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Dissociating temporal preparation processes as a function of the inter-trial interval duration

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Abstract

Preparation over time is a ubiquitous capacity which implies decreasing uncertainty about when critical events will occur. This capacity is usually studied with the variable foreperiod paradigm, which consists in the random variation of the time interval (foreperiod) between a warning stimulus and a target. With this paradigm, response time (RT) effects of the current and preceding foreperiods are usually observed (respectively called “foreperiod effect” and “sequential effects”). Both single-process trace conditioning mechanisms and dual-process accounts have been proposed to explain these behavioral effects. This study aimed at understanding how manipulations of the the inter-trial interval (ITI: 1 s vs. 20 s) and the task context (simple vs. choice RT task) affects the two behavioral effects. Results show that, regardless of the type of RT task, attenuated sequential effects were observed with the longer ITI, contrary to predictions derived from the trace conditioning literature. However, the influence that the ITI duration exerted on the FP effect critically depended on the task context, since the FP effect increased as a function of ITI with a choice RT task but decreased with a simple RT task. These findings support a dissociation between foreperiod and sequential effects, consistent with a dual-process account.

Keywords: variable foreperiod effect, sequential effects, preparatory interval, inter-trial interval, time processing.

Temporal preparation is the ability to pre-activate the perceptual and motor systems to an event by predicting its future occurrence (e.g., Bausenhart, Rolke, Hackley, & Ulrich, 2006; Hackley, Schankin, Wohlschlaeger, & Wascher, 2007). Temporal preparation can be initiated by following an explicit temporal cue or, more implicitly, by monitoring elapsing time. The latter is an important capacity in everyday life, whether it concerns a hunter trying to trap its quarry, a sprinter trying to predict the sound of a starting pistol, or a driver waiting for the green traffic light.

In experimental psychology, implicit temporal preparation has been extensively studied by means of the foreperiod (FP) paradigm (Bertelson & Boons, 1960; Los & van den Heuvel, 2001; Niemi & Näätänen, 1981; Steinborn & Langner, 2011; Vallesi & Shallice, 2007b; Woodrow, 1914). In this paradigm, a warning stimulus of any modality is followed by a target stimulus after a preparatory interval, called FP. When the FP varies randomly and equiprobably across trials, two behavioral effects usually emerge. Responses are faster for current longer FPs (variable FP effect), and they are slower for longer preceding FPs, especially for current short FPs (asymmetric sequential effects). These effects have been observed for different FP averages and ranges (Niemi & Näätänen, 1981), and for both simple and choice response time (RT) tasks (Correa, Lupiáñez, Milliken, & Tudela, 2004; Karlin, 1959; Simon & Slaviero, 1975; Steinborn, Rolke, Bratzke, & Ulrich, 2009; Vallesi, Shallice, & Walsh, 2007c).

Despite the robustness of these empirical findings, the exact underlying cognitive processes are still a matter of debate. According to many authors, the variable FP effect originates from a monitoring process, which continuously checks the increasing conditional probability of stimulus occurrence during the FP to optimize behavior (Cui, Stetson, Montague, & Eagleman, 2009; Elithorn & Lawrence, 1955; Gottsdanker, 1984; Näätänen & Merisalo, 1977; Stuss et al., 2005; Vallesi, 2010; Vallesi et al., 2007b). This probability is highest for the longest FPs, thus explaining the maximum RT benefit in this condition, provided that there are no catch trials (Correa et al., 2004). The use of catch trials, where no target is presented at all, would indeed decrease the conditional probability of target onset for the longest FPs (which would usually be 100% without catch trials) proportionally to their frequency of occurrence.

Recently, a single-process account has been put forward to explain both the variable FP effect and the sequential effects (Los & van den Heuvel, 2001). On this account, the FP effect is caused by the trace conditioning mechanisms underlying sequential effects. One conditioning mechanism consists of extinction of response preparation associated to short FPs, which takes place when these short FPs are overcome by longer ones during the course of the trial. This is probably due to the demanding and aversive need to keep the motor system in check to avoid anticipatory responses (e.g., Näätänen, 1971), especially in the presence of warning signals (Boulinguez, Ballanger, Granjon, & Benraiss, 2009). Another conditioning mechanism is represented by the reinforcement of response preparation associated to the specific FP which occurs in a given trial. Thus, on this account, sequential effects originate from the interplay between extinction and reinforcement of preparation associated to the different FPs. Since the longest FPs cannot be overcome by even longer ones, the preparation level associated to them is only reinforced (when they occur), thus also explaining the RT advantage for long FPs (i.e., the variable FP effect).

