

The design of the previous experiment, which replicated classic findings, leaves room for an alternative explanation of the filled-FP effect. In particular, since the auditory “filling” consisted of a continuation of the WS, the blank-FP condition selectively offered participants to recruit both onset and offset of the WS for their response timing (Los & Schut, 2008; Ross & Ross, 1980). Thus, the possibly ensuing difference in timing accuracy between blank and filled FPs constitutes a potential confound in Experiment 1, since it might contribute to the performance decrement with filled FPs – especially with short FPs as used here. Thus the experimental setting of Experiment 1 was slightly changed: auditory stimulation during the FP now consisted of a high-frequency sine tone that was well discriminable from the WS, enabling the use of WS offset for timing processes in both conditions. Predictions were the same as in Experiment 1.

#### 3.1. Method

##### 3.1.1. Participants

Twenty-five (10 males, 15 females) volunteers (mean age = 24.5 years, SD = 5.5) took part in this experiment. All participants but four were right-handed, and all of them had normal or corrected-to-normal vision.

##### 3.1.2. Stimuli and apparatus

The set-up exactly equaled Experiment 1, except that the additional auditory stimulation in the filled FP interval (1400 Hz sinus tone; 70 dB) was clearly discriminable from the WS (1000 Hz sinus tone; 70 dB; 100 ms duration).

##### 3.1.3. Task, design, and procedure

The experimental setting was equal to Experiment 1.

#### 3.2. Results and discussion

Data processing and statistical procedures were equal to Experiment 1. Complete statistical effects are listed in the Appendix (Table 1); Fig. 2 displays RT and EP separately for blank-FP (panels A and C) and filled-FP (panels B and D) conditions.

Despite equal possibilities to recruit both WS on- and offset for preparation in either condition, responses were still faster with blank than filled FPs (RTs: 374 vs. 388 ms; RT difference = 3.0%), as indicated by a significant main effect of Fill [ $F(1,24) = 7.1$ ; partial

$\eta^2 = 0.23$ ;  $p < 0.05$ ]. There also was a downward-sloping FP<sub>n</sub>-RT effect within each condition, as indicated by the significant main effect of FP<sub>n</sub> [ $F(2,48) = 50.7$ ; partial  $\eta^2 = 0.68$ ;  $p < 0.001$ ]. Critically, the slope of the FP<sub>n</sub>-RT function was again steeper with blank than filled FPs, as indicated by the significant Fill  $\times$  FP<sub>n</sub> effect [ $F(2,48) = 4.2$ ; partial  $\eta^2 = 0.15$ ;  $p < 0.05$ ]. Finally, despite an asymmetric sequential FP effect within conditions [ $F(4,96) = 15.6$ ; partial  $\eta^2 = 0.40$ ;  $p < 0.001$ ], there was no difference between the critical conditions (i.e., no three-way interaction effect on RT was observed:  $F < 1.1$ ). There were no significant effects on EP, except for a marginal main effect of Fill [ $F(1,24) = 4.0$ ; partial  $\eta^2 = 0.14$ ;  $p < 0.06$ ], driven by a somewhat lower error rate in the blank-FP compared to the filled-FP condition (EP: 4.0% vs. 4.9%; EP difference = 22.5%). In sum, the results of Experiment 2 replicated those of Experiment 1, ruling out the possibility that timing accuracy (due to the additional use of WS offset in the blank-FP condition of Experiment 1) had confounded the results of Experiment 1. As a whole, the outcome of Experiment 2 further attested to the robustness of the filled-FP effect.

As in Experiment 1, additional ANOVAs on RT were performed separately for the blank-FP and the filled-FP conditions. With blank FPs, there was a significant main effect of FP<sub>n</sub> [ $F(2,48) = 37.5$ , partial  $\eta^2 = 0.61$ ,  $p < 0.0001$ ], driven by the downward-sloping FP<sub>n</sub>-RT function, and a significant FP<sub>n-1</sub>  $\times$  FP<sub>n</sub> interaction [ $F(2,96) = 8.3$ , partial  $\eta^2 = 0.26$ ,  $p < 0.0001$ ], indicating the typical sequential FP effect. An analogous analysis also demonstrated these effects for the filled-FP condition: there was a main effect of FP<sub>n</sub> [ $F(2,48) = 36.6$ , partial  $\eta^2 = 0.60$ ,  $p < 0.0001$ ] and a significant FP<sub>n-1</sub>  $\times$  FP<sub>n</sub> interaction [ $F(2,96) = 8.2$ , partial  $\eta^2 = 0.25$ ,  $p < 0.0001$ ]. Thus, despite the modulation of the RT pattern by the presence of a distinct auditory FP filling, the asymmetric sequential FP effect was preserved in Experiment 2 as well.

### 4. Experiment 3

The flattening of the FP<sub>n</sub>-RT slope (i.e., the decrease in the variable-FP effect) in the filled-FP conditions of both Experiments 1 and 2 provides support for the distraction-during-FP hypothesis. However, in order to completely rule out the possibility that deficient or delayed FP-to-IS modality shifts at least partially contribute to the RT increase with filled FPs, we employed an auditory IS in Experiment 3. In this situation, shifting attention between modalities during the FP is unnecessary for task execution and, thus, should not differentially occur in the filled-FP condition. Since the use of an auditory IS, as opposed to a visual IS, has been shown to yield faster responses, we expected shorter average RT, perhaps accompanied by a flatter FP<sub>n</sub>-RT slope, compared to Experiments 1 and 2 (see Langner, Willmes, Chatterjee, Eickhoff, & Sturm, 2010; Miller, Franz, & Ulrich, 1999, for theoretical discussions of intensity effects on RT performance). In light of the findings in Experiments 1 and 2, which lent support to the distraction-during-FP hypothesis, our predictions regarding the effect of irrelevant auditory stimulation during the FP were as follows: The filled-FP condition should still yield a main effect of the factor Fill on RT, and, in addition, a selective effect on temporal preparation, as evidenced by a significant decrease in the FP<sub>n</sub>-RT slope (Fill  $\times$  FP<sub>n</sub> interaction on RT).

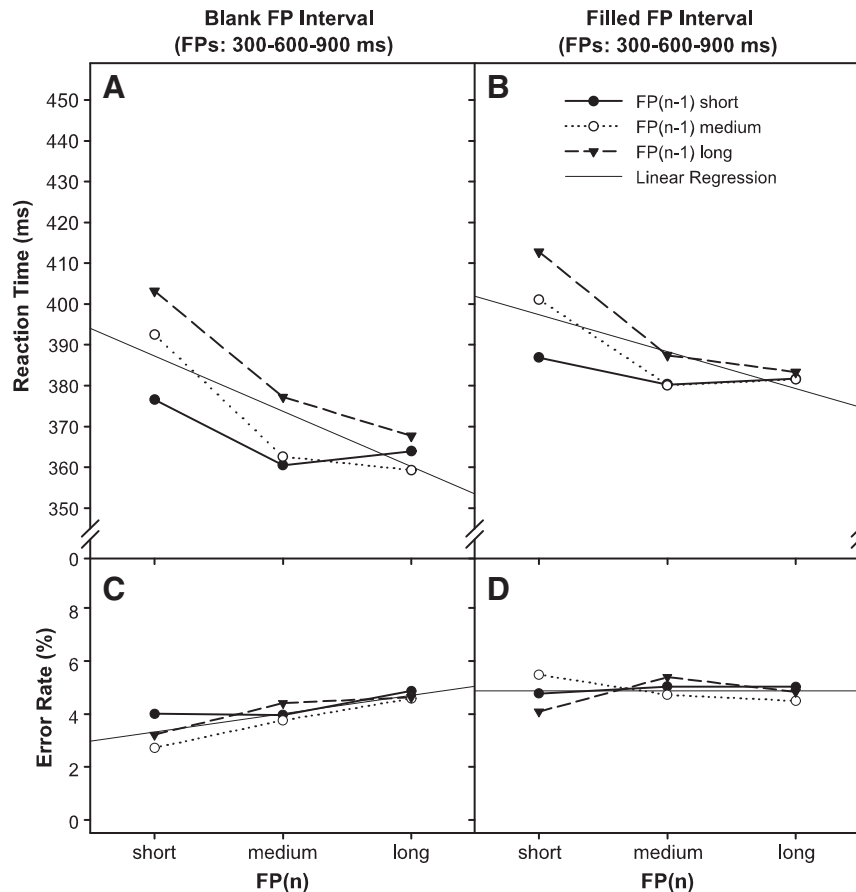
#### 4.1. Method

##### 4.1.1. Participants

Twenty-five (9 males, 16 females) volunteers (mean age = 24.9 years, SD = 4.9) took part in the experiment. All but six participants were right-handed, and all of them had normal or corrected-to-normal vision.

