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Functional dissociations in temporal preparation: evidence from dual-task performance

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Abstract

Implicit preparation over time is a complex cognitive capacity important to optimize behavioural responses to a target occurring after a temporal interval, the so-called foreperiod (FP). If the FP occurs randomly and with the same a priori probability, shorter response times are usually observed with longer FPs than with shorter ones (FP effect). Moreover, responses are slower when the preceding FP was longer than the current one (sequential effects). It is still a matter of debate how different processes influence these temporal preparation phenomena. The present study used a dual-task procedure to understand how different processes, along the automatic-controlled continuum, may contribute to these temporal preparation phenomena. Dual-task demands were manipulated in two experiments using a subtraction task during the FP. This secondary task was administered in blocks (Experiment 1) or was embedded together with a baseline single-task in the same experimental session (Experiment 2). The results consistently showed that the size of the FP effect, but not that of sequential effects, is sensitive to dual-task manipulations. This functional dissociation unveils the multi-faceted nature of implicit temporal preparation: while the FP effect is due to a controlled, resource-consuming preparatory mechanism, a more automatic mechanism underlies sequential effects.

Keywords: Foreperiod effect, sequential effects, temporal preparation, dual-task, time processing.

1. Introduction

Processing of temporal information is useful for virtually all cognitive operations and comprises many different neuro-cognitive mechanisms (Coull, 2009; Janssen and Shadlen, 2005; Koch et al., 2009; Meck, 2005; Nobre et al., 2007). Temporal preparation, for instance, is the capacity to process temporal information to optimize the perceptual and motor processing of the forthcoming event (Bausenhart et al., 2006; Coull and Nobre, 2008; Hackley et al., 2007). In particular, implicit temporal preparation occurs when temporal information is not relevant for the task at hand, and yet elapsing time produces robust behavioral effects. Traditionally, implicit temporal preparation has been studied by manipulating the foreperiod (FP) – the preparatory interval before the occurrence of a target stimulus (Woodrow, 1914). When the FP is variable and each FP in the range occurs with the same a priori probability, RTs are usually shorter for longer FPs than for shorter ones (FP effect; (Los and van den Heuvel, 2001; Niemi and Näätänen, 1981; Vallesi, 2010). Another phenomenon which occurs with this paradigm are the FP sequential effects: RTs are longer when the current FP is shorter than the preceding one, compared to when it is equal or longer (Karlin, 1959; Woodrow, 1914). As a result, sequential effects are asymmetrically more pronounced for short current FPs than for longer ones.

A single-process model was proposed about a decade ago in order to account for both the FP and the sequential effects (Los and van den Heuvel, 2001; Los, Knol & Boers, 2001). On this model, the preparation level associated with each FP in the range is regulated via trace conditioning mechanisms, so that it will increase (i.e., reinforcement) if a FP is repeated in consecutive trials, and it will decrease (i.e., extinction) if a FP is bypassed by longer FPs. This probably occurs because of the need to avoid premature responses, a process which is both resource-demanding and aversive (Näätänen, 1971). Consequently, RTs will be longer for shorter FPs. Conversely, RTs for the longest FPs will be shorter because the preparation level associated with them is always reinforced and never extinguished, given that these FPs are never overcome by even longer ones.

Thus, under this model (Los and van den Heuvel, 2001), the FP effect is considered as a by-product of the conditioning mechanisms underlying the sequential effects.

To probe their model, Los and van den Heuvel (2001) used a Posner-like temporal orienting task (see Coull & Nobre, 1998), in which a temporal cue signal preceded the FP. The signal could validly or invalidly cue the forthcoming FP duration (a neutral cue was also used). Participants showed an advantage in preparing for the validly cued FP, especially when it was a short one. Importantly, when the signal invalidly cued a long FP, and a short FP occurred instead, the cost of not having intentionally prepared for the correct FP was not constant, but it depended on the duration of the previous FP, as indicated by pronounced sequential effects. If those were due to intentional strategies, there was no reason why they should have emerged in a condition in which participants were intentionally using a cue to prepare a response after a certain FP. This empirical evidence demonstrates that the mechanisms underlying sequential effects are automatic.

However, the other implication of the single-process conditioning model – the FP effect being a by-product of the sequential effects – has been partially disconfirmed by the findings that the two effects are dissociable both developmentally and anatomically. Developmentally, 4-year-old children (Vallesi and Shallice, 2007b) and older adults (Vallesi, McIntosh, and Stuss, 2009b; also see Jurkowski, Stepp, and Hackley, 2005; cf. Bherer and Belleville, 2004) show normal-sized sequential effects but no FP effect, that is, their RTs are not modulated by the current FP length. Anatomically, permanent lesions (Stuss et al., 2005; Triviño, Correa, Arnedo, and Lupiañez, 2010; Vallesi et al., 2007a) or inhibitory Transcranial Magnetic Stimulation (Vallesi, Shallice, and Walsh, 2007c) in right lateral prefrontal cortex are associated with a reduction of the FP effect, whereas no substantial change in the sequential effects (when measured) has been observed. Moreover, activation of the right DLPFC in healthy adults positively correlates with the FP effect but shows no relationship with the sequential effects (Vallesi, McIntosh, Shallice, and Stuss, 2009a).

On a classic account, the variable FP effect is due to a process which continuously monitors the rising conditional probability of stimulus occurrence as time elapses without the stimulus being presented in order to optimize behavior (Elithorn and Lawrence, 1955; Näätänen, 1970; Niemi and Näätänen, 1981). This explanation is compatible with the observations that the variable FP effect, and more generally, attention to time (Coull and Nobre, 1998; Koch, Oliveri, Carlesimo, and Caltagirone, 2002) have a locus in the lateral prefrontal cortex. Indeed, this region has been thought to stand at the top of the perception-action cycle (Fuster, 2000), and to play a pivotal role in controlled processes such as monitoring and checking (Petrides, 2000; Shallice, 2004; Stuss, 2011), especially in the right hemisphere (Stuss and Alexander, 2007; Vallesi and Crescentini, 2011; Vallesi, 2012).

In an attempt to reconcile the available evidence, we recently proposed a dual-process account (Vallesi & Shallice, 2007b). On this account, the foreperiod effect is mainly due to the strategic monitoring process (Niemi & Näätänen, 1981), while sequential effects are mainly due to a more automatic process of modulation of the general activation level of the motor system (which we called 'arousal') by the duration of the previous preparation period.