Additional empirical evidence suggests that the FP and the sequential effects are due to at least partially different underlying neural and cognitive mechanisms, as it has been demonstrated by life-span (Vallesi et al., 2007b; Vallesi, McIntosh, & Stuss, 2009), neuroimaging (Vallesi, McIntosh, Shallice, & Stuss, 2009), TMS (Vallesi et al., 2007c) and neuropsychological (Stuss et al., 2005; Triviño, Correa, Arnedo, & Lupiáñez, 2010; Vallesi et al., 2007a) dissociations. This multimodal evidence shows that the monitoring process, which is traditionally thought as responsible for the variable FP effect (cf., Los & van den Heuvel, 2001), usually recruits the right dorsolateral prefrontal cortex (Stuss et al., 2005; Triviño et al., 2010; Vallesi et al., 2007a).

On the other hand, traditional strategic explanations of the sequential effects (e.g., Alegria, 1975; Granjon & Reynard, 1977) seem to be inappropriate because, although sequential effects vanish with valid temporal cues, they strongly re-emerge with invalid ones, when strategic processes are unlikely to occur (Los & van den Heuvel, 2001). The foreperiod and sequential effects are also dissociable in terms of their anatomical locus. Indeed, while lesions to right frontal regions cuase a reduction of the FP effect (Stuss et al., 2005; Vallesi et al., 2007a), lesions to left premotor regions are accompanied by a disappearance of the sequential effects (Vallesi et al., 2007a). In particular, left premotor patients do not show the RT advantage for short-short FP sequences, despite a normal FP effect.

Based on these findings, a dual-process account was put forward (Vallesi, 2010; Vallesi et al., 2007b,c). This account states that sequential effects are due to tonic arousal modulations deriving from the preparation duration on the previous trial. This assumption is motivated by evidence from developmental data. While adults usually do not show errors in this simple behavioral paradigm, 4 and 5 year old children show both anticipations during the FP and very slow or null responses (Vallesi et al., 2007b). These two types of errors are particularly revealing, since they were not evenly distributed across conditions. On the one hand, anticipations occurred more often after preceding short FPs, suggesting facilitatory mechanisms on motor arousal (also see Vallesi et al., 2007a). On the other hand, delayed and null responses were more frequent after long preceding FPs, compatible with a temporary refractory period at the motor arousal level. This motor refractoriness is supposed to be proportional to the preparation time (FP length) in the previous trial.

Since sequential effects are produced and sustained mainly by non-strategic processes originating from the previous trial (e.g., Los & van den Heuvel, 2001; Vallesi & Shallice, 2007b), it is conceivable that, on the dual-process account (Vallesi & Shallice, 2007a,b), the underlying motor arousal modulation is temporary in nature and decays with more spacing between trials. Thus, increasing the length of the resting time between trials (i.e., inter-trial interval, ITI) is expected to bring arousal levels closer to baseline values. Specifically, if RT facilitation of short-short FP sequences is time-sensitive, this facilitation effect should be reduced with long vs. short ITIs. Moreover, if refractoriness after a trial with a long FP recovers over time, RTs in long-short FP sequences would be shorter for long vs. short ITIs. In summary, both facilitation and refractory effects should decrease with long ITIs and, consequently, sequential effects should either diminish or disappear.

On the other hand, the dual-process account explains the variable FP effect through a strategic monitoring process which, starting from the onset of the warning stimulus, continuously checks the increasing conditional probability of target occurrence over time to optimize behavior (Vallesi et al., 2007b; Vallesi et al., 2009; also see Elithorn et al., 1955; Näätänen, 1970). Considering monitoring as an effortful, resource consuming process, a long resting period (ITI) between trials should allow participants to be more prepared to respond to a target. Consequently, a greater FP effect (shorter RTs for longer FPs than for shorter ones) should emerge with a long ITI than with a short one. Critically, if the FP effect originates from a monitoring mechanism different from the mechanism underlying sequential effects (cf., Los & van den Heuvel, 2001), its modulation by ITI duration should be independent of the ITI influence on the sequential effects.

We now turn to the possible predictions that could be derived from the point of view of a single-process conditioning account (Los & van den Heuvel, 2001), as far as the introduction of ITIs of different durations is concerned. The relationship between ITI manipulation and conditioning mechanisms, also called the trial-spacing effect, has been studied in many fields. For example, in appetitive conditioning, increasing the ITI may strengthen conditioning, possibly by means of a finer estimation of the reinforcement rate when the ITI is larger than the trial duration (e.g., Gallistel & Gibbon, 2000), or by extinguishing associations between conditioned stimuli and irrelevant contextual cues (e.g., Sunsay & Bouton, 2008). Similar results have been reported in eyelid conditioning (Prokasy, Grant, & Myers, 1958; Spence & Norris, 1950), in trace fear conditioning (e.g., Barela, 1999; Detert, Kampa, & Moyer, 2008), in taste aversion learning (Domjan, 1980) and in autoshaping (e.g., Papini & Brewer, 1994; Terrace, Gibbon, Farrell, & Baldock, 1975). However, some studies show no effect of ITI on conditioning (Carrillo, Thompson, Gabrieli, & Disterhoft, 1997; also see Prokasy, 1965).