##### 4.1.2. Stimuli and apparatus

The set-up was retained from Experiment 2, except for the following changes: A visual WS (a white star; 100 cd/m<sup>2</sup>; 2.4°  $\times$  2.4° angle of vision) was presented in the center of a computer screen



**Fig. 2.** Effects of a blank versus an auditorily filled FP interval on the sequential FP effect in Experiment 2. Reaction time and error percentage displayed as a function of the preceding foreperiod ( $FP_{n-1}$ ) and the current foreperiod ( $FP_n$ ), separately for the blank-FP condition (panels A and C) and the filled-FP condition (panels B and D). The linear regression plot (see Fig. 1 for computational details) only serves for illustrative purposes.

providing a gray ( $38.4 \text{ cd/m}^2$ ) background. The auditory FP filling consisted of white noise (70 dB SPL); the IS consisted of a low-frequency sine tone (1000 Hz; 70 dB SPL; requiring a left-hand response) or a high-frequency sine tone (1400 Hz; 70 dB SPL; requiring a right-hand response).

#### 4.1.3. Task, design and procedure

The setting was equal to the previous experiments.

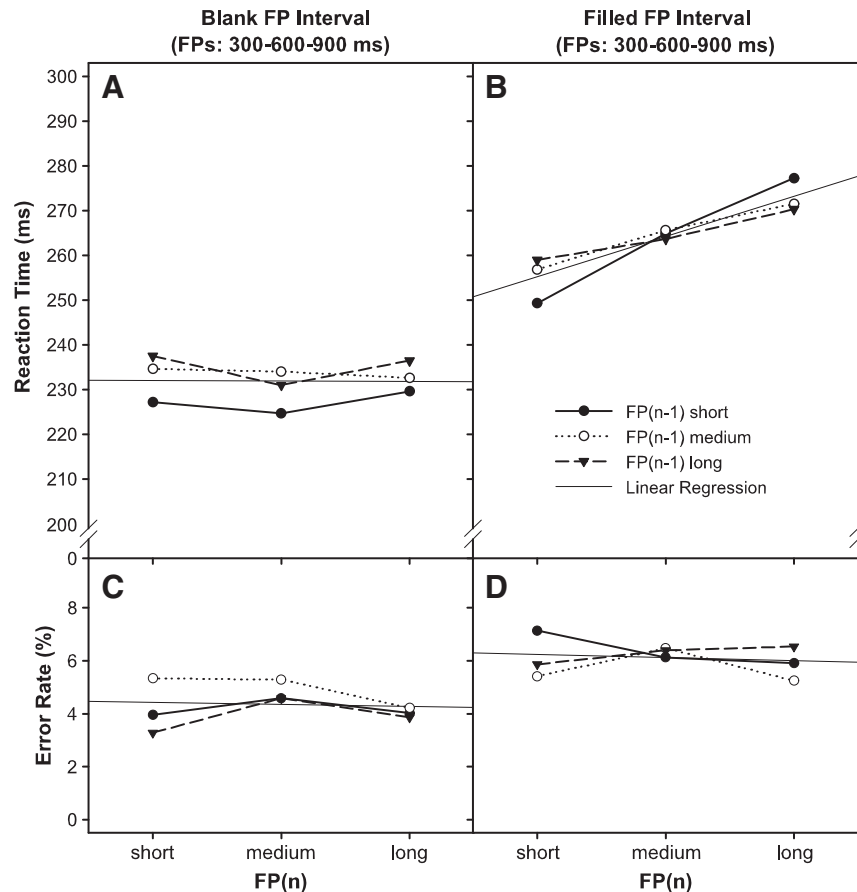
#### 4.2. Results and discussion

Data processing and statistical procedures were equal to previous experiments. Statistical effects are listed in the Appendix (Table 2); Fig. 3 displays RT and EP separately for blank-FP (panels A and C) and filled-FP (panels B and D) conditions.

As expected, responses were faster than in previous experiments with a visual IS (Experiments 1 and 2). Also, responses were again considerably faster with blank than filled FPs (231 vs. 261 ms; RT difference = 13%), as indicated by a significant main effect of Fill [ $F(1,23) = 65.1$ ; partial  $\eta^2 = 0.74$ ;  $p < 0.001$ ]. The RT increase in the filled-FP condition was moreover accompanied by a corresponding EP increase (4.3 vs. 6.1%; EP difference = 42.0%), as indicated by a significant main effect of Fill [ $F(1,23) = 7.3$ ; partial  $\eta^2 = 0.24$ ;  $p < 0.01$ ]. Critically, the filled-FP condition again yielded a selective RT increase on long- $FP_n$  trials, as indicated by the Fill  $\times$   $FP_n$  interaction [ $F(2,46) = 10.0$ ; partial  $\eta^2 = 0.30$ ;  $p < 0.001$ ]. We found especially intriguing that

the filled-FP condition yielded a positively sloped  $FP_n$ -RT function, indicating a strong impact of auditory stimulation on preparation for an impending auditory IS. This special finding is not predicted from theoretical models, but it clearly arises from the fact that the  $FP_n$ -RT function was flat in the blank-FP condition, so that any FP-related impairment of preparatory processing must yield a reversal of the  $FP_n$ -RT function. The manipulation of concurrent irrelevant sound by a filled FP, however, did not modulate the sequential FP effect, since the Fill  $\times$   $FP_n \times FP_{n-1}$  interaction on RT was far from significant ( $F < 1$ ).

Consistent with previous studies that used auditory targets in variable-FP experiments (e.g., Karlin, 1959), the auditory IS in Experiment 3 produced a pronounced speed-up of responses, which considerably decreased the  $FP_n$ -RT function and sequential effects. This was statistically verified by additional ANOVAs on RT, performed separately for the blank-FP and the filled-FP conditions. With blank FPs, both the  $FP_n$ -RT effect (main effect of  $FP_n$  on RT) and the asymmetric sequential FP effect ( $FP_{n-1} \times FP_n$  interaction) were far beyond significance level (all  $F < 1$ ). For the filled-FP condition, however, there was a significant  $FP_n$  main effect [ $F(2,46) = 10.7$ , partial  $\eta^2 = 0.32$ ,  $p < 0.0001$ ], arising from an upward-sloping (instead of the typical downward-sloping)  $FP_n$ -RT function. Also, the  $FP_{n-1} \times FP_n$  interaction was marginally significant [ $F(2,92) = 2.7$ , partial  $\eta^2 = 0.11$ ,  $p < 0.06$ ]. Comparing only the extreme values (i.e., RT on long-FP trials against RT on short-FP trials) with simple contrasts (Bonferroni-corrected), the filled-FP condition yielded a stronger upward-sloping  $FP_n$ -RT effect



**Fig. 3.** Effects of a blank versus an auditorily filled FP interval on the sequential FP effect in Experiment 3. Reaction time and error percentage displayed as a function of the preceding foreperiod ( $FP_{n-1}$ ) and the current foreperiod ( $FP_n$ ), separately for the blank-FP condition (panels A and C) and the filled-FP condition (panels B and D). The linear regression plot (see Fig. 1 for computational details) only serves for illustrative purposes.

$[F(1,23) = 16.5, \text{partial } \eta^2 = 0.42, p < 0.0001]$  and even a more symmetrical sequential modulation of FP [ $F(1,23) = 8.7, \text{partial } \eta^2 = 0.27, p < 0.01$ ], as compared to when all FP values (short, medium, and long) were included in the ANOVA. Such symmetrical sequential FP effects have also been reported by Alegria (1975b), using extremely dense FP intervals (FPs: 500, 600, and 700 ms), and by Vallesi and Shallice (2007) in very young children.

