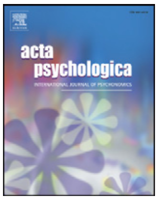
Acta Psychologica 136 (2011) 405–418

Contents lists available at ScienceDirect

Acta Psychologica

journal homepage: www.elsevier.com/ locate/actpsy



Distraction by irrelevant sound during foreperiods selectively impairs temporal preparation

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ARTICLE INFO

Article history:
Received 24 October 2010
Received in revised form 31 December 2010
Accepted 10 January 2011
Available online 21 February 2011

PsycINFO classification:
2330
2221
2340
2343
2346

Keywords:
Variable foreperiod effect
Sequential foreperiod effect
Attention
Temporal preparation
Multimodal stimulation

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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doi:10.1016/j.actpsy.2011.01.008

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; Stilitz, 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_n trials are assumed to be facilitated when following a short-FP_{n-1} trial, due to an increase in the motor-activation level. In contrast, responses on short-FP_n trials are slowed when following a long-FP_{n-1} trial, due to a decrease in the motor-activation level. On long-FP_n trials, however, responses are fast, irrespective of FP_{n-1}, because the motor-activation decrement following long-FP_{n-1} 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_n 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 fo 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_n 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_n trials (yielding a flattening of the FP_n–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_n–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_n 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, & Derkzen, 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° × 0.5° 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°×0.86° angle of vision) served as the IS and was displayed in blue (7.1 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 ("FP_{n-1}": 300 vs. 600 vs. 900 ms) and current foreperiod length ("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), FP_{n-1} (short vs. medium vs. long) and 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 FP_n–RT effect, as indicated by the significant main effect of FP_n [$F(2,46) = 27.7$; partial $\eta^2 = 0.55$; $p < 0.001$]. Critically, the slope of the FP_n–RT function was steeper with blank than filled FPs, as indicated by the significant Fill × FP_n 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