Thus, if the two FP phenomena are governed by trace conditioning rules (Los & van den Heuvel, 2001), the ITI should either strengthen the conditioned responses associated with those phenomena or leave those effects unaffected, as these two patterns have been observed in the other types of conditioning paradigms reviewed above. Importantly, according to the single-process model (Los & van den Heuvel, 2001), the FP and sequential effects should be similarly modulated, whatever the direction of the influence is, since it is assumed that they are due to the same primary conditioning mechanisms.

A few studies in the earlier literature had already started to investigate the effect of ITI on the FP phenomena. Gosling and Jenness (1974) used 6 FPs, ranging from 0.5 to 10.5 s, in a simple RT task with a variable FP paradigm, and two ITIs (5 and 10 s) in different blocks. Two groups of adolescents (with and without intellectual disabilities) were tested. The effect of ITI manipulation was not significant in the control group. In the group with intellectual disabilities, when the longer ITI was used, RTs tended to decrease as the FP increased (i.e., increasing FP effect), and tended to increase as previous FP increased (i.e., increasing sequential effects). Given the null effect of ITI manipulation for the control group, these early results cannot help distinguishing between current theories of FP phenomena.

Granjon and collaborators (Granjon, Possamai, Reynard, & Oberti, 1979) used a simple RT task with a variable FP paradigm (FPs of 1.5 and 3 s) and manipulated the ITI as follows: no ITI or ITI of different length (3, 6, and 9 s) administered block-wise. They found that RTs on the longest FP were significantly shorter with ITIs than without (also see Granjon et al., 1977). This RT advantage was consistent regardless of the duration of the ITI. From the point of view of the dual-process account, these results suggest that the introduction of an ITI provides some resting to the effortful monitoring process, making it more effective by shortening RTs in long FPs. Moreover, RTs in short-short FP sequences were shorter without an ITI than with one, regardless of the ITI duration. Since previous studies found that longer ITIs increase the effects of associative learning, this result would not be consistent with conditioning theories of sequential effects. On the dual-process account, the introduction of an ITI would diminish the non-strategic motor facilitation in short FPs following short FPs. Thus, the results by Granjon and colleagues (1977) seem to support, in part, the dual-process account. However, a reduction in RT for short FPs following long FPs was not found, suggesting that the refractory period, if it exists, is resistant to ITI manipulations.

In order to better clarify the mechanisms specifically underlying sequential and FP effects, we conducted two variable FP experiments, in which we manipulated the ITI duration. The ITI was varied between blocks to avoid confounding influence from possible FP-like effects of variable ITIs (i.e., a general RT reduction after long vs. short ITIs). For the short ITI, we used a duration of 1 s, similar to the range normally used in the FP literature (e.g., Los & van den Heuvel, 2001; Steinborn et al., 2011; Vallesi et al., 2007b). For the long one, we used a duration which was beyond those employed before (i.e., 20 s), in order to increase the sensitivity of the experimental manipulation and to find boundary conditions which were unexplored by previous studies on the effect of ITI on the FP phenomena (Gosling et al., 1974; Granjon et al., 1979; Granjon et al., 1977). In the first experiment, we used a 2-choice RT task. This manipulation was meant to engage participants in the task and prevent anticipatory responses. In the second one, we used a simple RT task, following some classical research on non-specific preparation (e.g., Niemi & Näätänen, 1981). A number of studies reported that the FP phenomena are qualitatively similar across the two types of tasks (e.g., Los & Horoufchin, 2011; Stuss et al., 2005). Nevertheless, we wanted to check whether our main findings would hold across different task contexts. Moreover, if task-dependent dissociations between FP and sequential effects could be observed, this finding would be in favor of a dual-process account.

Experiment 1

In Experiment 1 we used a variable FP paradigm with a choice-RT task, and manipulated the ITI block-wise (1 vs. 20 s). According to the dual-process account (Vallesi & Shallice, 2007b), we expected a reduction of sequential effects and an enhancement of the FP effect in the 20 s ITI blocks with respect to the 1 s ITI blocks. On the other hand, if we extrapolate from the previous literature, the conditioning perspective (Los & van den Heuvel, 2001) would predict either a parallel increase of both effects (Detert, Kampa, & Moyer, 2008; Prokasy, Grant, & Myers, 1958; Sunsay & Bouton, 2008) or no change at all (e.g., Carrillo et al., 1997). In other words, while both the conditioning account and the dual-process model would be consistent with an increase of the FP effect with longer ITIs, although for different reasons, they differ in their predictions concerning the modulation of the sequential effects, which should be enhanced for the former and reduced for the latter as a function of ITI duration.

Method

Participants

Thirty-seven young volunteers (22 females, average age: 25 years, range: 18-35) took part in the experiment. All of them were right-handed with an average score of 82 on the Edinburgh Handedness Inventory (Oldfield, 1971). All reported having normal or corrected-to-normal vision and no auditory or neurological impairment. Participants signed an informed consent form and received 8 Euros for participating. Data from one female participant were excluded from the analysis because her accuracy was more than two standard deviations below the group mean.