In sum, the fact that irrelevant sound during the FP selectively slowed RT on long-FP trials even when presented on the same (i.e. auditory) sensory channel like the IS, strongly argues against the attention-to-modality hypothesis as an explanation for the auditory filled-FP effect. In contrast, it provides further support for the distraction-during-FP hypothesis. That is to say, Experiment 3 shows clearly that a modality shift from FP to IS is unlikely the source of the  $FP_n$ -RT modulation, since an even more pronounced modulation was revealed when both FP and IS were auditory (as an auditorily filled FP even reversed the  $FP_n$ -RT function). Therefore, the results of Experiment 3 ruled out the possibility that the modality-shift hypothesis can account for the filled-FP effect. Rather, it appears that FP-IS modality shifts, as compared to FP-IS modality repetitions, are even beneficial, making it easier to detect a visual IS than an auditory IS after an auditorily filled FP. However, two potential limitations remain: (1) the filled-FP condition did not only yield a response slowing but also a remarkably high error rate; (2) although Experiment 3 did not require an attentional shift between FP-filling modality and IS modality, it still required a shift between WS

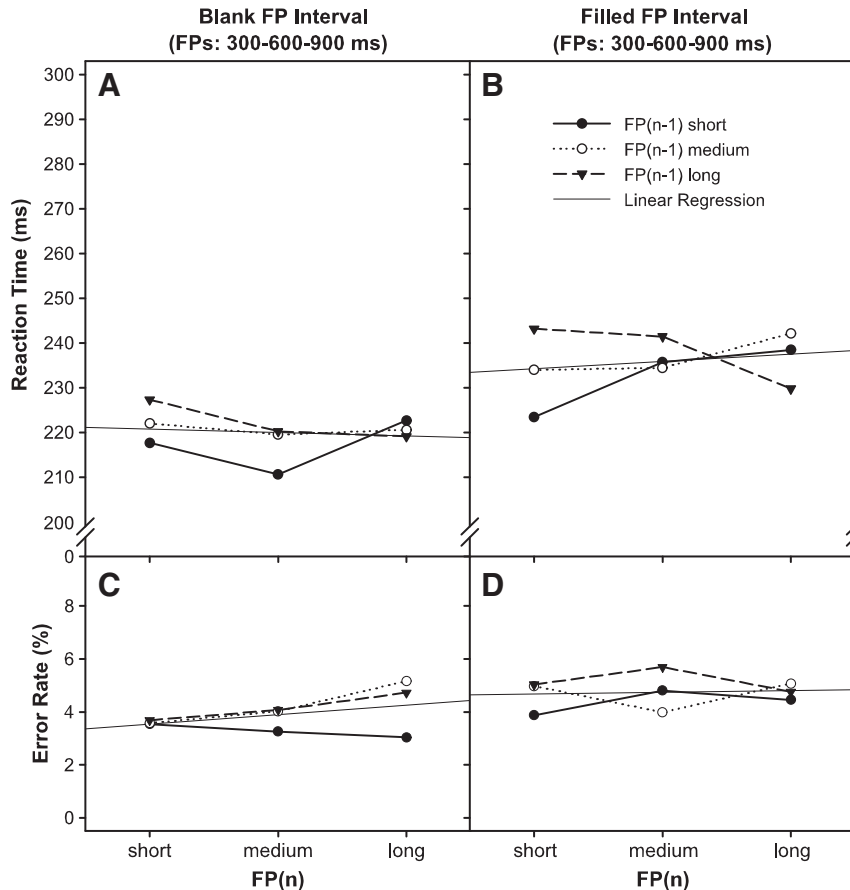
modality and IS modality.<sup>1</sup> Both limitations were resolved in Experiment 4.

## 5. Experiment 4

In Experiment 4 (visual WS, auditorily filled FP), we aimed to reduce errors to similar levels in blank- and filled-FP conditions by using an IS that was redundantly presented in the visual (“L” vs. “R”) and auditory (low-frequency vs. high-frequency tone) modality (cf. Miller, 1986, 1991). This IS redundancy also obviated the necessity to shift attention from the visual to auditory modality between WS and IS. Again, we expected a decrease (or even inversion) of the  $FP_n$ -RT slope in the filled-FP compared to the blank-FP condition, which should be indicated by a  $\text{Fill} \times FP_n$  interaction effect on RT.

<sup>1</sup> As pointed out by an anonymous reviewer, the shift from visual WS modality to auditory IS modality in Experiment 3 might have a moderating influence on performance that may affect our conclusions. We argue that this kind of modality-related WS-IS incongruity effect may be negligible here, since the potential influence of a visual WS is outweighed by the effects of the interspersed auditory FP filling, which should induce an attentional shift to the auditory (i.e., IS) modality before IS processing. Nevertheless, any remaining interpretational problems regarding this issue are circumvented in Experiment 4 by presenting the IS redundantly in the visual and auditory modality, which obviates the necessity to shift attention from visual WS modality to auditory IS modality.





**Fig. 4.** Effects of a blank versus an auditorily filled FP interval on the sequential FP effect in Experiment 4. Reaction time and error percentage displayed as a function of the preceding foreperiod ( $FP_{n-1}$ ) and the current foreperiod ( $FP_n$ ), separately for the blank-FP condition (panels A and C) and the filled-FP condition (panels B and D). The linear regression plot (see Fig. 1 for computational details) only serves for illustrative purposes.

## 5.1. Method

### 5.1.1. Participants

Twenty-five (10 males, 15 females) volunteers (mean age = 27.2 years,  $SD = 6.8$ ) took part in the experimental session. All but three participants were right-handed, and all of them had normal or corrected-to-normal vision.

### 5.1.2. Stimuli and apparatus

The set-up was the same as in Experiment 3 (visual WS, auditorily filled FP), except that the IS was simultaneously presented both visually and auditorily. The auditory IS consisted of a low-frequency sine tone (1000 Hz; 70 dB; left-hand response) or a high-frequency sine tone (1400 Hz; 70 dB; right-hand response). The visual IS consisted of the letter “L” or “R” ( $1.14^\circ \times 0.86^\circ$  angle of vision) and was displayed in blue ( $7.1 \text{ cd/m}^2$ ) at the center of a computer screen providing a gray ( $38.4 \text{ cd/m}^2$ ) background.

### 5.1.3. Task, design and procedure

The experimental setting was equal to Experiment 3.

## 5.2. Results and discussion

Data processing and statistical procedures in Experiment 4 were equal to the previous experiments. Complete statistical effects are listed in the Appendix (Table 2); Fig. 4 displays RT and EP separately for blank-FP (panels A and C) and filled-FP (panels B and D) conditions.

Responses again were faster in the blank-FP than the filled-FP condition (220 vs. 236 ms; RT difference = 7.0%), as indicated by a significant main effect of Fill [ $F(1,24) = 12.9$ ; partial  $\eta^2 = 0.35$ ;  $p < 0.001$ ]. Critically, the  $FP_{n-1}$ -RT function was slightly downward-sloping with blank FPs, whereas it became slightly upward-sloping with filled FPs, as indicated by the Fill  $\times$   $FP_n$  interaction [ $F(2,48) = 3.2$ ; partial  $\eta^2 = 0.11$ ;  $p < 0.05$ ]. There was a modulation of the sequential FP effect by irrelevant auditory stimulation, indicated by the Fill  $\times$   $FP_n \times FP_{n-1}$  interaction effect on RT [ $F(2,48) = 2.8$ ; partial  $\eta^2 = 0.10$ ;  $p = 0.05$ ], yet the effect became more, instead of less, asymmetric in the filled-FP condition. Errors varied only slightly and there were no statistically significant effects on EP.

Similar to the previous experiments, additional ANOVAs on RT were performed, separately for the blank-FP and the filled-FP condition. With blank FPs, there was a marginally significant  $FP_n$  main effect [ $F(2,48) = 3.1$ , partial  $\eta^2 = 0.11$ ,  $p < 0.058$ ] and a marginally significant  $FP_{n-1} \times FP_n$  interaction [ $F(4,96) = 2.1$ , partial  $\eta^2 = 0.08$ ,  $p < 0.095$ ]. To test these effects with a more sensitive analysis (as suggested by one reviewer), we additionally performed simple contrasts (Bonferroni-corrected), in which only the extreme FP values (short vs. long) were compared with each other. Contrasting RT on long-FP trials against RT on short-FP trials for the blank-FP condition yielded a significant  $FP_{n-1} \times FP_n$  interaction [ $F(1,24) = 6.4$ , partial  $\eta^2 = 0.21$ ,  $p < 0.02$ ]. For the filled-FP condition, there was no significant effect of  $FP_n$  on RT ( $F < 1$ ), since the  $FP_n$ -RT function was neither substantially downward-sloping nor upward-sloping. There was, however, a significant  $FP_{n-1} \times FP_n$  interaction [ $F(4,96) = 10.7$ , partial  $\eta^2 = 0.32$ ,  $p < 0.001$ ], indicating the typical asymmetric sequential FP effect.

In sum, the results of Experiment 4 replicated the results of Experiment 3 with avoiding interpretational problems related to a high error rate and WS–IS modality shifts. Thus, the results corroborate the findings of the previous experiments, providing clear-cut support for the idea that the auditory filled-FP effect substantially arises from a disturbance of preparatory-related processing during the FP interval, rather than from a failure to shift attention from the auditory to the visual modality.