The hypothesis of a monitoring process is also useful to account for the fact that sequential effects are asymmetrically more pronounced for short FPs. In particular, the asymmetric reduction or absence of the sequential effects towards the longest FPs in the range used has been explained, besides from a possible form of spontaneous decay, also by attributing a 'protective' role to the monitoring process against sequential effects when the conditional probability of target presentation is high (Vallesi & Shallice, 2007b; Vallesi et al., 2007c; Vallesi, 2010). Indeed, since the high-level processes producing the FP effect are probably not mature in 4-year old children, and thus no compensation is possible, these children show more symmetric sequential effects than older children (Vallesi et al., 2007b, Experiment 2; but see Elliot, 1970 for different results with 5-7 year old children).

However, there is no direct evidence to date in favor of the hypothesis that the FP effect is due to a controlled monitoring process. Recent studies showed that the variable FP effect is resistant to manipulations that generally increase mental fatigue and prolong absolute RTs, such as the use of longer FP ranges (Langner, Steinborn, Chatterjee, Sturm, & Willmes, 2010; Vallesi, 2007; but see Bjorklund, 1992). Langner and colleagues (2010) interpreted this result as evidence against the view that the mechanisms underlying the FP effect are controlled. However, an alternative interpretation is that the controlled monitoring mechanism thought to give rise to the FP effect is a distinct cognitive process with respect to the mechanisms underlying non-specific mental fatigue, thus explaining the observed dissociation. Putative evidence in favor of this alternative view comes from the observation that the capacity to combat fatigue is related to the functionality of the anterior cingulate cortex (e.g., Stuss et al., 2007; Vallesi et al., 2009a), suggesting a different neural basis from that associated to the FP effect (i.e., right DLPFC) and, somewhat more indirectly, different underlying cognitive processes (e.g., Stuss et al., 2005; Vallesi et al., 2007a; see Langner & Eickhoff, in press, for a quantitative review).

The current study tests whether it is possible to behaviorally dissociate the FP and the sequential effects in healthy young adults, thus supporting a multi-process account of the FP phenomena. In particular, using dual-task manipulations that require processing resources by taxing working memory, it investigates whether the FP effect suffers from dual-task interference more than the sequential effects. This scenario would demonstrate that the underlying mechanisms are more controlled and resource-demanding (Shiffrin & Schneider, 1977) – compatible with the dual-process account (Vallesi et al., 2007b; Vallesi et al., 2007c; Vallesi, 2010). This approach has been already successfully employed in the past for different (e.g., Logan, 1978; Logan, 1979; Hommel & Eglau, 2002) and similar (Capizzi, Sanabria, & Correa, 2012; Capizzi, Correa, & Sanabria, 2013) domains. It is generally agreed (e.g., Capizzi et al., 2012; Kahneman, 1973; Logan, 1978; but see Pashler, 1994), for a critical discussion) that an interaction between memory load (secondary task) and other ongoing task requirements (primary task) is diagnostic of processing capacity limits of the primary task, while additivity between the primary and secondary tasks would indicate a higher degree of automaticity.

Following this logic, a recent study (van Lambalgen & Los, 2008) tried to disentangle between single- and dual-process models of the FP phenomena. In that study, participants were asked to perform a 1-back secondary task while also performing a dual-choice spatial RT task with a variable foreperiod paradigm (stressing speed for the performance of this primary task). In the 1-back task, participants were presented, during the FP, with a number every 500 ms, and they had to count the number of subsequently repeated numbers for later report. The authors failed to observe any modulation of the FP effect by dual-task performance while, quite unexpectedly, there was a load-dependent reduction of sequential effects. The latter finding could be explained on both single- and dual-process accounts as due to a low preparatory state under dual-task condition. On the single-process account (Los & van den Heuvel, 2001), less extinction is necessary when a short foreperiod is bypassed, since the risk of anticipations is lower in a low preparatory state, which however did not have any consequence for the FP effect, contrary to its other assumptions. On the dual-process account (Vallesi et al., 2007b), low preparation state would bring a low arousal modulation and, consequently, smaller sequential effects.

Moreover, there are some possible reasons for a lack of a load-dependent modulation of the FP effect in that study, which do not necessarily rule out a strategic account for the FP effect. For instance, the cognitive demands of secondary task (1-back) were not continuous, as it would have been necessary to interfere with the enduring monitoring process thought to underlie the FP effect. To perform the task, it was only necessary to update the information in working memory (number of times a digit was subsequently repeated), which was necessary only for subsequently repeated digits, and then maintain this value in working memory for the FP duration. Moreover, the instructions seemed to favor speed in the simple RT task with respect to the working memory one. We speculate that this might have possibly biased participants to optimize response speed in the primary task, thus favoring the strategic production of a FP effect.

Another recent study (Capizzi et al., 2012) combined temporal orienting and foreperiod paradigms with a working memory secondary task. The secondary task consisted in counting and remembering the number of times in which the temporal cue occurred in each of three possible colours (blue, green or red) during a block of trials. This secondary task (which implied updating working memory content at each cue onset) could be carried out quite early and probably not beyond the duration for the short FP. It is not surprising thus that implicit temporal preparation was selectively impaired for the short FP (longer RTs in the dual-task condition than in the single-task one), while responses on the long FP remained relatively unaffected by dual-task manipulations, thus producing an enhanced rather than a decreased FP effect (Capizzi et al., 2012).

Hence, the issue whether the FP effect suffers from dual-task interference, thus favoring a strategic account, is not completely settled. This is the aim of the present study, that adopted a secondary task manipulation which was more suitable to interfere with the tonic and strategic process of monitoring conditional probability of stimulus occurrence during both the short and the long FPs by using a continuous subtraction task.

2. Experiment 1

In this experiment we wanted to test whether it is possible to obtain a reduction in the FP effect as a function of working memory load, if one uses a task with a different structure which requires a continuous working memory update until the target occurrence that does not only tax preparation during the shorter FPs, but also during the longer ones. The secondary task used was a serial subtraction task. In one version of this task, participants had to progressively subtract 1, 2, 3, 4, and 5 from a starting number and then from the subsequent resulting minuends, respectively. For instance, if the starting number was 34, the numbers they had to generate and verbally pronounce would be 33, 31, 28, 24, and 19. This version was initially meant to mostly affect preparation for longer FPs, since the most difficult subtractions are towards the end of the series given the increase in the subtrahend magnitude. A second version consisted of serially subtracting 5, 4, 3, 2, and 1 from a starting number and then from each subsequent minuend, respectively. The latter manipulation was meant to mostly affect preparation for shorter FPs, since the most difficult subtractions should be the first ones. Under the assumption that the FP effect is mainly due to controlled temporal preparation processes, we predicted a decrease of the FP effect especially in the 1-to-5 version of the subtraction task. We also expected no change in the sequential effects, since those are thought to originate from more automatic processes (Capizzi, Correa, &Sanabria, 2013; Los & van den Heuvel, 2001; Vallesi & Shallice, 2007b).