Apparatus and Materials

The experiment was conducted using E-prime 2 (Schneider, Eschman, & Zuccolotto, 2002), with responses collected from a standard keyboard. Participants viewed the display at a distance of ~60 cm from the centre of the computer screen, with the index finger of the left and right hands resting on keys Z and M, respectively. Headphones (SONY MDR-CD280) were used to present the auditory warning stimulus at a comfortable level during the whole experiment. All visual stimuli were presented on a black background. The warning signal was a 1500 Hz pure tone presented for 50 ms. A centrally presented cross, consisting of two yellow crossed bars 1.0 x 0.5 cm in size, was used as the fixation stimulus, and marked the whole preparatory period. The target was either a white square or a white equilateral triangle (height: 3 cm) presented for 300 ms. Two FPs of 1 and 3 s were presented randomly on an equal number of trials, drawn from a rectangular a priori probability distribution. The ITI was manipulated block-wise (1 or 20 s).

Procedure and Task

Participants were tested individually in a silent and normally illuminated room. They received written instructions explaining both the course of events and the task. The experiment began only after the participants were confident that they had understood the task. Participants had to discriminate between a square and a triangle, to which they responded with their index fingers by pressing a button of the computer's keyboard (Z or M). The assignment between target shapes and response keys was counterbalanced across participants. Participants were instructed to stress speed and accuracy equally.

A trial started with the ITI, consisting in a black screen lasting 1 or 20 s, which was fixed within the same block of trials. Both the fixation cross and the auditory warning stimulus were presented after the ITI to announce the imminent appearance of the target. The fixation cross remained on the screen until target presentation (1 or 3 s). The target disappeared with the response key-press or after a deadline of 1.5 s, whichever happened first. After this, a new trial began.

The whole task consisted of two blocks of trials which only differed in the ITI duration (1 or 20 s). Each block was formed by 4 practice trials, followed by 80 experimental trials, which were divided in two sets of 40 trials each, with a short pause in between. Feedback on wrong responses was provided for the practice trials only. The order of presentation of the two ITI blocks was counterbalanced between participants.

Data Analysis

RTs were analyzed with repeated-measures 2x2x2 ANOVAs including the following within-subject factors: ITI (1, 20 s), preceding FP (1, 3 s), and current FP (1, 3 s). Since accuracy data were not normally distributed by the Lilliefors test, we used the non-parametric Wilcoxon matched pairs test to separately analyze the effect of ITI, preceding FP and current FP on accuracy. Performance data from practice trials, the first trials of each run, trials with the RT outside the 150-1200 ms range and with false alarms during the FP were discarded from further analyses.

Results

Accuracy. There were more errors for short FPs (2.8%) than for long ones (1.7%) [Z = 2.33, *p* = .019]. There was no effect of ITI (*p*=.2) or preceding FP (*p*=.66). False alarms during the FP (0.13%), anticipatory responses given during the first 150 ms after stimulus onset (0%), delayed responses over 1200 ms (0.07%), and null responses (0.06%) were very infrequent, if any.

Response Times. Mean RTs and their standard error of the mean are reported in Table 1.

Table 1. Mean RT (and standard error of the mean) according to the ITI, preceding foreperiod (FP) and current FP for the two experiments.