## 6. General discussion

Two mechanisms have been proposed to explain the finding that responses become slower when irrelevant sound is presented during the FP (compared to a silent standard condition) – a phenomenon termed the *auditory filled-FP effect*: First, it was argued that additional stimulation distracts individuals from strategic preparatory processing during the FP (Terrell & Ellis, 1964). Alternatively, it was suggested that the auditory filled-FP effect reflects the difficulty to shift attention from FP modality to IS modality (Kellas & Baumeister, 1968). Across four experiments, varying several ancillary variables, a filled FP consistently yielded a selective impairment at late critical moments (i.e., on long-FP<sub>n</sub> trials), thus supporting the hypothesis that preparatory processing be affected by irrelevant sound during FP. Since the effect occurred irrespective of FP–IS modality congruence (in fact, it was even larger with an IS of the same modality as the FP-filling stimulation; cf. Experiments 3 and 4), the present results cannot be interpreted in terms of shifting costs from FP modality to IS modality. We therefore argue that our results provide a strong argument against the proposal that a visual IS is not sufficiently attended to after an auditorily filled FP. Instead, our results corroborate the distraction-during-FP hypothesis, which holds that a filled FP distracts individuals from processing temporal and probability information. Notably, the asymmetry of the sequential FP effect was not decreased by a filled-FP (see Vallesi & Shallice, 2007), but even slightly increased in Experiment 4.

Globally, the present findings are consistent with other studies that examined effects of auditory stimulation on behavioral performance in other cognitive domains (e.g., Colle & Welsh, 1976; Horvath & Winkler, 2010; Jones & Macken, 1993; Klemen, Büchel, Bühler, Menz, & Rose, 2010; Macken et al., 2009; Marsh, Hughes, & Jones, 2009; Parmentier, Elsley, & Ljungberg, 2010). Our results may therefore contribute to understanding auditory distraction and the irrelevant-sound effect. We extended prior findings to the domain of temporal preparation, demonstrating an impairment of preparatory processes by task-irrelevant sound during the FP. It is important to note that the distracting effects in our study occurred with sound that was moderate in loudness (70 dB), fully predictable, and continuous (no change of auditory characteristics). This indicates that the core mechanism underlying temporal preparation in variable-FP paradigms is rather fragile, since it can be perturbed easily. To our knowledge, this study is the first to systematically examine factors potentially underlying the auditory filled-FP effect. In contrast, previous studies mainly applied a filled-FP condition to tap individual differences in maintaining attention (e.g., Baumeister & Wilcox, 1969; Terrell & Ellis, 1964), without sufficiently considering the cognitive mechanisms underlying the observed performance impairments produced by irrelevant stimulation during the FP.

### 6.1. Mechanisms underlying the filled-foreperiod effect

Across all four experiments, the filled-FP condition produced a selective RT increase on long-FP<sub>n</sub> trials, flattening (or even reversing) the FP<sub>n</sub>–RT slope. This finding suggests that irrelevant auditory stimulation during the FP specifically hampers mechanisms related to the preparatory process. Accordingly, if individuals are

prevented from reading out information from the time-tagged event sequence, their preparatory state will be suboptimal at critical moments, and this deficit should become greater with FP<sub>n</sub> length. Moreover, the present results demonstrate that continuous audition during the FP is a suitable experimental manipulation to disturb preparatory activity, since the effects are comparable (with respect to patterning and size) to a transient inhibition of the rDLPFC via TMS (cf. Vallesi, Shallice et al., 2007). Given that irrelevant sound during the FP similarly impairs rDLPFC functioning, as has been shown by neuroimaging studies (cf. Campbell, 2005), the present study contributes to current research by providing a new and easily implemented technique to study the effects of perceptual load and additional stimulation during FP intervals on temporal preparation.

In our series of experiments, we tried to narrow down the mechanisms behind the filled-FP effect by ruling out alternative explanations. Experiment 1 established the effect with a design used previously (e.g., Baumeister & Wilcox, 1969; Terrell & Ellis, 1964). Experiment 2 showed clearly that a potential benefit from additionally using WS offset for preparation had only negligible effects. Experiment 3 ruled out the possibility that the costs of shifting attention between FP and IS modalities be responsible for the modulation of the FP<sub>n</sub>–RT slope. The results of Experiment 4 corroborated this latter finding, while error rates were kept comparable between blank- and filled-FP conditions by means of redundant IS presentation (visually and auditorily at the same time). The results of Experiment 3 more directly contradicted the attention-to-modality hypothesis, since we demonstrated a pronounced negative effect on RT (and EP) in a situation where both the FP-filling stimulation and the IS were presented auditorily. In this situation, concurrent auditory stimulation during the FP interval even yielded an upward-sloping FP<sub>n</sub>–RT function, presumably induced by strong within-modality distraction. These results are in line with studies in related domains, showing that attentional-shift (including attentional-blink or refractory-like) phenomena are larger within modalities than between modalities (e.g., Hazeltine, Ruthruff, & Remington, 2006; Jolicoeur, 1999; Talsma, Doty, Strowd, & Woldorff, 2006).

Finally, it is worth mentioning that the employment of an auditory IS in Experiments 3 and 4 yielded a pronounced flattening of the standard downward-sloping FP<sub>n</sub>–RT function in the blank-FP condition. In our view, this finding may well be related to the stronger alerting properties of auditory versus visual targets (Posner, 1978, p. 139), corresponding to previous findings of globally decreased RT and specific interactions between target intensity and FP length. In fact, the literature on this subject reports several situations in which a flattening of constant-FP effects on RT was shown as a function of target intensity (e.g., Niemi & Lehtonen, 1982; Seifried, Ulrich, Bausenhardt, Rolke, & Osman, 2010). We, therefore, argue that the flattening of the FP<sub>n</sub>–RT function in Experiments 3 and 4 does not undermine our conclusions regarding the effect of auditorily filled FPs on temporal preparation. Rather, it even strengthens their generalizability by showing that the putative distracting effect of auditory FP fillings is also present with a flat FP<sub>n</sub>–RT function, leading to a reversal of the typically downward-sloping function (without affecting sequential FP effects). A steeper (i.e., “normal”) FP<sub>n</sub>–RT function may probably be obtained by using auditory targets of lower intensity, by increasing temporal uncertainty, or both. In sum, the experiments presented here provide evidence in favor of the idea that irrelevant sound during FP disturbs preparatory processes via distraction.

### 6.2. Implications for models of temporal preparation

Two theoretical models are currently being debated regarding their potential to explain variable-FP phenomena, that is, temporal preparation under time uncertainty. A dual-process view (Vallesi, Shallice et al., 2007) adopts a strategic-preparation perspective,

assuming that individuals engage in effort-demanding processes of monitoring temporal events during the FP, and of optimizing an internal state of readiness according to the conditional IS probability. An alternative trace-conditioning model (Los & Van den Heuvel, 2001) advocates a non-strategic process: Elapsed time (FP duration) is mentally represented as an ordered sequence of time-tagged events, and individuals are assumed to automatically register the flow of time, thus being able to unintentionally prepare for upcoming critical moments. In contrast to the dual-process view, unintentional preparation does not necessarily depend on a controlled-processing mode but is considered to proceed in a rather automatic fashion or a preattentive processing mode (Bueti et al., 2010; Los et al., 2001; Moore et al., 1998). Precisely, sensory WS features are assumed to initiate a cascade of activation that runs forward in time until the IS occurs at a particular time point on the cascade (cf. Dickinson, 1980; Moore et al., 1998; Steinborn et al., 2009, 2010). According to Los and colleagues, the  $FP_n$ -RT function is assumed to directly arise from the asymmetric sequential FP effect. In contrast, according to Vallesi and colleagues, the sequential FP effect has an entirely different origin, since it is assumed to arise from the interaction of trial-to-trial variations in motor responsiveness (response-generated arousal) and a strategic conditional-probability monitoring process (see Introduction for details).

The results reported here allow us to propose a tentative picture of what is generating the RT increase in an auditory filled-FP condition with respect to timing mechanisms. According to a strategic view, supervisory monitoring during FP depends on the availability of attentional resources, and manipulations that reduce applicable resources are predicted to impair monitoring efficiency. Given that irrelevant sound captures attention and draws off resources by tapping rDLPFC functions, as has been shown in behavioral (Jones & Macken, 1993; Macken et al., 2009) and neuroimaging studies (Campbell, 2005), the observed decrease of the  $FP_n$ -RT function in the filled-FP condition may arise from distraction-impaired attentional monitoring. This, in turn, would lead to a failure to compensate arousal decreases following long-FP trials, consistent with the dual-process view. Yet, it cannot be excluded that non-strategic mechanisms are affected as well, albeit via a different mechanism. For example, Poulton (1977, 1979) argued that continuous sound acts as a mask. He assumed that any intrusive stimulation particularly impairs performance by masking relevant cues that provide on-line sensory feedback during the task (Greenwald, 1970). Hence, if internal signals from the time-tagged event sequence are masked, upcoming critical moments along this sequence may be overlooked and time-point specific encoding and/or retrieval may not take place adequately. This explanation is clearly consistent with the trace-conditioning view: If a filled FP masks internal signals that indicate upcoming critical moments, even pre-attentive mechanisms of processing temporal information along this sequence may be impaired.