2.1. Material and methods

2.1.1. Participants

Twenty-five healthy volunteers (15 females; mean age: 25 years, range: 19-34; all right-handed) took part in the experiment. All of them reported to have normal or corrected-to-normal vision and no psychological/psychiatric impairment. They were compensated with either money (5 Euros) or university credits.

2.1.2. Apparatus and Materials

Participants viewed the screen at a distance of approximately 60 cm. The FP lengths used were 3 and 5 sec. FPs were long enough to provide participants with enough time to engage in the task before being required to respond, even in the shorter FP. At the beginning of the baseline FP tasks, a ‘XX’ was displayed in the centre of the screen. This double X was substituted by a two-digit number (starting minuend) in the subtraction tasks. Together with this initial cue, an auditory warning stimulus (a 1500 Hz pure tone) was presented for 50 ms through speakers. The target stimulus, which was presented at the end of the FP, was a downward pointing white arrow (with maximum length and width of 2 cm).

2.1.3. Procedure and Task

Two blocks of 30 baseline trials were used to calculate the FP phenomena without dual-task. To control for the effects of learning and fatigue, one baseline block was administered before and the other after the two subtraction tasks. The two subtraction tasks consisted of 64 trials each. Although these blocks might appear short, this was necessary to prevent participants from becoming skilled due to excessive practice on the dual-task (cf. van Lambalgen & Los, 2008). However, the length of the blocks ensured enough data for reliable analyses (i.e., ~16 trials per condition). In the 1-to-5 version of the subtraction task, participants had to vocally subtract progressively 1, 2, 3, 4, and 5 from a starting number and the subsequent differences. A second version – the 5-to-1 subtraction task – consisted of verbally subtracting progressively 5, 4, 3, 2, and 1 from a starting number and the successive differences. During both subtraction tasks, verbal responses were recorded for later analyses. The order of presentation of these tasks was counterbalanced between participants. Two-digit numbers randomly drawn from 20 to 90 were used as the starting minuend. Selection of initial minuends occurred with the constraint that, in the case of 5-to-1 subtraction, numbers ending with 5 or 0 were avoided, since the first subtraction might have been too easy. Another restriction was that two subsequent starting numbers could not have the same last digit (e.g., 91 and 31) to avoid facilitation effects from one trial to another.

Participants were instructed to verbally perform as many subtractions as possible before the target appeared, while their voice was recorded. At the end of the FP, when the target appeared, they had to interrupt their current serial subtraction task at whatever stage it was and press the spacebar of a computer keyboard as quickly as possible. An initial training phase with 4 trials was used before each subtraction block to ensure that participants followed these instructions.

2.1.4. Data Analysis

Trials with RTs outside the 100-1500 ms range and with anticipated responses (i.e., responses before the target) were discarded from further analyses. In addition, the first trial of each block was eliminated because it was not preceded by any previous FP. For both mean RTs and accuracy analyses, a 3x2x2 within-subject ANOVA was used with task (single-task, 1-to-5 subtraction, 5-to-

1 subtraction), FP_n (3 vs. 5 sec) and FP_{n-1} (3 vs. 5 sec) as the independent variables. To find the sources of significant effects involving more than two levels, the Tukey's HSD test was used.

For the secondary subtraction task, accuracy was measured as the percentage of correctly performed subtractions (out of five possible total subtractions), from the onset of the initial number on the screen to the appearance of the target stimulus (arrow). The participants were aware that when a mistake was made in a subtraction, the produced (although wrong) difference had to be used as the next minuend, since the accuracy of the next subtraction would be calculated offline later according to that minuend. Therefore, they were discouraged to make online corrections and go on with whatever difference they had generated (even if wrong). Preliminary piloting suggested that it was extremely rare that a participant could complete all the five possible subtractions during the FP duration, not even when the FP was the longer one. Thus, although it was quite unlikely to reach an accuracy of 100% on the subtraction task, this was not an issue since the main aim of this manipulation was to keep participants' working memory (and cognitive resources) focused on this secondary task until the end of the FP.

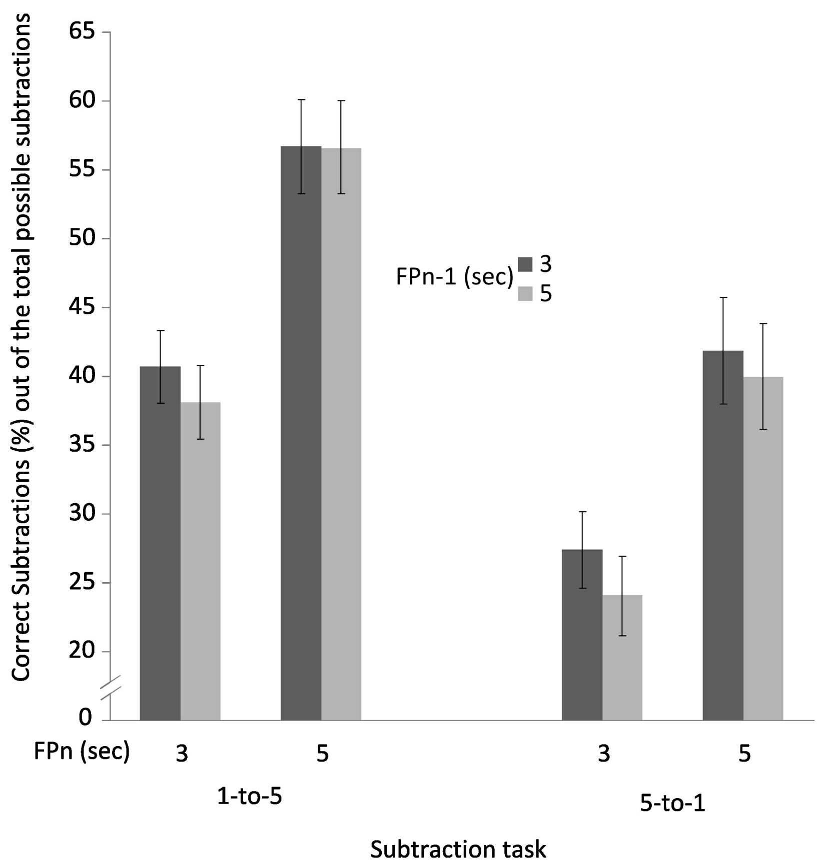
2.2. Results

2.2.1. Accuracy

For the primary simple RT task, anticipated responses (RT<100 ms or responses before the target onset) were 0.8%; delayed (RT>1500 ms) and null responses were 0.4%. Given this low number of errors, these data were discarded from further analyses.