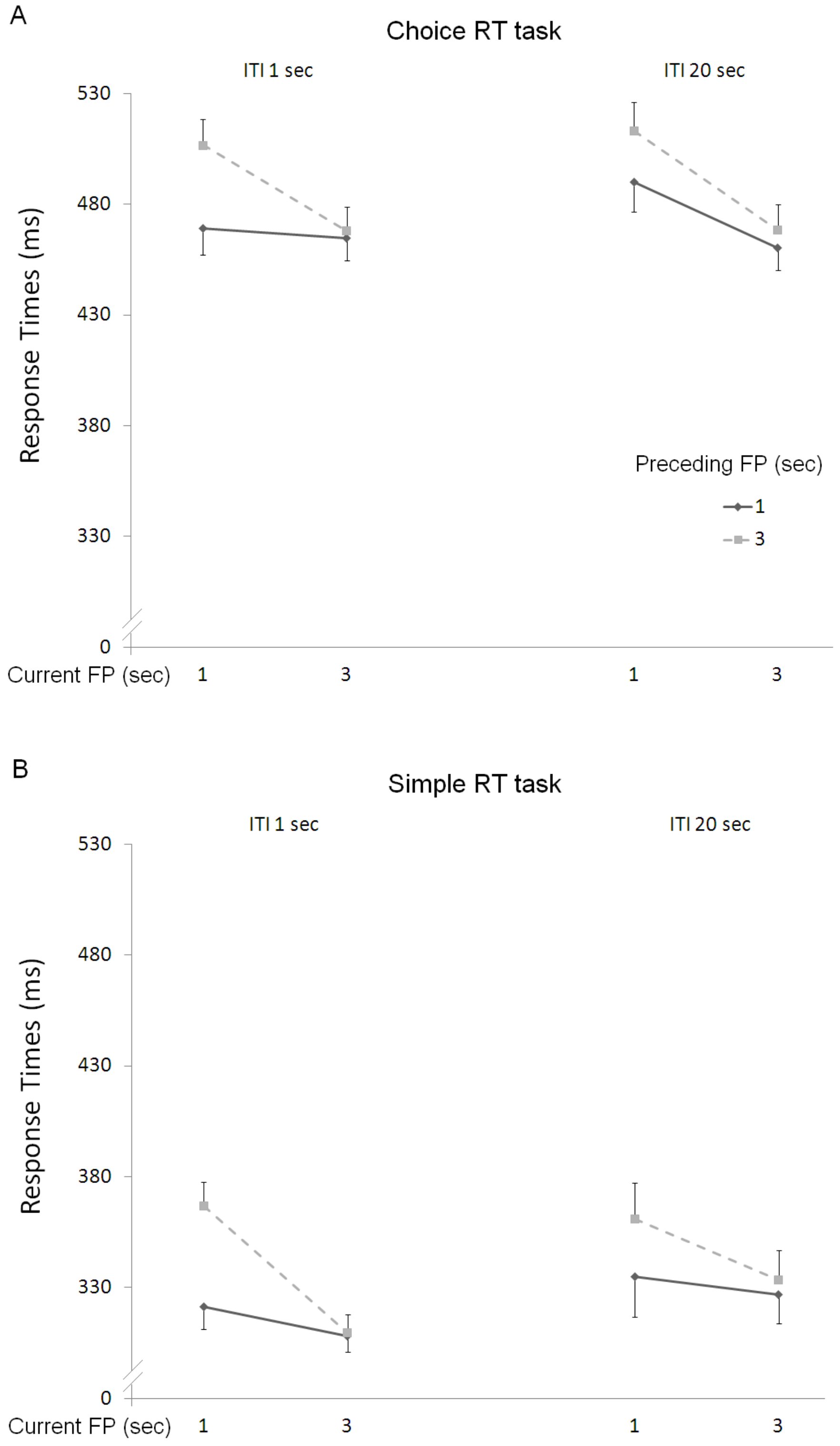
	Preceding FP 1 sec		**Preceding FP 3 sec**	
	Current FP 1 sec	**Current FP 3 sec**	**Current FP 1 sec**	**Current FP 3 sec**
Experiment 1				
ITI 1 sec	469 (12)	465 (10)	507 (12)	468 (11)
ITI 20 sec	490 (14)	460 (10)	513 (13)	468 (12)
Experiment 2				
ITI 1 sec	316 (9)	305 (7)	361 (9)	305 (7)
ITI 20 sec	318 (7)	316 (7)	348 (10)	322 (7)

RTs were shorter for current longer FPs than for shorter ones [current FP main effect: *F*(1, 35)=59.9, *p*<.00001, partial η^2=.63, see Figure 1a]. The FP effect was increased in the 20 s ITI block (38 ms) with respect to the 1 s (22 ms) one [ITI x FP interaction: *F*(1, 35)= 5.9, *p*=.02, partial

η^2=.14] Although the FP effect differed between the two ITIs, it was significant for both the 1 s ITI (*p*<.0001) and the 20 s one (*p*<.00001). However, no significant RT difference was present between the two ITIs either for the short FP (*p*=.12) or for the long one (*p*=.77).

RTs were longer for previous longer FPs than for previous short ones [preceding FP main effect: *F*(1, 35)=37.1, *p*<.00001, partial η^2=.51]. This sequential effect was asymmetrically more pronounced for current short FPs [FP x preceding FP interaction: *F*(1, 35)=17.2, *p*=.0002, partial η^2=.33]. Sequential effects for current short FPs (long FPn-1 vs. short FPn-1) were present for both the 1 s ITI block [*t*(35)=7.2, *p*<.00001] and the 20 s ITI block [*t*(35)=3.6, *p*<.001], but they were not significant for current long FPs (for both, *p*>.19). A three-way interaction [*F*(1, 35)=5.05, *p*=.03, partial η^2=.13; see Figure 1a] showed that sequential effects on current short FPs were smaller in the 20 s ITI block (23 ms) than in the 1 s ITI one (37 ms), as also demonstrated by planned comparisons (*p*=.025). In particular, RTs were longer for short-short sequences in the 20 s ITI than in the 1 s one [*t*(35)=2.25, *p*<.03]. The RT difference between the two ITIs was not significant for long-short sequences (p=.49).

Figure 1. Mean RTs (ms) and standard errors of the mean (error bars) according to current FP, preceding FP and ITI in Experiments 1 (Panel A) and 2 (Panel B).