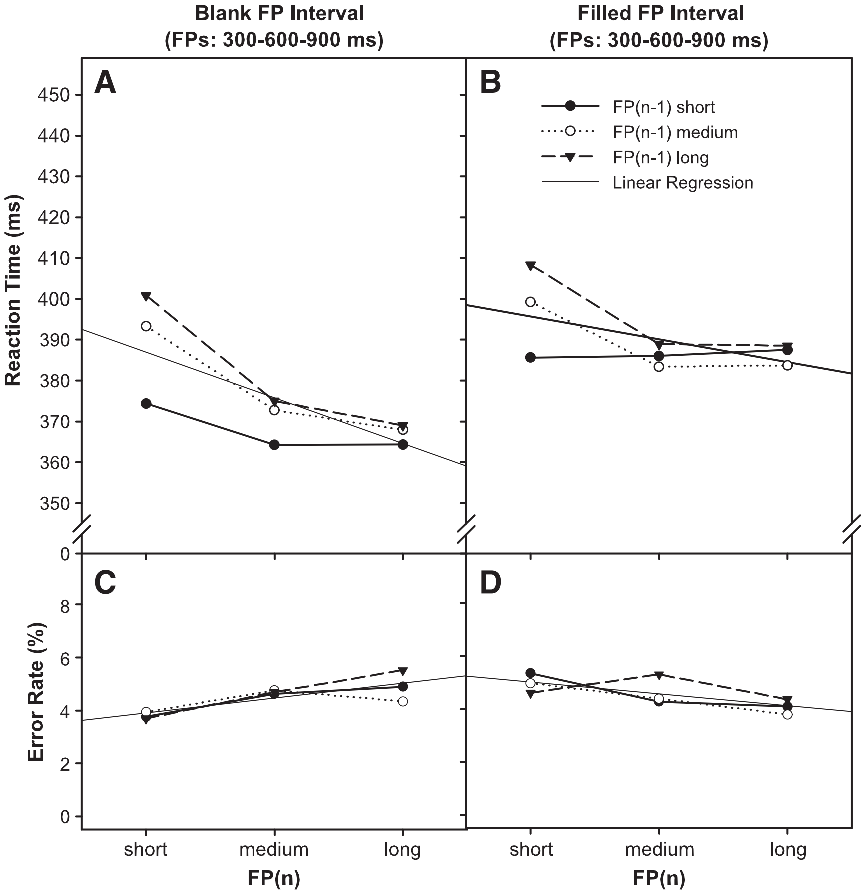

Fig. 1. Effects of a blank versus an auditorily filled FP interval on the sequential FP effect in Experiment 1. Reaction time and error percentage are displayed as a function of the preceding foreperiod (FP_{n-1}) and the current foreperiod (FP_n), separately for the blank-FP condition (panels A and C) and the filled-FP condition (panels B and D). The linear regression plot (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 × FP_n 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_n [$F(2,46) = 26.0$, partial $\eta^2 = 0.52$, $p < 0.0001$], indicating the downward-sloping FP_n–RT function, and a significant $\text{FP}_{n-1} \times \text{FP}_n$ 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_n main effect [$F(2,46) = 9.6$, partial $\eta^2 = 0.30$, $p < 0.001$] and an $\text{FP}_{n-1} \times \text{FP}_n$ 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_n–RT effect within each condition, as indicated by the significant main effect of FP_n [$F(2,48) = 50.7$; partial $\eta^2 = 0.68$; $p < 0.001$]. Critically, the slope of the FP_n–RT function was again steeper with blank than filled FPs, as indicated by the significant Fill × FP_n 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_n [$F(2,48) = 37.5$, partial $\eta^2 = 0.61$, $p < 0.0001$], driven by the downward-sloping FP_n–RT function, and a significant $\text{FP}_{n-1} \times \text{FP}_n$ 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_n [$F(2,48) = 36.6$, partial $\eta^2 = 0.60$, $p < 0.0001$] and a significant $\text{FP}_{n-1} \times \text{FP}_n$ 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_n–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_n–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_n–RT slope (Fill × FP_n 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^2; 2.4° × 2.4° angle of vision) was presented in the center of a computer screen

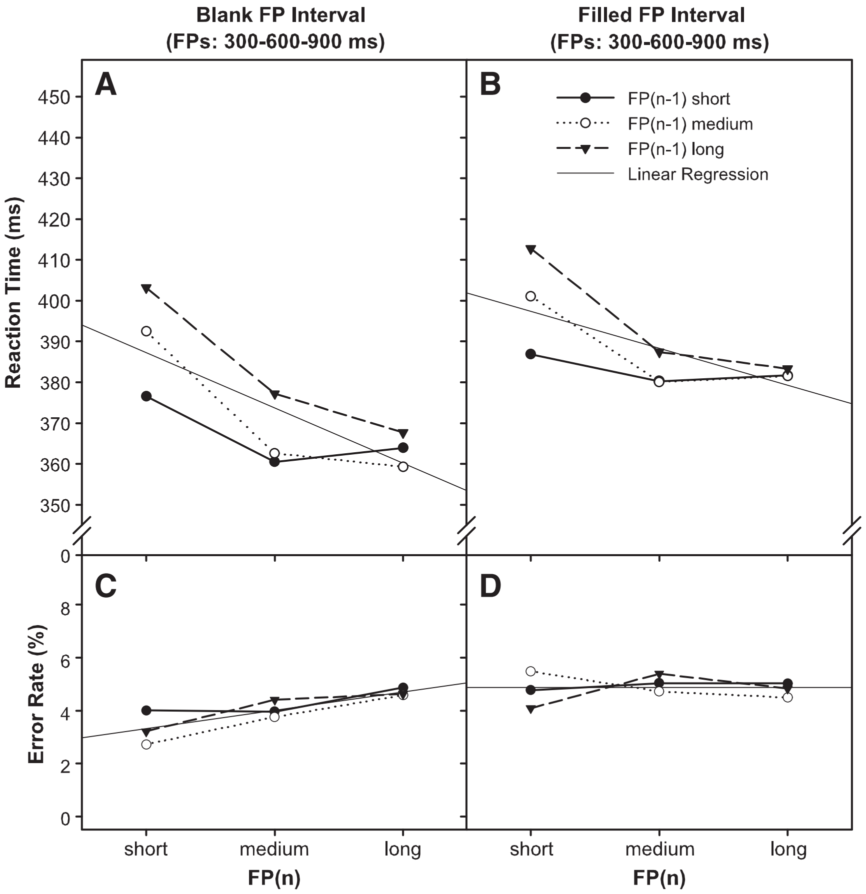

Fig. 2. Effects of a blank versus an auditorily filled FP interval on the sequential FP effect in Experiment 2. Reaction time and error percentage displayed as a function of the preceding foreperiod (FP_{n-1}) and the current foreperiod (FP_n), separately for the blank-FP condition (panels A and C) and 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 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 × 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 × FP_n × 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} × 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} × 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