In the ANOVA concerning accuracy in the secondary task (see Figure 1), the following effects were significant. A higher number of correct subtractions was produced in the 1-to-5 version than in the 5-to-1 version of the task [task main effect, $F(1,24)=226.1$, $p<.0001$, partial $\eta^2=.91$]. More correct subtractions were produced during a long FP_n than during a short one [FP_n main effect, $F(1,24)=411.1$, $p<.0001$, partial $\eta^2=.94$], as it could be expected given the greater amount of time available. More correct subtractions were produced after a short FP than after a long one in the previous trial [FP_{n-1} main effect, $F(1,24)=14.3$, $p<.001$, partial $\eta^2=.38$]. The effect of the preceding FP was present for the short FP_n only [FP_n x FP_{n-1} interaction, $F(1,24)=6.8$, $p=.015$, partial $\eta^2=.24$], with accuracy being higher after a short FP_{n-1} than after a long one (Tukey's $p<.001$), whereas accuracy during the long FP_n was not affected by the length of the FP_{n-1} (Tukey's $p=.24$).

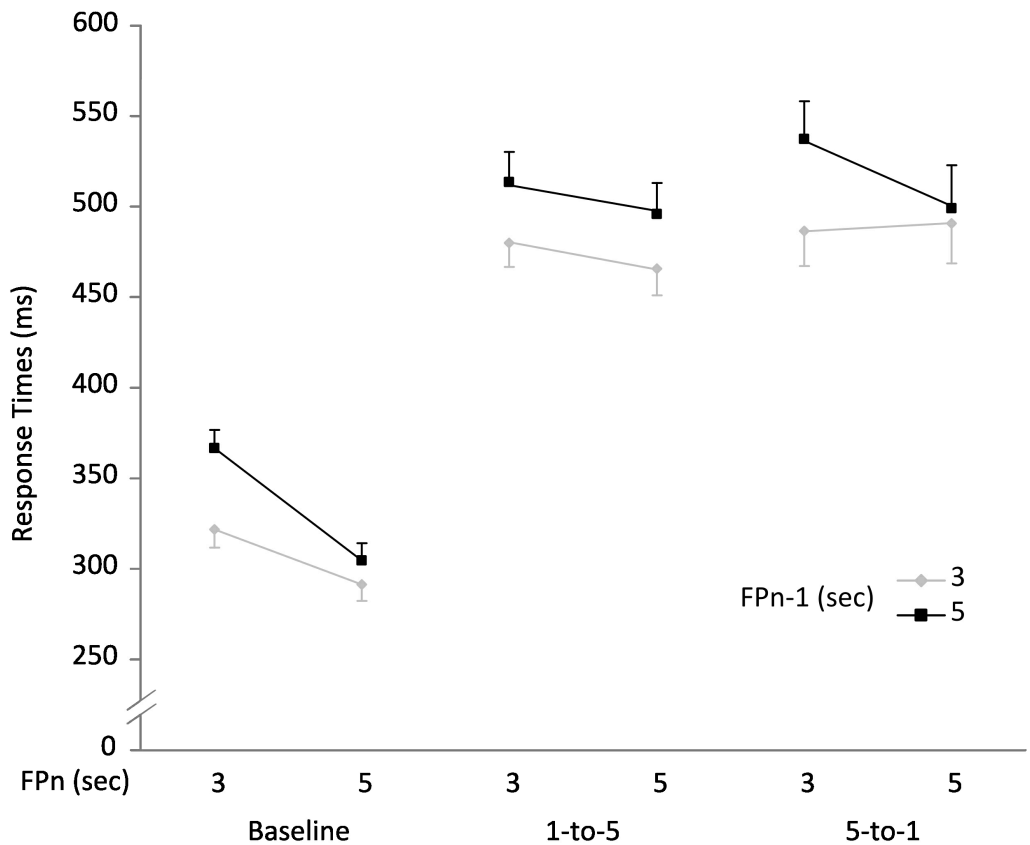
Figure 1



2.2.2. Response Times

Mean RTs are displayed in Figure 2. RTs were shorter for the single-task than for the two dual-tasks [task main effect: $F(1.53,36.87)=67.5$, $p<.0001$, partial $\eta^2=.74$, adjusted for sphericity violation with Greenhouse & Geisser's correction; Tukey's ps $< .001$], but there was no difference between the two dual-tasks (Tukey's $p=.68$). The FP_n effect [$F(1,24)=58.3$, $p<.0001$, partial $\eta^2=.708$] and the FP_{n-1} effect [$F(1,24)=54.8$, $p<.0001$, partial $\eta^2=.693$] were significant. These effects were better qualified by a FP_{n-1} by FP_n 2-way interaction [$F(1,24)=9.8$, $p<.01$, partial $\eta^2=.293$], which replicated the typical asymmetric sequential effects. Although generally asymmetric, sequential effects were present for both the short FP_n (short vs. long FP_{n-1}, Tukey's $p<.001$) and the long FP_n (short vs. long FP_{n-1}, Tukey's $p = .03$). A task by FP_n interaction [$F(2,48)=6$, $p<.005$, partial $\eta^2=.198$] was due to the RT difference between short and long FP_n being significant in the single-task condition (FP effect: 46 ms; Tukey's $p<.001$) but not in the 5-to-1 and 1-to-5 subtraction dual-tasks (FP effect: 16 ms and 17 ms, respectively; Tukey's $p>.21$ and $p>.15$, respectively). The difference between the FP effect in the single-task and in each of the two dual-tasks was significant (for both, $p<.01$), but the FP effect was not significantly different in the two dual-tasks ($p=.92$). Relevant for the present purposes, the task by FP_{n-1} interaction was not significant ($p=.93$), indicating that the sequential effects were not modulated by the three different tasks. Conversely, the task by FP_n by FP_{n-1} interaction was significant [$F(2,48)=3.2$, $p<.05$, partial $\eta^2=.118$]. This interaction showed that the asymmetry of the sequential effects was not constant across the three tasks. In particular, separate ANOVAs on each of the three tasks revealed that sequential effects were symmetrically present for both short and long FPs_n in the 1-to-5 subtraction task only, as demonstrated by an FP_{n-1} main effect [$F(1,24)=22.2$, $p<.0001$, partial $\eta^2=.48$] accompanied by the absence of a FP_n x FP_{n-1} interaction ($p=.81$). The latter interaction was instead significant in the single-task condition [$F(1,24)=18$, $p=.0002$, partial $\eta^2=.42$] and in the 5-to-1 dual-task condition [$F(1,24)=9.6$, $p<.005$, partial $\eta^2=.29$].

Figure 2



2.3. Discussion

Experiment 1 showed that the FP effect is reduced when the FP is filled with a working memory secondary task that requires resources throughout the whole FP duration. This effect demonstrates that our dual-task manipulation was successful because it was able to disrupt the resource-demanding monitoring process thought to underlie the variable FP effect (Vallesi & Shallice, 2007b). The two versions of the subtraction task used were meant to disrupt strategic preparation relatively more towards the long FP (1-to-5) or the short one (5-to-1). The FP effect was absent in both versions, suggesting that the monitoring process supposed to underlie strategic preparation and the FP effect was disrupted to the same extent (see Steinborn & Langner, 2011, for somewhat related results obtained with a distraction manipulation).