Given the possibility that irrelevant sound during the FP has multiple effects on both strategic and automatic processes, we cannot distinguish between models of temporal preparation without analyzing sequential FP effects, which were not examined in prior studies on the filled-FP effect. It may be argued that if an auditorily filled FP flattened the  $FP_n$ -RT slope, resulting from a symmetrization of the sequential FP effect, this would clearly be consistent with the dual-process view (cf. Vallesi & Shallice, 2007; Vallesi, Shallice et al., 2007, for applying this logic). If, on the other hand, the filled FP yielded no modulation of the sequential FP effect and, consequently, the  $FP_n$ -RT slope, this would be consistent with a trace-conditioning view. Our data show that neither model's prediction is completely confirmed or disconfirmed, since the filled FP flattened the  $FP_n$ -RT slope but without symmetrization. Put differently, the variable-FP effect was modulated but independently of the sequential FP effect, which remained stable (i.e., asymmetric; see Experiments 1–3). In Experiment 4, we even obtained a flattened  $FP_n$ -RT slope with a slightly increased

asymmetry of the sequential FP effect. In the following, we discuss critical factors that might be responsible for the obtained RT pattern.

An important issue concerns the unexpected absence of a symmetrical sequential FP effect in the presence of a flattened  $FP_n$ -RT function with auditorily filled FPs. As mentioned earlier, the dual-process model assumes an enhancement of arousal during the response, which decreases steadily with increasing length of the subsequent FP. Therefore, if irrelevant sound disturbed the strategic (monitoring) process but left the automatic (arousal) process unaffected, a symmetrical FP effect should have occurred (Vallesi & Shallice, 2007). In fact, the asymmetry of the sequential FP effect was not influenced by a filled FP (Experiments 1, 2, and 3), and in Experiment 4, there was even a slight increase in this asymmetry.<sup>2</sup> We suggest that the filled-FP condition has impaired temporal preparation but has retained arousal/motor activation at a consistently high level (even in long-long FP sequences), which may have protected the asymmetry of the sequential FP effect. Poulton (1977) argued that noise induces arousal (at subjective or physiological levels), although it may not inevitably induce a performance improvement but may impair performance efficiency by increasing error rate (as was actually the case in Experiment 3). We consider this view consistent with a dual-process model, but for the reasons mentioned earlier, it does not strongly argue against the contribution of associative learning to the emergence of variable-FP phenomena.

We conclude that our results do not directly falsify strategic or non-strategic (associative learning) accounts of variable-FP phenomena. Our findings, however, clearly favor a multi-process (as opposed to a single-process) view of temporal preparation under time uncertainty. Specifically, this is evidenced by the differential impact of auditory FP-fillings on the  $FP_n$ -RT function (versus the asymmetric sequential FP effect). This effect strongly argues against a view that considers the FP-RT slope as directly (and exclusively) resulting from a single process such as associative learning, that is, from trial-to-trial modulations of RT according to FP-length variability, as indicated by asymmetric sequential FP effects (cf. Los & Van den Heuvel, 2001). It should be emphasized, however, that our data do not argue principally against any contribution of such associative processes to variable-FP phenomena.

### 6.3. Future directions and general conclusions

To test a multi-process view of temporal preparation in subsequent research, it is necessary to work out the contribution of the basic mechanisms involved in the processing of time (Grondin, 2010; Rammesayer, 2010; Wearden, Norton, Martin, & Montford-Bebb, 2007), the detection of upcoming critical (i.e., potentially imperative) moments by "scan and check"-like processes of (spatio-)temporal search (Ambinder & Lleras, 2009; Ariga & Yokosawa, 2008; Yashar & Lamy, 2010), and potential distraction or masking influences of concurrent irrelevant sound during the FP interval. It may also be necessary to

<sup>2</sup> As pointed out by an anonymous reviewer, the results of Experiment 4 revealed an increased (instead of a decreased) asymmetry of the sequential FP effect that cannot be explained easily within current models of temporal preparation. In fact, the dual-process model would predict a symmetrization instead of an asymmetrization under restricted resource availability (Vallesi & Shallice, 2007), while no straightforward prediction would be made from the trace-conditioning model (Los & Van den Heuvel, 2001). Given that future studies reproduce this asymmetrization, potential explanatory variables need to be tested. From the perspective of the dual-process model, it could be tentatively suggested as a working hypothesis that the transiently exhausting effect of preparatory processing on long-FP trials (see Vallesi & Shallice, 2007; Vallesi, Shallice et al., 2007) is larger when the FP is filled with sound. This may be because individuals have to additionally shield against the intruding effects of sound, thereby demanding more effort and depleting more attentional resources used for compensatory strategic monitoring during the distraction-filled long FPs. In turn, this may lead to larger RT differences between subsequent short-FP and long-FP trials.

delineate the specific conditions in which (fully predictable) FP fillings distract individuals from preparatory-related processes, as well as to reveal situations in which FP fillings do not exert such influences. For example, when selective (besides nonspecific) preparation is additionally enforced by biasing target probabilities (e.g., Holender & Bertelson, 1975; Wagener & Hoffmann, 2010), it would be interesting to examine whether filled-FP distraction differentially affects responses to low-versus high-probability events. In addition, FP fillings may even have beneficial effects in situations where a filling can be used as time marker (Simon & Slaviero, 1975) or when it provides rhythmic context (cf. Ellis & Jones, 2010; Sanabria, Capizzi, & Correa, 2011).

Refined experimental manipulations might be taken to examine how individuals search for critical events along the time line during the FP and whether these processes rely on either pre-attentive or deliberate-attention mechanisms. The dual-process model assumes that temporal monitoring is guided by a supervisory attentional system (Norman & Shallice, 1986; Shallice et al., 2008), which is resource-demanding and should be affected by any variables that tap on the same or superordinate resources. The trace-conditioning model assumes that time is tracked pre-attentively along a chained event sequence, which does not require attentional resources (see Bueti et al., 2010; Janssen & Shadlen, 2005; Los & Van den Heuvel, 2001; Moore et al., 1998), but may still be susceptible to structural interference effects. The filled-FP method may be useful for distinguishing between both models, by using either cognitive load or masking stimulation to tap the proposed mechanism. Yet, the challenge will consist of implementing manipulations that exclusively tap attentional resources without interfering with pre-attentive processes, or by implementing manipulations that mask pre-attentive time-scanning processes without diverting attention away from the task.

In further research, the effectiveness of FP fillings may also be enhanced by standard manipulations of salience (e.g., stimulus intensity, contrast, etc.) and predictability (i.e., uncertainty about FP-filling modality and intensity). As we argued in the Introduction, an FP filling will be the more effective as a distractor the more salient it is, whereby it is likely that auditory or vibrotactile stimuli will be more effective than visual ones. Moreover, we would expect that trial-to-trial shifts from frequent to rare FP-filling modalities should

be more detrimental than shifts from rare to frequent modalities. In addition, the insertion of novel FP fillings should distract individuals more than FP fillings to which participants are already adapted. Finally, it is likely that trial-to-trial shifts between different FP-filling modalities are asymmetric (e.g., shifts from visual to auditory FP fillings more detrimental than vice versa), as has been demonstrated in related domains (cf. Spence & Driver, 2004). These issues are relevant but beyond the scope of our study. Here we demonstrated that our participants were hindered from optimally preparing for the moment of IS presentation by FP-related irrelevant sound that was fully predictable and moderately intense.

Taken together, the present results indicate that the auditory filled-FP effect mainly arises from distraction during the preparatory period and not from modality-shift costs at the transition between the FP and the IS onset. Although a filled FP yielded a global RT slowing in all four experiments, the *distraction-during-FP* hypothesis was supported by the finding of an overadditive RT increase on long-FP trials across all four experiments, suggesting that irrelevant sound during the FP interferes with preparatory processes. This effect occurred reliably between different (Experiments 1 and 2) and within equal (Experiments 3 and 4) modalities. The results of Experiments 3 and 4 particularly contradicted the *attention-to-modality* hypothesis, since we demonstrated a pronounced negative effect on RT (and error rate) in a situation where both the FP-filling stimulation and the IS were presented in the auditory modality. In this situation, concurrent auditory stimulation even yielded an upward-sloping  $FP_n$ -RT function, presumably induced by strong within-modality distraction. Although our results might not be taken to distinguish between principal accounts of temporal preparation (i.e., the “associative” trace-conditioning model vs. the “strategic” dual-process model), they nevertheless argue for a *multi-process account*, which may include strategic and non-strategic processes. Thus, we also consider our work a useful contribution to the discussion concerning the mechanisms underlying the variable-FP phenomena.