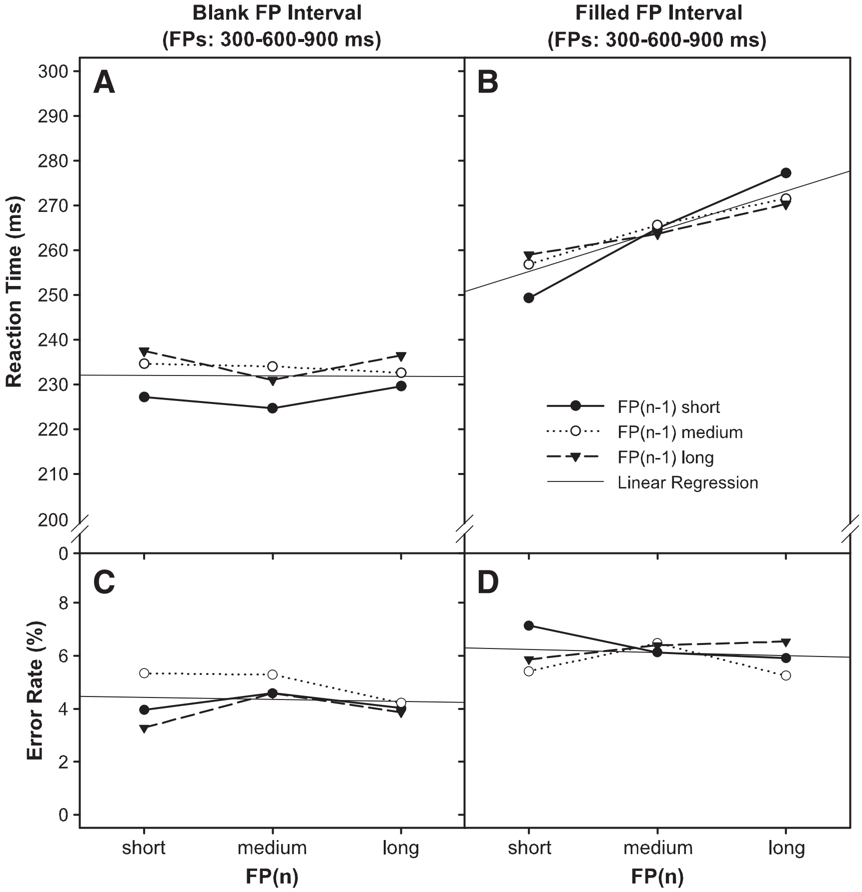

Fig. 3. Effects of a blank versus an auditorily filled FP interval on the sequential FP effect in Experiment 3. Reaction time and error percentage displayed as a function of the preceding foreperiod (FP_{n-1}) and the current foreperiod (FP_n), separately for the blank-FP condition (panels A and C) and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

[$F(1,23) = 16.5$, partial $\eta^2 = 0.42$, $p < 0.0001$] and even a more symmetrical sequential modulation of FP [$F(1,23) = 8.7$, 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.[1] 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 Fill × FP_n interaction effect on RT.

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[1] 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 incongruency 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.