However, one aspect of the data is compatible with a selectively greater disruption of strategic preparation for long FPs in the 1-to-5 subtraction task. Sequential effects were symmetric in this task since they did not differ between the short and long FPs (no significant FP_n x FP_{n-1}

interaction), demonstrating that the compensatory role of strategic processes against sequential effects during long FPs could not fully work in this condition (see Vallesi et al., 2007b), for developmental data supporting this account). However, given that this is the first time that symmetric sequential effects are demonstrated in healthy adults, a replication, possibly with a bigger sample size, is desirable before further speculating on these results (see Experiment 2).

On the other hand, sequential effects were never reduced by the dual-task manipulation. The fact that the sequential effects do not suffer from dual-task interference suggests that they do not require as many attentional resources as the FP effect, further demonstrating their obligatory automatic nature (Capizzi, Correa, & Sanabria, 2013; Los & van den Heuvel, 2001; Vallesi & Shallice, 2007b). A potentially interesting novel finding of this study is that the sequential effects also have an influence on specific aspects of task preparation. More correct subtractions were produced during short current FPs preceded by a short FP than by a long one in the previous trial. This finding, which was not expected, suggests that the preparation during previous FPs not only has refractory or facilitatory effects on unspecific motor preparation in the current trial, but also on the performance of other ongoing cognitive tasks. An alternative or complementary explanation is that performing the secondary task for a long vs. short FP, rather than just preparing a motor response (primary task) during a long vs. short FP, is exhaustive and requires time to recover. Since this was not a central point of this experiment, Experiment 2 investigates this aspect further.

2.4. Control Experiment 1b

In both dual-task conditions of Experiment 1 the participants were instructed to engage in the subtraction task during the whole FP length to avoid monitoring of elapsing time. In order to control that in these conditions full priority was given to the subtraction task and no switching of attentional resources occurred between the primary and secondary tasks, an additional control experiment was carried out. In this experiment, a completely different sample of 12 healthy volunteers (7 females; mean age: 21 years, range: 19-26; all right-handed) was required to perform the subtraction task only. In other words, the task remained the same as in Experiment 1 with the exception that, when the target appeared at the end of the FP, the participants did not have to press the spacebar of a keyboard. The apparatus and materials were exactly the same. The procedure of the Experiment 1b was slightly changed since we did not administer the baseline blocks before and after the subtraction task.

Two separate ANOVAs were conducted to compare performance on the subtraction task during each of the two dual-task conditions of Experiment 1 and the control Experiment 1b. Each ANOVA included the current FP as the within-subject factor, experiment (1 vs. 1b) as the between subjects factor, and percentage of accurate subtractions on each FP as the dependent variable. Apart from a FP main effect, which confirmed previous results of Experiment 1 [for both, $p<.001$], there was no significant difference in the 1-to-5 subtraction task [experiment main effect, $p=.28$] and a significant difference in the 5-to-1 subtraction task [experiment main effect, $F(1,35)= 6.8$, $p=.013$, partial $\eta^2=.16$]. Moreover, for both ANOVAs, there was a FP by experiment interaction [for both, $F(1,35)>8.6$, $p<.01$, partial $\eta^2>.19$], which indicated that the participants of Experiment 1 produced more accurate subtractions than those in Experiment 1b especially during a long FP. Overall, these results demonstrate that the number of correct subtractions was higher in Experiment 1, indicating that in the dual-task condition the participants were even more engaged in the subtraction task than in the single-task condition. Since the accuracy in the single-task control experiment matched or was even lower than in the dual-task condition we can assume that participants in Experiment 1 gave full priority to the subtraction task that thereby interfered with the monitoring process thought to underlie the FP effect.

3. Experiment 2

The aim of Experiment 2 was threefold. First, we wanted to replicate the pattern of symmetric sequential effects with the 1-to-5 subtraction task used as a secondary task. The second aim was to disambiguate whether more efficient subtractions are due to preceding short (vs. long) unspecific preparation or to preceding short (vs. long) specific subtraction. To this purpose, Experiment 2 adopted a 2x2x2 design, which randomly combined the subtraction task (present vs. absent), the FP (short vs. long) and the previous FP (short vs. long). In this way, the efficiency of subtractions in $trial_n$ could be analyzed according to whether it was preceded by a short vs. long FP_{n-1} and/or by a subtraction vs. baseline task. Finally, by embedding the single task condition together with the dual-task one, the general task set and context would be matched, although the specific task demands would change phasically on a trial by trial basis. Thus, replicating the results of the previous experiment with this new design, in particular the reduction of the FP effect under dual-task conditions but not under single-task ones, would increase our confidence about their controlled nature.

3.1. Method

3.1.1. Participants

Thirty-three healthy volunteers (21 females; mean age: 26 years, range: 19-48; all right-handed) took part in the experiment. All of them reported to have normal or corrected-to-normal vision and no psychological/psychiatric impairment. They received either money (5 Euros) or university credits in compensation for their time. One extra male participant had to be discarded because he did not comply with the instructions of the secondary task.

3.1.2. Apparatus and Materials

The apparatus and materials were similar to those of the Experiment 1.

3.1.3. Procedure and Task

Similarly to Experiment 1, two baseline blocks with 32 trials each were used to calculate the FP phenomena without dual-task; one was administered before and the other one after the experimental session, to control for practice and fatigue effects. Unlike in Experiment 1, four blocks of 64 trials were presented in Experiment 2 during the dual-task session to increase power while still trying to prevent over-learning (~32 trials per condition). In every dual-task block, half of the trials belonged to the single-task condition, and the other half to the dual-task one. Trials using the different tasks and FPs were administered pseudo-randomly but equiprobably, in order to obtain approximately the same number of trials per condition. In this experiment, only the 1-to-5 version of the subtraction task was used. In this version, participants had to progressively subtract the numbers 1, 2, 3, 4 and 5 from a starting number and the subsequent results. The 5-to-1 subtraction task was not used, because it was not relevant for the hypotheses to be tested, and because more correct subtractions were produced in the 1-to-5 version than in the 5-to-1 version of the task. As for Experiment 1, verbal responses were recorded during the subtractions to allow offline analysis of the accuracy of this secondary task. Two-digit numbers randomly drawn from 27 to 90 were used as the starting minuend. As for Experiment 1, participants were instructed to verbally subtract as many numbers as possible before the target appeared. When the target was presented at the end of the FP, they had to interrupt the subtraction task at whatever stage it was and press the spacebar of a computer keyboard as quickly as possible. To ensure that they understood the instructions and familiarize with the tasks, 4 trials preceded the single-task and the dual-task sessions.