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## Appendix

**Table 1**  
ANOVA results for Experiments 1 and 2.

Source	Reaction Time				Error Percentage		
	dfs	F	p	$\eta^2$	F	p	$\eta^2$
<i>Experiment 1</i>							
1 Fill	1,23	9.1	0.006	0.28	0.2	0.686	0.01
2 $FP_{n-1}$	2,46	16.3	0.000	0.42	0.7	0.496	0.03
3 $FP_n$	2,46	27.7	0.000	0.55	0.3	0.763	0.01
4 $Fill \times FP_{n-1}$	2,46	4.8	0.013	0.17	0.0	0.980	0.00
5 $Fill \times FP_n$	2,46	4.1	0.023	0.15	6.7	0.003	0.23
6 $FP_{n-1} \times FP_n$	4,92	12.0	0.000	0.34	0.6	0.657	0.03
7 $Fill \times FP_{n-1} \times FP_n$	4,92	0.23	0.919	0.01	0.6	0.687	0.02
<i>Experiment 2</i>							
1 Fill	1,24	7.1	0.014	0.23	4.0	0.058	0.14
2 $FP_{n-1}$	2,48	54.0	0.000	0.69	0.5	0.602	0.02
3 $FP_n$	2,48	50.7	0.000	0.68	1.9	0.167	0.07
4 $Fill \times FP_{n-1}$	2,48	2.9	0.062	0.11	0.6	0.555	0.02
5 $Fill \times FP_n$	2,48	4.2	0.021	0.15	1.9	0.156	0.07
6 $FP_{n-1} \times FP_n$	4,96	15.6	0.000	0.40	0.7	0.575	0.03
7 $Fill \times FP_{n-1} \times FP_n$	4,96	1.0	0.452	0.04	0.9	0.444	0.04

Note. Effect size: partial  $\eta^2$ ; experimental factors: Fill (blank FP vs. auditory-filled FP);  $FP_{n-1}$  (short vs. medium vs. long);  $FP_n$  (short vs. medium vs. long); IS modality = visual (“L” vs. “R”).

**Table 2**  
ANOVA results for Experiments 3 and 4.

Source	Reaction Time				Error Percentage			
	dfs	F	p	$\eta^2$	F	p	$\eta^2$	
<i>Experiment 3</i>								
1 Fill	1,23	65.2	0.000	0.74	7.3	0.013	0.24	
2 $FP_{n-1}$	2,46	1.4	0.254	0.06	0.3	0.751	0.01	
3 $FP_n$	2,46	3.5	0.039	0.13	1.9	0.164	0.07	
4 Fill $\times$ $FP_{n-1}$	2,46	1.6	0.211	0.07	2.3	0.108	0.09	
5 Fill $\times$ $FP_n$	2,46	10.0	0.000	0.30	0.3	0.780	0.01	
6 $FP_{n-1} \times FP_n$	4,92	2.0	0.096	0.08	1.3	0.282	0.05	
7 Fill $\times$ $FP_{n-1} \times FP_n$	4,92	0.8	0.550	0.03	1.1	0.351	0.05	
<i>Experiment 4</i>								
1 Fill	1,24	12.9	0.001	0.35	3.9	0.059	0.14	
2 $FP_{n-1}$	2,48	7.1	0.002	0.23	3.9	0.037	0.14	
3 $FP_n$	2,48	0.5	0.642	0.02	0.7	0.467	0.03	
4 Fill $\times$ $FP_{n-1}$	2,48	0.0	0.978	0.00	0.6	0.545	0.02	
5 Fill $\times$ $FP_n$	2,48	3.2	0.050	0.11	0.4	0.631	0.02	
6 $FP_{n-1} \times FP_n$	4,96	9.2	0.000	0.28	1.4	0.245	0.06	
7 Fill $\times$ $FP_{n-1} \times FP_n$	4,96	2.8	0.034	0.10	2.1	0.096	0.08	

Note. Effect size: partial  $\eta^2$ ; experimental factors: Fill (blank FP vs. auditory-filled FP);  $FP_{n-1}$  (short vs. medium vs. long);  $FP_n$  (short vs. medium vs. long); IS modality = visual ("L" vs. "R").

**Table 3**  
Mean reaction time (RT) and standard error of the mean (SE) as a function of the factors filling of foreperiod (Fill), previous foreperiod ( $FP_{n-1}$ ), and current foreperiod ( $FP_n$ ), displayed for Experiments 1 to 4.

Experimental conditions	Exp. 1		Exp. 2		Exp. 3		Exp. 4				
	Fill	$FP_{n-1}$	$FP_n$	RT	SE	RT	SE	RT	SE		
1	A	1	1	374	3.8	377	2.9	227	4.9	218	3.9
2	A	1	2	364	3.8	361	3.1	225	3.9	211	3.4
3	A	1	3	364	2.8	364	4.3	230	4.4	223	2.7
4	A	2	1	393	3.7	392	3.7	235	4.2	222	2.9
5	A	2	2	373	3.2	363	3.7	234	5.9	220	4.5
6	A	2	3	368	3.2	359	3.8	233	3.5	221	3.5
7	A	3	1	401	5.1	403	4.9	238	3.5	227	3.1
8	A	3	2	375	3.6	377	4.3	231	3.5	220	2.7
9	A	3	3	369	3.0	368	3.4	236	5.0	219	2.9
10	B	1	1	386	3.7	387	4.0	249	4.6	223	3.6
11	B	1	2	386	2.8	380	3.2	265	3.1	236	3.5
12	B	1	3	388	4.1	382	2.8	277	4.3	238	3.2
13	B	2	1	399	4.2	401	4.3	257	3.6	234	3.5
14	B	2	2	383	2.1	380	3.5	266	3.5	234	3.5
15	B	2	3	384	2.9	382	3.7	272	3.7	242	3.9
16	B	3	1	408	4.6	413	3.7	259	4.7	243	3.6
17	B	3	2	389	3.2	387	3.2	264	3.4	241	3.4
18	B	3	3	389	4.6	383	2.9	270	3.8	230	3.0

Notes. Factor levels of the experimental conditions: Fill: A = blank FP; B = filled FP;  $FP_n/FP_{n-1}$ : 1 = short, 2 = medium, and 3 = long FP. SE was adjusted for within-subject designs according to Cousineau (2007).

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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  $FP_{n-1}$ . 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 & Delhaye-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<sub>n</sub> trials, irrespective of FP<sub>n–1</sub> 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<sub>n</sub> trials, responses are assumed to be facilitated when following a short-FP<sub>n–1</sub> trial, relative to a long-FP<sub>n–1</sub> 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<sub>n</sub> trials, however, responses are fast irrespective of previous FP length, because the decrement in arousal following long-FP<sub>n–1</sub> 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<sub>n–1</sub>.

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<sub>n</sub> 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<sub>n</sub>–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, & Derkzen, 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<sub>n</sub> that was previously reinforced by an equally long FP<sub>n–1</sub>, compared to a short FP<sub>n–1</sub>. Instead, conditioned response strength at a late critical moment should increase (or at least remain stable) after a long FP<sub>n–1</sub> 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<sub>n–1</sub> than after a long FP<sub>n–1</sub> (Vallesi & Shallice, 2007, p. 1386).

According to Vallesi and Shallice (2007, p. 1386), decreased arousal after a long FP<sub>n–1</sub> 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<sub>n–1</sub>, 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<sub>n</sub> when FP<sub>n–1</sub> was short compared to when FP<sub>n–1</sub> 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).<sup>1</sup>

### 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.

<sup>1</sup> 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 ( $7.1 \text{ cd/m}^2$ ) at the center of the computer screen.