Discussion

In the first experiment, the ITI manipulation resulted in a reduction of the sequential effects and an increase of the FP effect as a function of ITI duration. As revealed by additional analyses, the former result was mainly due to a reduction in the facilitatory effect for short-short sequences as a function of increasing ITI duration. The dual-process model (Vallesi et al., 2007b) is able to account for these findings by assuming that the automatic facilitation in the arousal level due to sequentially fast preparation processes (as it occurs in short-short FP sequences) decays over time. On this account, the increase of the FP effect can be explained by assuming that the monitoring process, being controlled and resource demanding, benefits from long resting periods, such as in the 20 s ITI blocks. This second finding, however, may depend on the task context and not only on the ITI duration. If the task would be less engaging than in Experiment 1 (e.g., simple vs. choice RT task), the FP effect might show a decrease as a function of ITI due to reduced motivation, and therefore less intensity of effort allocated (Ackerman, 2010). On the other hand, the ITI manipulation should have a similar influence on the sequential effects (i.e., ITI-dependent reduction), under the assumption that they are more automatic and independent of task context. We shall test this hypothesis in the next experiment.

Experiment 2

In Experiment 2, we wanted to test whether the results from Experiment 1 could be generalized to a simple-RT task context. An ITI of 20 s could turn out to be boring when employed for a simple RT task. In order to check this, we decided to measure variations in motivation, attention, boredom, and fatigue in the two ITI conditions. Therefore, in this experiment, we asked participants to self-evaluate their subjective state along these 4 dimensions (Helton & Warm, 2008; Matthews & Davies, 2001; Matthews & Westerman, 1994). If our manipulation would be successful, we expect motivation and attention to decrease in the 20 s ITI blocks compared to the 1 s ITI blocks. Conversely, we expected fatigue and boredom to increase in the 20 s ITI blocks with respect to the 1 s blocks. For the sequential effects, we expected to replicate the main findings of Experiment 1: a clear reduction of sequential effects with the use of a simple RT task as one moves from a 1 s ITI to a 20 s ITI. However, it is not straightforward to predict how the FP effect would be modulated by

ITI. On the one hand, we would expect to replicate the results of Experiment 1, that is, an increase in the FP effect with ITI, possibly due to a benefit of the strategic monitoring process from the extra resting provided by the long ITI. On the other hand, the FP effect could be reduced with ITI length if, in this simple RT task, this manipulation also decreases motivation and attention, which are relevant to gather the resources necessary to sustain the strategic monitoring process supposed to underlie this effect (Stuss et al., 2005; Vallesi et al., 2007b).

For the conditioning view, besides from an expected increase of the sequential effects (and of the FP effect) with ITI, as can be predicted based on the previous literature (e.g., Sunsay & Bouton, 2008; Prokasy et al., 1958), the specific task requirements and motivational factors are not supposed to influence the basic FP phenomena. This is due to the fact that, on this account, both the sequential effect and the epiphenomenal FP effect are due to unintentional processes. Previous evidence has indeed shown that these specific processes remain unchanged even with more direct manipulations of motivation, such as a financial reward based on performance (Los & van den Heuvel, 2001).

Method

Participants.

Twenty-four volunteers [12 females average age: 25 years, range: 20-33] took part in Experiment 2. A male participant was excluded from further analyses since his RTs were more than 4 standard deviations above the group mean. One participant had already participated in the first experiment four months before. All the participants were right-handed with an average score of 79 on the Edinburgh Handedness Inventory (Oldfield, 1971). All had normal or corrected-to-normal vision and no auditory or neurological impairment. Participants signed an informed consent form and received 8 Euros for their participation.

Apparatus and Materials.

The material was the same as in Experiment 1. In addition, information about the subjective state of the participants was also collected through the evaluation of four items. Participants had to subsequently self-evaluate their state of motivation, boredom, fatigue, and attention, on a visual analog scale, as outlined below.

Procedure and Task

While the apparatus and stimuli remained the same, the task changed. It consisted in a simple-RT detection task in which participants had to respond as quickly as they could to the presentation of an image (a square or a triangle) by pressing the space bar with their right index finger.

Moreover, at four evenly spaced moments within each block (i.e., every 20 experimental trials), participants were asked about their subjective state of attention, motivation, boredom and fatigue. The order of these questions was randomized. Participants responded with the mouse, by moving a small bar over a horizontal bar, where the left-most extreme meant low level (“0”) and right-most extreme meant a high level (“100”) of each of the 4 states under investigation. After participants answered the 4 questions, they were asked to resume the simple RT-task by pressing any key.

Data Analysis

RTs were analyzed with a repeated-measures 2x2x2 ANOVA including the following within-subject factors: ITI (1, 20 s), preceding FP (1, 3 s), and current FP (1, 3 s). Performance data from practice trials, the first trials of each run, trials with the RT outside the 150-1200 ms range and with false alarms during the FP, were discarded from further analyses.

Results

Accuracy. False alarms during the FP (1.36%), anticipatory responses given during the first 150 ms after stimulus onset (0.03%), delayed responses over 1200 ms (0.03%), and null responses (0.1%) were very infrequent.