3.1.4. Data Analysis

Trials with RTs outside the 100-1500 ms range, with responses occurring before the target onset and null responses were discarded from further analyses. The first trial of each block was eliminated because it was not preceded by any previous FP. For the secondary subtraction task, accuracy was measured in the same way as in Experiment 1. Subtraction accuracy data were analysed with a 2x2x2 within-subject ANOVA, with $Task_{n-1}$ (single-task, dual-task), FP_n (3 vs. 5 sec) and FP_{n-1} (3 vs. 5 sec) as the independent variables. The preceding task factor ($Task_{n-1}$) was introduced here to help interpreting the accuracy results of Experiment 1 as described above. For the mean RT analysis, a 3x2x2 within-subject ANOVA was employed with task (baseline single-task, embedded single-task, dual-task), FP_n (3 vs. 5 sec) and FP_{n-1} (3 vs. 5 sec) as the independent variables. To find the sources of significant effects involving more than two levels, the Tukey HSD test was used.

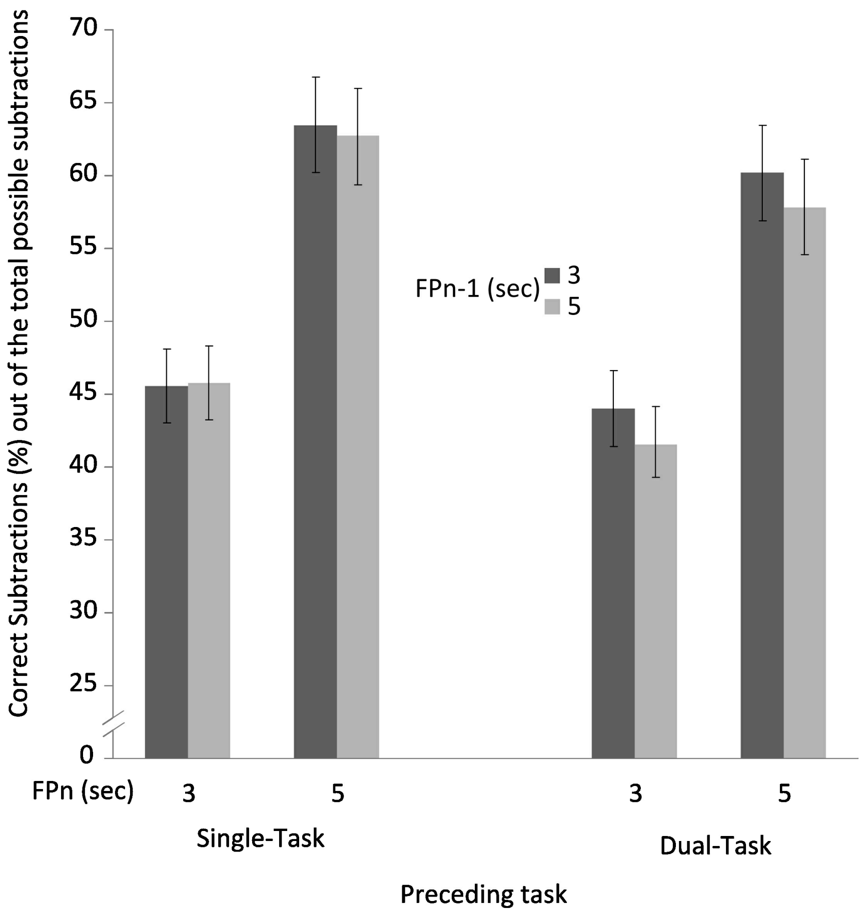
3.2. Results

3.2.1. Accuracy

For the primary simple-RT task, anticipated responses (RT<100 ms or responses before the target onset) were 0.58%; delayed (RT>1500 ms) and null responses were 0.33%. Given this low number of errors, these data were discarded from further analyses.

In the ANOVA concerning accuracy in the secondary subtraction task, the following effects were significant (see Figure 3). More correct subtractions were produced during a long FP_n than during a short one [FP_n main effect, $F(1,32)=304.1$, $p<.0001$, partial $\eta^2=.9$], as it could be expected. More correct subtractions were produced after a short FP than after a long one in the previous trial [FP_{n-1} main effect, $F(1,32)=6.8$, $p=.014$, partial $\eta^2=.17$] and after a single-task than after a dual-task in the previous trial [$Task_{n-1}$ main effect, $F(1,32)=29.2$, $p<.0001$, partial $\eta^2=.48$]. However, the $Task_{n-1}$ x FP_{n-1} interaction [$F(1,32)=7.4$, $p=.01$, partial $\eta^2=.19$], indicates that the efficiency of the subtraction task was modulated by the length of FP_{n-1} only when participants had to perform the subtraction task in the preceding trial (Tukey's $p<.001$), whereas no effect of FP_{n-1} on the accuracy of the subtraction task was observed if the preceding trial required a single-task (Tukey's $p=.991$).