<sup>2</sup> 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; Rammsayer & 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

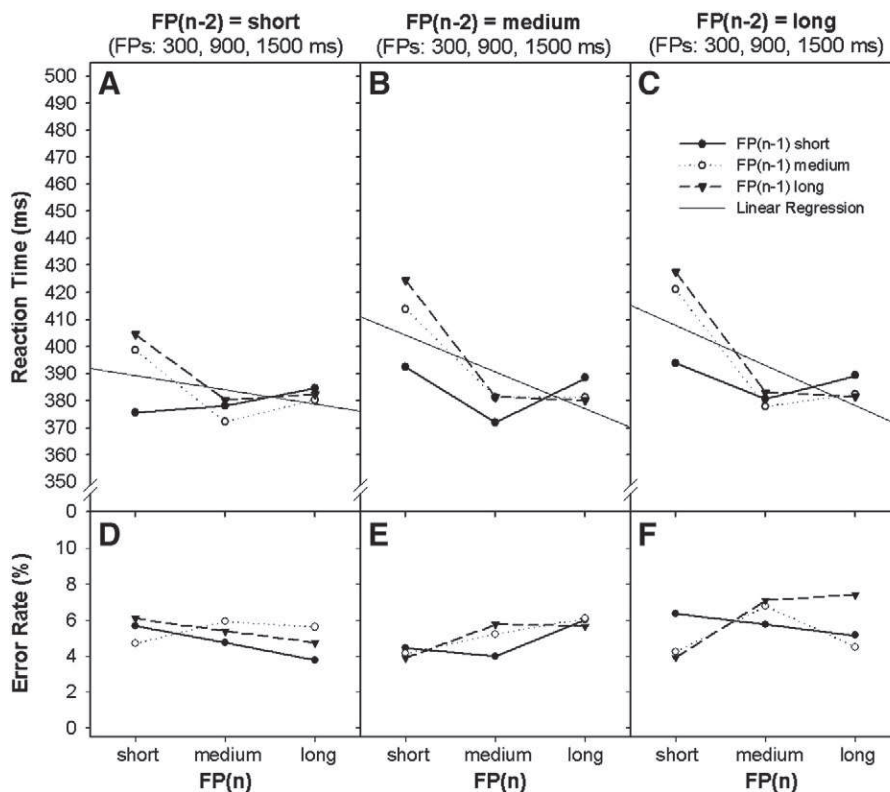


Fig. 1. Higher-order sequential foreperiod effects in Experiment 1. Reaction time and error rate as a function of the preceding ( $FP_{n-1}$ ) and current ( $FP_n$ ) foreperiod, separately displayed for short (panels A, D), medium (panels B, E), and long (panels C, F) foreperiods ( $FP_{n-2}$ ) two trials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

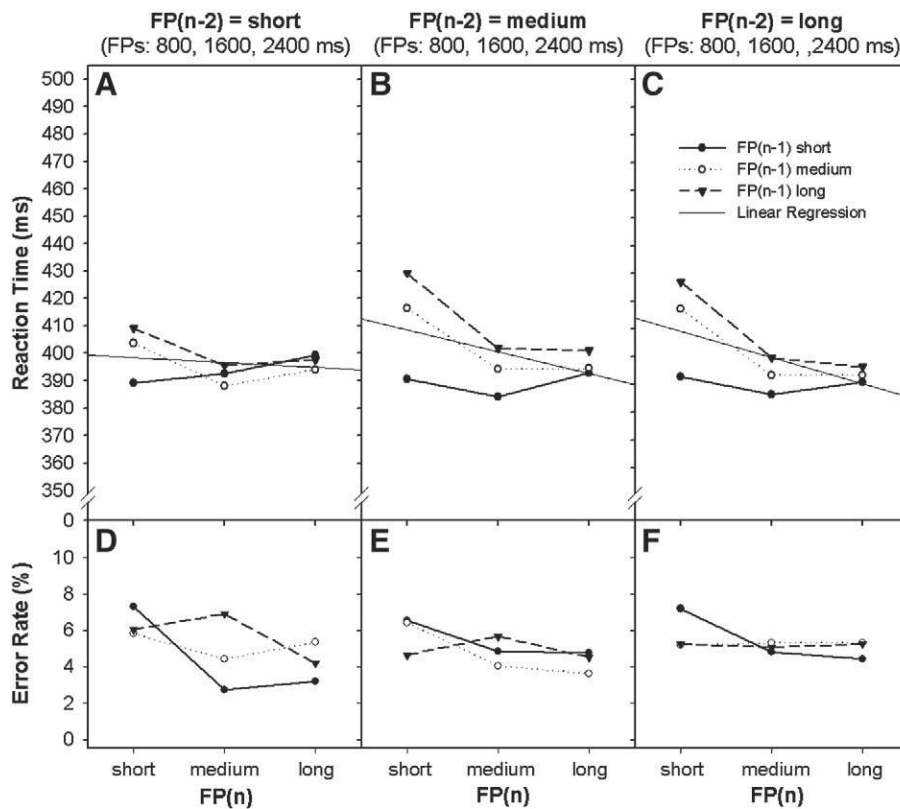
The main effect of  $FP_{n-1}$  on RT indicated that responses were globally faster when a current trial was preceded by a short  $FP_{n-1}$  as compared to a medium or long  $FP_{n-1}$  (RTs: 391, 399, 406 ms). The main effect of  $FP_n$  on RT indicated that responses became generally faster with increasing  $FP_n$  (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

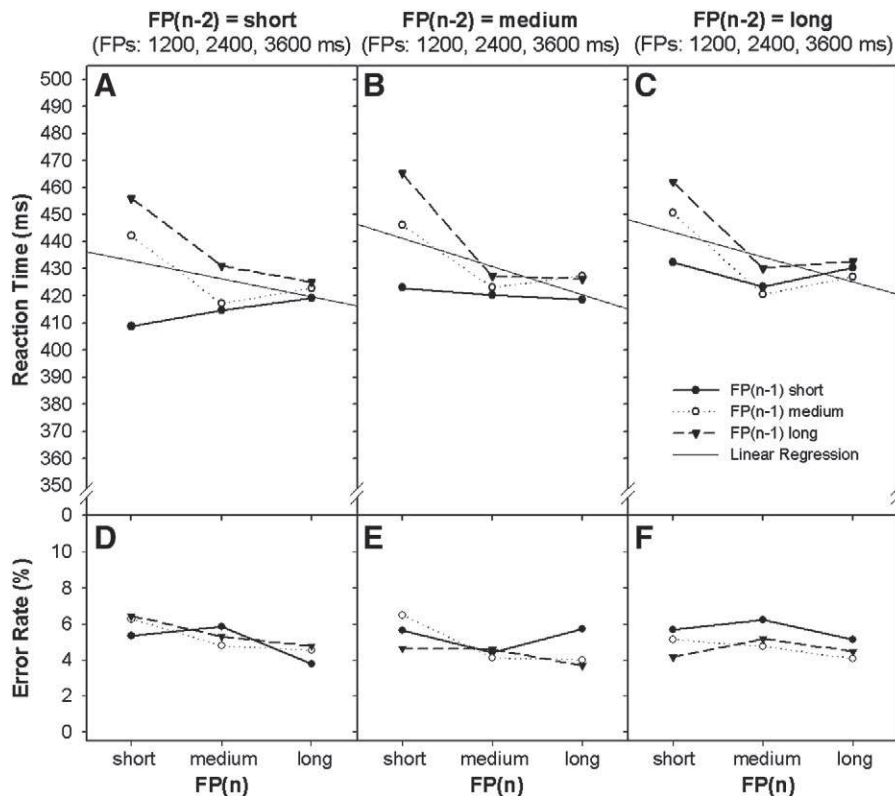


Fig. 3. Higher-order sequential foreperiod effects in Experiment 3. Reaction time and error rate as a function of the preceding ( $FP_{n-1}$ ) and current ( $FP_n$ ) foreperiod, separately displayed for short (panels A, D), medium (panels B, E), and long (panels C, F) foreperiods ( $FP_{n-2}$ ) two trials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

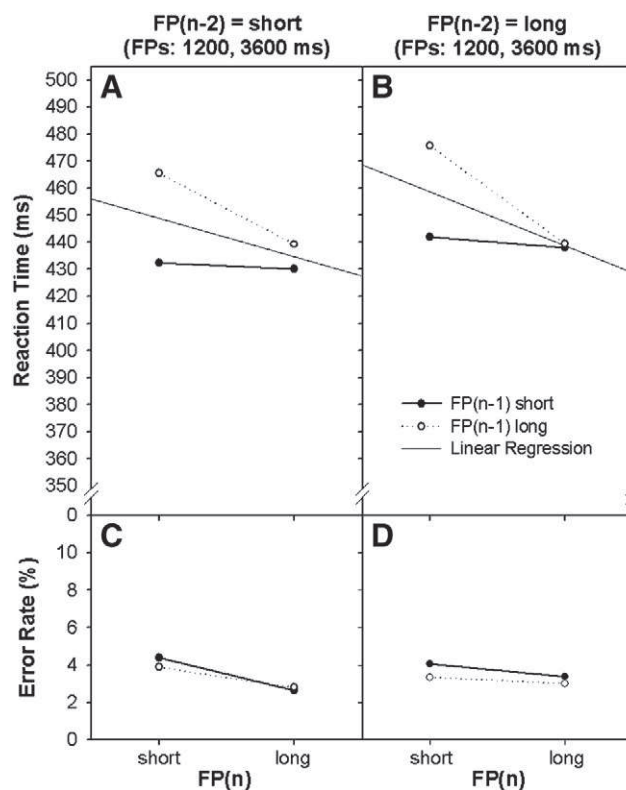


Fig. 4. Higher-order sequential foreperiod effects in Experiment 4. Reaction time and error rate as a function of the preceding ( $FP_{n-1}$ ) and current ( $FP_n$ ) foreperiod, separately displayed for short (panels A, B) and long (panels C, D) foreperiods ( $FP_{n-2}$ ) two trials previously.