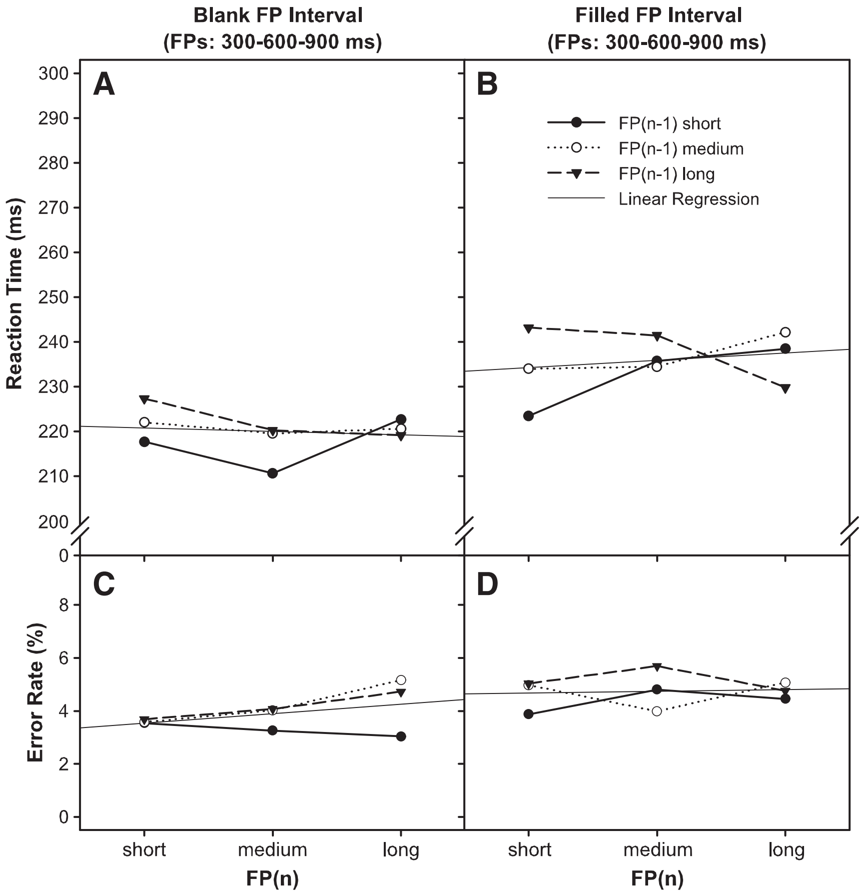

Fig. 4. Effects of a blank versus an auditorily filled FP interval on the sequential FP effect in Experiment 4. Reaction time and error percentage displayed as a function of the preceding foreperiod (FP_{n-1}) and the current foreperiod (FP_n), separately for the blank-FP condition (panels A and C) and 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° × 0.86° angle of vision) and was displayed in blue (7.1 cd/m^2) at the center of a computer screen providing a gray (38.4 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–RT function was slightly downward-sloping with blank FPs, whereas it became slightly upward-sloping with filled FPs, as indicated by the Fill × 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 × FP_n × 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_n 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_n trials, flattening (or even reversing) the FP_n–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_n 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_n–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_n–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_n–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, Bausenhart, Rolke, & Osman, 2010). We, therefore, argue that the flattening of the FP_n–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_n–RT function, leading to a reversal of the typically downward-sloping function (without affecting sequential FP effects). A steeper (i.e., "normal") FP_n–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 as 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.[2] 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; Rammsayer, 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

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[2] 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 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.

Acknowledgement

We thank two anonymous reviewer for helpful comments on an earlier version of this paper.

Appendix

Table 1
ANOVA results for Experiments 1 and 2.

	Reaction Time				Error Percentage		
Source	dfs	F	p	η^2	F	p	η^2
		Experiment 1					
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 × FP_{n-1}	2,46	4.8	0.013	0.17	0.0	0.980	0.00
5 Fill × FP_n	2,46	4.1	0.023	0.15	6.7	0.003	0.23
6 FP_{n-1} × FP_n	4,92	12.0	0.000	0.34	0.6	0.657	0.03
7 Fill × FP_{n-1} × FP_n	4,92	0.23	0.919	0.01	0.6	0.687	0.02
		Experiment 2					
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 × FP_{n-1}	2,48	2.9	0.062	0.11	0.6	0.555	0.02
5 Fill × FP_n	2,48	4.2	0.021	0.15	1.9	0.156	0.07
6 FP_{n-1} × FP_n	4,96	15.6	0.000	0.40	0.7	0.575	0.03
7 Fill × FP_{n-1} × FP_n	4,96	1.0	0.452	0.04	0.9	0.444	0.04

Note. *Effect size*: partial η^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 dfs	F	p	η^2	Error Percentage F	p	η^2
		Experiment 3					
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 × FP_{n-1}	2,46	1.6	0.211	0.07	2.3	0.108	0.09
5 Fill × FP_n	2,46	10.0	0.000	0.30	0.3	0.780	0.01
6 FP_{n-1} × FP_n	4,92	2.0	0.096	0.08	1.3	0.282	0.05
7 Fill × FP_{n-1} × FP_n	4,92	0.8	0.550	0.03	1.1	0.351	0.05
		Experiment 4					
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 × FP_{n-1}	2,48	0.0	0.978	0.00	0.6	0.545	0.02
5 Fill × FP_n	2,48	3.2	0.050	0.11	0.4	0.631	0.02
6 FP_{n-1} × FP_n	4,96	9.2	0.000	0.28	1.4	0.245	0.06
7 Fill × FP_{n-1} × FP_n	4,96	2.8	0.034	0.10	2.1	0.096	0.08

Note. *Effect size*: partial η^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	Fill	FP_{n-1}	FP_n	Exp. 1 RT	SE	Exp. 2 RT	SE	Exp. 3 RT	SE	Exp. 4 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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