Figure 3



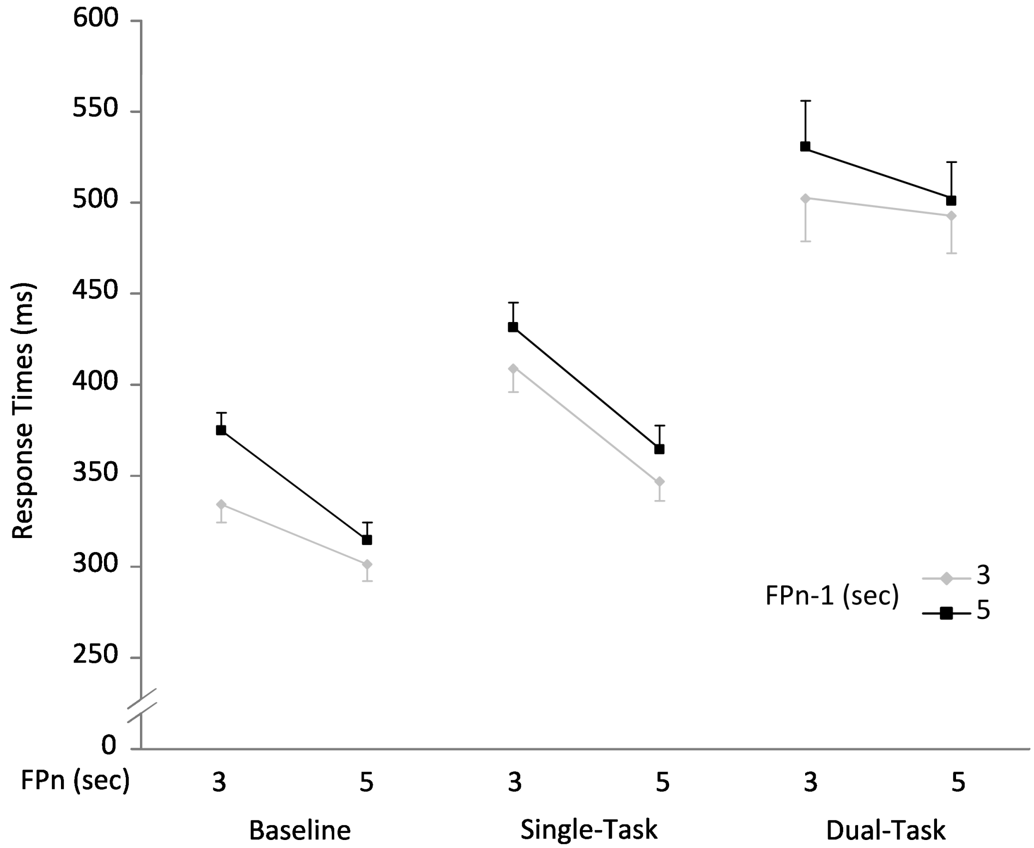
3.2.2. Response Times

Mean RTs are displayed in Figure 4. The task main effect [F(2,64)=78.4, p<.0001, partial η^2=.71] indicates that the RTs were different across the three task conditions. In particular, RTs were significantly shorter in the baseline single-task than in the embedded single-task (Tukey's p=.0007) and in the embedded single-task than in the dual-task (Tukey's p=.0001). Participants were generally faster with long current FPs than with short ones [FP_n main effect, F(1,32)=134.3, p<.0001, partial η^2=.81] and when the preceding FP was short rather than long [FP_{n-1} main effect, F(1,32)=72.02, p<.0001, partial η^2=.69]. The typical asymmetric sequential effects were replicated [FP_{n-1} by FP_n interaction, F(1,32)=15.02, p<.0005, partial η^2=.32], although sequential effects were present for both short FP_n (short vs. long FP_{n-1}, Tukey's p=.00016) and long FP_n (short vs. long FP_{n-1}, Tukey's p=.0016).

The FP effect was different across the three task conditions [task by FP_n interaction, $F(2,64)=17.44$, $p<.0001$, partial $\eta^2=.35$]. Although this effect was present in all three conditions (baseline single-task: 47 ms; Tukey's p=.0001; embedded single-task: 65 ms; Tukey's p=.0001; dual-task: 18 ms; Tukey's p=.007), it was significantly smaller in the dual-task condition than in each of the two single-task conditions (planned comparison: with baseline task, p=.0029; with embedded single-task, p<.00003) and it was also smaller in the baseline than in the embedded single-task (planned comparison p=.00037). Relevant for the present purposes, neither the task by FP_{n-1} interaction nor the task by FP_n by FP_{n-1} interaction were significant (p>.38 and p>.2, respectively).

Since in Experiment 1 the analyses revealed that sequential effects were symmetrically present for both short and long FPs_n in the 1-to-5 subtraction task, separate ANOVAs were performed on each of the 3 tasks to check if this effect could be replicated. These analyses revealed that in the dual-task condition sequential effects were asymmetrically present as the FP_{n-1} main effect [$F(1,32)=11.1$, $p=.002$, partial $\eta^2=.25$] was accompanied by a FP_n x FP_{n-1} interaction [$F(1,32)=4.3$, $p<.046$, partial $\eta^2=.12$]. The same FP_n x FP_{n-1} interaction also occurred for the baseline single task [$F(1,32)=12.9$, $p=.001$, partial $\eta^2=.29$]. An unexpected finding was the absence of a FP_n x FP_{n-1} interaction (p=.54) for the embedded single-task, that indicates symmetric sequential effects [FP_{n-1} main effect, $F(1,32)=30.48$, $p<.0001$, partial $\eta^2=.49$].

Figure 4



3.3. Discussion

The results of the second experiment replicated the main findings of Experiment 1, in that they showed that the FP effect is reduced under a dual-task condition with respect to a single-task condition, both when the latter is embedded together with the dual-task and when it is executed in isolation. Embedding dual- and single-task conditions in the same experimental blocks also resulted in a larger FP effect under the embedded single-task condition. A possible reason for this is that having performed a dual task before causes a deployment of cognitive resources, which may have increased RTs especially for the short FPs, and when switching from a difficult (i.e., dual-task) to an easy (i.e., single-task) trial (e.g., Langner, Eickhoff, & Steinborn, 2011). In order to corroborate these points, we run a new ANOVA with the preceding task (single vs. dual), current task (single vs. dual), FP_{n-1} and FP_n. We only report here the effects of interest. This analysis yielded an interaction between the preceding task and FP_n [$F(1, 32)=15.71$, $p=.00039$]. This was due to the fact that having performed a dual-task in the preceding trial increased the FP effect in the current one, mainly by increasing RTs for short FPs. As planned comparisons demonstrated, indeed, the RT increase for short FPs was larger than that for long ones ($p<.001$).

We did not replicate the finding of symmetric sequential effects under dual-task conditions. This pattern is apparently conflicting not only with what would be predicted from the findings of Experiment 1, but also from the dual-process view (Vallesi & Shallice, 2007b): sequential effects should be symmetric when there is no compensation by the mechanism underlying the FP effect. However, contrary to what happened in the previous experiment, the FP effect in experiment 2 was not fully eliminated but only reduced during dual-task (vs. single-task) conditions. This residual FP effect, and especially the mechanism underlying it, may explain residual strategic compensation of sequential effects in long-long FP sequences.

Another unexpected observation concerned the pattern of symmetric sequential effects under the embedded single-task. No interaction between FP_{n-1}, FP_n and preceding task was observed in the exploratory ANOVA which included the preceding task factor. Therefore, this pattern cannot be fully explained by taking into account specific task sequences (cf. Steinborn et al., 2009), and is probably more generally due to the mixture of dual-task trials and single-task ones within the same block. As shown in Figure 4, this task context quantitatively (although not statistically) reduced sequential effects for the short FPn (23 ms) with respect to pure variable FP baseline blocks (41 ms). However, this occasional symmetrization/reduction of sequential effects under certain experimental conditions (also see Steinborn et al., 2009), especially when not accompanied by a simultaneous absence of the variable FP effect (cf. Vallesi & Shallice, 2007b; Steinborn & Langner, 2011), still awaits further experimental investigation and a fully satisfactory explanation.

Finally, the interaction between the sequential effects and the secondary subtraction task was only present when the latter had also been performed in the previous trial, suggesting a task-specific carryover effect and no interference effects on the secondary task due to the preceding FP length per se. The current findings thus demonstrate that the preceding FP plays a specific role in modulating temporal preparation and not other ongoing high-level processes, such as working memory operations.