Response Times. Mean RTs and their standard error of the mean are reported in Table 1. RTs were shorter for current longer FPs than for shorter ones [current FP main effect: $F(1, 22)=23.9$, $p<.0001$, partial $\eta^2=.52$]. The FP effect was reduced in the 20 s ITI block (14 ms) with respect to the 1 s (34 ms) condition [ITI x FP interaction: $F(1, 22)= 10.6$, $p=.004$, partial $\eta^2=.32$], a modulation that was opposite to what found in the previous experiment. In particular, responses for the long FP condition became slower from the 1 s ITI to the 20 s one ($p=.027$), while there was no difference in RTs for the short FP ($p=.7$). Moreover, the FP effect, although reduced in the 20 s ITI, remained significant ($p=.022$).

RTs were also longer for previous longer FPs than for previous short ones [preceding FP main effect: $F(1, 22)=71.7$, $p<.00001$, partial $\eta^2=.76$]. Sequential effects were asymmetrically more pronounced for current short FPs [FP x preceding FP interaction: $F(1, 22)=57.5$, $p<.00001$, partial $\eta^2=.62$]. The sequential effects were significant on the current short FP both in the 1 s ITI block [$t(22)=11$, $p<.00001$] and in the 20 s ITI block [$t(22)=5$, $p<.0001$], but not for current long FPs (1 s ITI: $p>.91$; 20 s ITI: $p>.096$).

A three-way interaction [$F(1, 22)=15.7$, $p=.0006$, partial $\eta^2=.42$; see Figure 1b] indicated that, for the current short FP, sequential effects were reduced in the 20 s ITI block (30 ms) with respect to the 1 s ITI block (45 ms), as also demonstrated by planned comparisons ($p=.008$). However, the sequential effects for current short FPs (long FPn-1 vs. short FPn-1) were significant both for the 1 s ITI ($p<.00001$) and for the 20 s ITI ($p<.0001$). Moreover, the RT difference between the two ITI conditions (1 s vs. 20 s ITI) was not significant either in the long-short sequences ($p=.11$) or in the short-short ones (p>.7), suggesting that the ITI effect was due to an overall reduction of sequential effects at short FPs in the 20 s ITI condition.

As far as the scores for the mental state self-assessment are concerned (averaged across the four assessments), motivation and attention decreased from the 1 s ITI blocks to the 20 s ITI blocks [$t(22)=-3.27$, $p=0.0035$ and $t(22)=-5.02$, $p=0.00005$, respectively], while the opposite occurred for boredom and fatigue [$t(22)=5.29$, $p=0.000026$ and $t(22)=3.29$, $p=0.00335$, respectively].

Discussion

In Experiment 2, we replicated again the classical FP effect and asymmetrical sequential effects often reported in the literature of nonspecific preparation (Niemi & Näätänen, 1981). Like for Experiment 1, a significant reduction of sequential effects in the 20 s ITI condition was also obtained here. Significant changes in the measured mental states (attention, motivation, boredom and fatigue) as a function of the ITI were obtained, indicating that our ITI manipulation was successful in producing two different subjective states. Previous studies have already shown that neither asymmetrical sequential effects nor the FP effect are affected by mental fatigue (Langner, Steinborn, Chatterjee, Sturm, & Willmes, 2010; Vallesi, 2007). In contrast to these studies, in the present experiment we were able to show a reduction in the variable FP effect. However, in previous studies (Langner et al., 2010; Vallesi, 2007), the ITI was not dramatically lengthened as in our Experiment 2. Moreover, in these earlier studies mental fatigue was indirectly inferred from time-on-task and increase in absolute RTs, and not directly measured (like we did in our experiment 2), thus lacking evidence for a reduction in participants' motivation and attention.

In contrast to the results of Experiment 1, by using a simple RT task, the FP effect was reduced in the long ITI condition. The nature of the task could have modulated the direction of the changes. In Experiment 1, participants were engaged in a perceptual discrimination (i.e., choice RT) task. Conversely, in Experiment 2, they just had to detect either target by pressing a key (simple RT task). In Experiment 2, RTs in long FPs were significantly longer in the 20 s as compared to the 1 s ITI condition, while in Experiment 1 they were comparable between the two ITIs. Recent models of attention suggest that less engaging tasks, such as a simple RT task, require more active control of attention and vigilance when they have to be performed for extended periods of time (Pilcher, Band, Odle-Dusseau, & Muth, 2007; Walker, Muth, Odle-Dusseau, Moore, & Pilcher, 2009). A reduction of attention and motivation, together with a parallel increment in boredom and fatigue, might have affected performance in long FPs. Consistent with the dual-process account, this finding can be explained with an impairment of the monitoring process with longer ITIs due to a larger demand of processing resources under this less engaging task context.

General Discussion

In this study, we investigated the effects of task context (simple vs. choice RT task) and ITI duration (short vs. long) on the variable FP phenomena. The ITI manipulation in Experiment 1 showed opposite results for the FP effect (increased with longer ITI) and the sequential effects (reduced with longer ITI), while in Experiment 2 we found a reduction in both the FP effect and sequential effects as a function of ITI. If, on the single-process account, these two effects were due to the same cognitive process (Los & van den Heuvel, 2001), they should have changed in the same direction in both studies. However, our results suggest that there are at least partially different processes underlying these effects, supporting the dual-process account (Vallesi et al., 2007b).