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

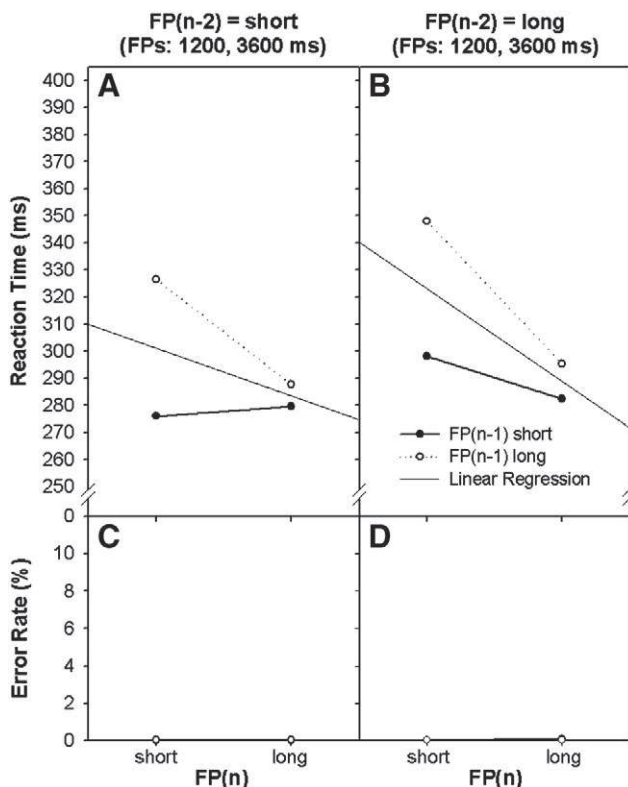
Task and stimuli were equal to the previous experiments, that is, the letters “L” and “R” served as the IS to which participants were to respond with the right shift-key by using their right index finger.

### 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.<sup>3</sup> 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

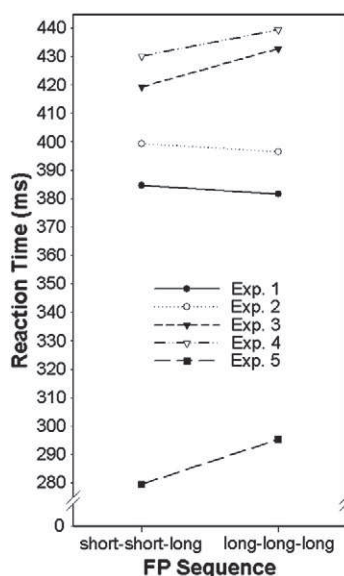
<sup>3</sup> It should be noted that Los et al.'s (2001) formal modeling of the conditioning processes thought to underlie sequential FP effects was able to produce this RT pattern (i.e., slightly slower responses in long-long than in short-long FP sequences) with at least one set of plausible parameter 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	$\eta^2$	F	p	$\eta^2$
<i>Experiment 1 (FPs: 300, 900, 1500 ms, choice reaction)</i>							
1 FP <sub>n-2</sub>	2,98	22.0	0.000	0.31	3.1	0.050	0.06
2 FP <sub>n-1</sub>	2,98	23.3	0.000	0.32	1.0	0.401	0.02
3 FP <sub>n</sub>	2,98	55.3	0.000	0.53	2.0	0.142	0.04
4 FP <sub>n-2</sub> × FP <sub>n-1</sub>	4,196	0.5	0.749	0.01	0.9	0.496	0.02
5 FP <sub>n-2</sub> × FP <sub>n</sub>	4,196	14.7	0.000	0.23	4.0	0.005	0.08
6 FP <sub>n-1</sub> × FP <sub>n</sub>	4,196	38.0	0.000	0.44	3.3	0.013	0.06
7 FP <sub>n-2</sub> × FP <sub>n-1</sub> × FP <sub>n</sub>	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 <sub>n-2</sub>	2,98	4.2	0.019	0.08	0.4	0.682	0.01
2 FP <sub>n-1</sub>	2,98	51.8	0.000	0.51	0.0	0.699	0.01
3 FP <sub>n</sub>	2,98	24.8	0.000	0.34	8.0	0.001	0.14
4 FP <sub>n-2</sub> × FP <sub>n-1</sub>	4,196	5.5	0.001	0.10	1.7	0.154	0.03
5 FP <sub>n-2</sub> × FP <sub>n</sub>	4,196	6.2	0.000	0.11	0.9	0.478	0.02
6 FP <sub>n-1</sub> × FP <sub>n</sub>	4,196	25.2	0.000	0.34	4.8	0.001	0.09
7 FP <sub>n-2</sub> × FP <sub>n-1</sub> × FP <sub>n</sub>	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 <sub>n-2</sub>	2,98	21.0	0.000	0.30	0.8	0.435	0.02
2 FP <sub>n-1</sub>	2,98	52.3	0.000	0.52	1.5	0.232	0.03
3 FP <sub>n</sub>	2,98	32.0	0.000	0.40	4.7	0.011	0.10
4 FP <sub>n-2</sub> × FP <sub>n-1</sub>	4,196	2.9	0.027	0.06	1.7	0.161	0.03
5 FP <sub>n-2</sub> × FP <sub>n</sub>	4,196	1.9	0.114	0.04	1.8	0.135	0.04
6 FP <sub>n-1</sub> × FP <sub>n</sub>	4,196	26.1	0.000	0.35	1.2	0.316	0.02
7 FP <sub>n-2</sub> × FP <sub>n-1</sub> × FP <sub>n</sub>	8,392	0.9	0.463	0.02	0.8	0.539	0.02]

Note. Effect size: partial  $\eta^2$ ; Experimental factors: FP<sub>n-2</sub>/FP<sub>n-1</sub>/FP<sub>n</sub>: 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	$\eta^2$	F	p	$\eta^2$
<i>Experiment 4 (FPs: 1200, 3600 ms; choice reaction)</i>							
1 FP <sub>n-2</sub>	1,34	65.6	0.000	0.66	0.2	0.899	0.00
2 FP <sub>n-1</sub>	1,34	124.0	0.000	0.79	3.5	0.069	0.09
3 FP <sub>n</sub>	1,34	37.0	0.000	0.52	10.6	0.003	0.24
4 FP <sub>n-2</sub> × FP <sub>n-1</sub>	1,34	3.5	0.069	0.09	0.8	0.387	0.02
5 FP <sub>n-2</sub> × FP <sub>n</sub>	1,34	9.2	0.005	0.21	4.9	0.034	0.13
6 FP <sub>n-1</sub> × FP <sub>n</sub>	1,34	110.2	0.000	0.76	1.2	0.282	0.03
7 FP <sub>n-2</sub> × FP <sub>n-1</sub> × FP <sub>n</sub>	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 <sub>n-2</sub>	1,14	41.1	0.000	0.75	-	-	-
2 FP <sub>n-1</sub>	1,14	113.1	0.000	0.89	-	-	-
3 FP <sub>n</sub>	1,14	13.6	0.002	0.49	-	-	-
4 FP <sub>n-2</sub> × FP <sub>n-1</sub>	1,14	0.2	0.630	0.02	-	-	-
5 FP <sub>n-2</sub> × FP <sub>n</sub>	1,14	10.9	0.005	0.44	-	-	-
6 FP <sub>n-1</sub> × FP <sub>n</sub>	1,14	60.9	0.000	0.81	-	-	-
7 FP <sub>n-2</sub> × FP <sub>n-1</sub> × FP <sub>n</sub>	1,14	1.0	0.336	0.07	-	-	-]

Note. Effect size: partial  $\eta^2$ ; Experimental factors: FP<sub>n-2</sub>/FP<sub>n-1</sub>/FP<sub>n</sub>: 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<sub>n-2</sub>), first-order previous foreperiod (FP<sub>n-1</sub>), and current foreperiod (FP<sub>n</sub>), displayed for Experiments 1 to 3.

	Factor levels			Experiment 1		Experiment 2		Experiment 3	
	FP <sub>n-2</sub>	FP <sub>n-1</sub>	FP <sub>n</sub>	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<sub>n-2</sub>, FP<sub>n-1</sub>, FP<sub>n</sub>): 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<sub>n-2</sub>), first-order previous foreperiod (FP<sub>n-1</sub>), and current foreperiod (FP<sub>n</sub>), displayed for Experiments 4 and 5.

	Factor levels			Experiment 4		Experiment 5	
	FP <sub>n-2</sub>	FP <sub>n-1</sub>	FP <sub>n</sub>	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<sub>n-2</sub>, FP<sub>n-1</sub>, FP<sub>n</sub>): 1 = short FP, 2 = long FP.

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