3.4. Control Experiment 2b

As for Experiment 1, to control if the subtraction task was fully prioritized also in Experiment 2, we conducted another control experiment with a different sample of 12 healthy volunteers (11 females; mean age: 19 years, range: 18-22; all right-handed). The participants of experiment 2b were instructed to carry out the subtraction task only with no FP task. As in Experiment 2, half of the trials belonged to the simple RT task condition and the other half to the subtraction task condition. However, in the subtraction task of experiment 2b, when the target appeared at the end of the FP, the participants were instructed not to press the spacebar of a keyboard. Both apparatus and materials remained the same as in Experiment 2, while the baseline blocks before and after the subtraction task were not administered.

An ANOVA was run to compare efficiency on the subtraction task during the dual-task condition of Experiment 2 and the control Experiment 2b. This analysis included the current FP as the within-subject factor, experiment (2 vs. 2b) as the between subjects factor, and percentage of accurate subtractions on each FP as the dependent variable. Apart from a FP main effect [$p<.001$], which confirmed previous results of Experiment 2, there was no significant effect involving the between-subjects factor experiment [for all, $p>.25$]. This result confirmed that in the dual-task condition of Experiment 2, the subtraction task was given full priority.

4. Conclusions

The present study was designed to test whether the FP and the sequential effects derive from common mechanisms (Los and van den Heuvel, 2001) or from different ones (e.g., Vallesi and Shallice, 2007b). If the latter is the case, it should be possible to dissociate the two effects not only anatomically and ontogenetically, as already shown in previous studies (see Vallesi, 2010, for a review), but also functionally in healthy young adults.

Experiment 1 was conceived to obtain an under-additive interaction between the FP effect and task-load by maintaining a constant task-load throughout the short and long FPs. The subtraction tasks successfully absorbed processing resources thought to be necessary for the controlled monitoring process underlying the FP effect (Näätänen, 1970; Vallesi and Shallice, 2007b). The FP effect indeed was significantly reduced under the dual-task condition as compared to the single-task one. This finding is compatible with the view that the FP effect is due to a prefrontally-based strategic process, which probably optimizes behavior by monitoring the increasing conditional probability of target presentation along the FP, a mechanism which was less efficient when a demanding subtraction task had to be performed in parallel. It should be noted that it remains unclear which specific strategic sub-process is actually being modulated by the dual-task manipulation (e.g., conditional probability monitoring, optimization of the preparatory state as a function of this monitoring, or both), and further investigation should address this issue.

Another possible explanation of the under-additive interaction between FP effect and task-load could be the presence of a bottleneck kind of phenomenon (see Pashler, 1994). We chose to use completely different response modalities for the two tasks (finger press and voice) to exclude at least specific effector-dependent bottleneck effects. However, one might suppose that selecting a response in the subtraction task constitutes a bottleneck at a non-motor stage and that temporal preparation influences the FP task at a stage which is also before the bottleneck, that is at a visuo-perceptual stage (e.g., Hackley et al., 2007). Although we cannot fully rule out this alternative account with the current study, even if a bottleneck for perceptual processes might have been at work here, it is unclear why it would affect the foreperiod effect and not the sequential effects, which have been shown to have a functional locus in perceptual processes as well (e.g., Yashar & Lamy, 2013).

Sequential effects were not significantly reduced by the dual-task manipulation and this pattern further demonstrates the unintentional nature of the processes underlying them. Previous studies have already demonstrated the automatic nature of these effects (e.g., Los and van den Heuvel, 2001). The resistance of sequential effects to changes due to cognitive task-load manipulation does not imply that it is not possible to obtain the opposite dissociation, that is reduced sequential effects with a constant FP effect, under different task manipulations. For instance, switching from an auditory warning stimulus to a visual one or shifting between its qualitatively different tone characteristics, attenuates the sequential effects but does not affect the FP effect (Steinborn et al., 2009; Steinborn et al., 2010). A possible source of the sequential effects is motor facilitation/refractoriness as a function of preparation time during the previous trials. Compatible with a motor locus of the sequential FP effects, surgical lesions to left pre-motor regions nullifies the RT facilitation of short-short FP sequences (Vallesi et al., 2007a). Interestingly, this category of patients showed no sequential effects with a normal-sized FP effect – a dissociation that is opposite to the one obtained in the present study. These double dissociations demonstrate that the two effects are independent, although they might interact under normal circumstances (cf. Los and van den Heuvel, 2001).

However, it is also possible that, in Experiment 1, the duration of preceding FPs influenced not only subsequent unspecific preparation, but also specific preparation, since performance on the subtraction task was also worse after a long preceding FP as compared to a short one. Experiment 2 tested the contribution of either unspecifically preparing for a simple RT task or engaging in a challenging secondary task for a long FP in the previous trial on the efficiency of the secondary task in the current one, by using a mixture of single- and dual-task manipulations within the same experimental block (as opposed to different blocks). The results of experiment 2 demonstrated that the duration of the previous FP did not modulate the efficiency of the secondary subtraction task, unless a subtraction task was being performed during that preceding FP. However, no modulation of the secondary task performance by the previous FP was observed when the latter was empty (single-task condition). These findings show that refractory/facilitatory effects of previous FPs do not extend over and above unspecific motor preparation, speaking in favor of a possible functional modularity (in the sense of a domain-specificity) of sequential foreperiod effects.

In conclusion, the current findings represent a functional dissociation between the FP and the sequential effects. The variable FP effect is due to processes that suffer from dual-task interference. The present behavioral study strongly corroborates previous neuropsychological and neuroimaging evidence suggesting a prefrontally-based monitoring process as the neural underpinning of the FP effect (e.g., Vallesi et al., 2009a; Triviño et al., 2010). On the other hand, the sequential effects are more robust to dual-task interference, confirming their more automatic nature. Thus, the present study demonstrates that different processes along the automatic-controlled continuum underlie implicit preparation over time.

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Figure Captions

Figure 1. Percentage of correct subtractions (and standard errors of the mean) produced according to the current FP_n (x-axis), the preceding FP_{n-1} (lines), and the subtraction task (panels) in Experiment 1.

Figure 2. Mean response times as a function of the current FP_n (x-axis), the preceding FP_{n-1} (lines), and subtraction task (panels) in Experiment 1. Vertical lines indicate standard errors of the mean.

Figure 3. Percentage of correct subtractions (and standard errors of the mean) produced according to the current FP_n (x-axis), the preceding FP_{n-1} (lines), and the subtraction task (panels) in Experiment 2.

Figure 4. Mean response times as a function of the current FP_n (x-axis), the preceding FP_{n-1} (lines), and subtraction task (panels) in Experiment 2. Vertical lines indicate standard errors of the mean.