The most important finding of both experiments was a reduction of sequential effects in the 20 s ITI condition, compared to the 1 s ITI which, at least in Experiment 1, was mainly caused by an increment of RTs in short-short sequences. These results confirmed, in part, the hypotheses derived from the dual-process account. On this account, sequential effects should be reduced with an ITI of 20 s, both by a loss of facilitation in short-short sequences, and by an RT reduction in long-short sequences. These predictions are explained as follows. On the dual-process account, higher levels of arousal are transferred to the next trial after shorter FPs than after longer ones (facilitation effect in short-short sequences). On the contrary, maintaining a high state of preparation in long FPs is tiring and effortful, posing a refractory period after them. This effect is greater for current short FPs. With current short FPs, indeed, the preparation process gets exhausted from the previous trial and cannot be compensated through probability monitoring, which benefits longer FPs only (when the probability of target occurrence is highest). As a consequence, participants are slower in long-short sequences. Thus, although refractoriness may affect both short and long FPs, in the latter case it can be compensated by the process monitoring the increasing conditional probability of stimulus occurrence in time. Thus, although the two kinds of processes (motor arousal regulation and monitoring) can be dissociated neurally and developmentally (Vallesi et al., 2007a; Vallesi & Shallice, 2007b), they interact in terms of overt RTs under normal conditions.

Our data support the facilitation mechanism, which was reduced in the long ITI condition, though significantly so in Experiment 1 only, confirming previous data by Granjon and colleagues (1977). However, the refractory period does not seem to decrease over time: providing participants with extra time to rest and recover did not significantly decrease RTs in long-short sequences. It is possible that with the 20 s ITI, phasic refractoriness decreased, but at the cost of boredom and tonic fatigue, thus masking possible resting benefits. We acknowledge the limitation of the subjective self-evaluations of mental state and suggest that future research should use more objective (i.e., electrophysiological) measures of fatigue and arousal. Another alternative explanation for a lack of ITI effect on refractoriness is related to the task switching literature, where the residual exogenous switch costs cannot be prevented even with long ITIs, which implies that the task-set reconfiguration needs the next target onset to be fully implemented (e.g., Rogers & Monsell, 1995). On a similar vein, it is possible that, also in the variable FP paradigm, motor refractoriness is not completely resolved unless a new response is executed after the onset of the next imperative stimulus, at least up to the longest ITI tested here (20 s). At this stage of knowledge, this is only an analogy and the issue clearly deserves further investigation.

Nonetheless, we were successful in obtaining an overall reduction of sequential effects for the current short FP in the long 20 s ITI blocks (in both experiments), a finding that is compatible with the arousal account of the sequential effects, as put forward in the dual-process model (Vallesi & Shallice, 2007b). A reduction of sequential effects is however at odds with the trace conditioning theory (Los & van den Heuvel, 2001), since the trace conditioning literature found either no ITI effect (Carrillo et al., 1997) or an enhancement of conditioning mechanisms with longer ITIs (Detert et al., 2008; Prokasy et al., 1958; Spence & Norris, 1950; Sunsay & Bouton, 2008).

The present study focused on the task-irrelevant time (ITI), which being by definition a resting period does not necessarily require the processing resources that generally sustain performance. Consistent with this consideration, we did not find an ITI main effect on absolute RTs. Other studies focused more on the task-relevant FP context (Steinborn & Langner, 2012; Vallesi, 2007, experiments 1 and 2; also see Niemi & Näätänen, 1981). The resource-demanding monitoring process is more intensely required (and drains the available resources at a larger extent) during the FP than during the ITI. Increasing the FP average duration is thus expected to proportionally decrease the available processing resources with consequent worsening of the performance level. These studies have indeed demonstrated that the RT performance globally declined when the FP average duration increased across experiments and, more locally, when the longest FPs in the range were repeated in higher order sequences of trials (e.g., Steinborn & Langner, 2012).

In conclusion, the FP effect was modulated by the nature of the task in the 20 s ITI condition. In Experiment 1, it increased using a choice RT task, while in Experiment 2 it diminished using a simple RT task. However, sequential effects were reduced in both cases. Thus, the modulation of sequential effects and FP effect by the ITI length did not always occur in the same direction. This pattern of findings goes in favor of theories postulating different underlying processes for these two FP phenomena.

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Acknowledgments

This work was partially supported by a Spanish grant from the Plan Nacional I+D+i programme, (PSI2010-15399; Ministerio de Innovación y Ciencia) to A.C. and A.V., by a master fellowship from the Spanish Ministry of Education (Beca de Movilidad de Máster) and by a pre-doctoral fellowship from SISSA, Trieste, Italy to V. L.