Highlights:

> The ERP correlates of dual-task interference on temporal preparation were explored.

> Cue-related ERPs showed no modulation of the CNV under dual-task conditions. > Target-related ERPs reported interference with late stages of processing. > Results demonstrate that dual-task disrupted the key markers of temporal preparation. 

Temporal orienting of attention is interfered by concurrent working memory updating
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#### ABSTRACT

A previous dual-task study (Capizzi, Sanabria, &, Correa, 2012) showed that temporal orienting of attention was disrupted by performing a concurrent working memory task, while sequential effects were preserved. Here, we recorded event-related potentials (ERPs) during single- and dual-task performance to investigate how this behavioural dissociation would be expressed in neural activity measures. The singletask condition required participants to respond to a visual target stimulus that could be anticipated on the basis of a highly predictive temporal cue. The dual-task condition introduced a concurrent working memory task, in which colour information had to be updated on every trial. The behavioural results replicated our previous findings of impaired temporal orienting, but preserved sequential effects, under dual-task relative to single-task conditions. The ERPs results showed that temporal orienting and sequential effects both modulated the cue-locked preparatory contingent negative variation (CNV) and the target-locked N2 amplitude and P3 latency only under single-task, but not under dual-task conditions. Differently from temporal orienting, sequential effects were also observed at the early target-locked P1 and N1 potentials. Crucially, only the P1 modulation survived to dual-task interference. These findings provide novel electrophysiological evidence that performance of a concurrent working memory task may interfere in a selective way with neural activity specifically linked to temporal orienting of attention.

### 1. Introduction

Temporal expectancies are critical in many of our everyday activities such as driving, playing sport or music (Nobre, Correa, & Coull, 2007). In soccer, for example, anticipating the goalkeeper's movements before kicking the penalty may determine the success or failure of the kicker when choosing the direction of the shot (Núñez, Oña, Raya, & Bilbao, 2009).

In laboratory settings, temporal expectancies have been widely investigated through a temporal variant of Posner's spatial orienting task (Posner, Snyder, & Davidson, 1980). In a typical temporal orienting task (Correa, 2010; Nobre, 2001; Coull & Nobre, 1998), participants have to respond as fast as possible to the onset of a target stimulus. Before the target is presented, a symbolic cue indicates whether the target is likely to appear early (e.g., after 1000 ms) or late (e.g., after 2000 ms). On a large proportion of trials (e.g., 0.75), the cue is valid so that participants are encouraged to use it in order to anticipate the subsequent target onset (valid condition). On the remaining trials, the target appears either earlier or later than expected (invalid condition). Results typically show faster and more accurate responses for targets occurring at early validly cued temporal intervals as compared to earlier than expected late targets, i.e., the so-called "validity effects". At the long time interval, validity effects are usually smaller or even absent because if the target does not appear shortly as predicted by the early cue, participants infer that it would appear later, which enables them to re-orient their attention to the late moment (e.g., Correa, Lupiáñez, Milliken, & Tudela, 2004; Coull & Nobre, 1998; Karlin, 1959).

Participants' reaction time (RT) in temporal orienting tasks is affected not only by the predictive information given by the cue, but also by the duration of the cue-target

interval (i.e., foreperiod) that was used on the previous trial. Namely, for current short time intervals, participants' RTs are typically faster if the previous interval was short as compared to when it was long, a phenomenon known as "sequential effects" (e.g., Drazin, 1961; Los & Van den Heuvel, 2001; Steinborn, Rolke, Bratzke, &Ulrich, 2008; Vallesi & Shallice, 2007; Woodrow, 1914). Sequential effects are usually asymmetric since for current long time intervals, participants' RTs are faster independently of whether the previous interval was short or long.

Los' "trace conditioning" model (Los, 1996; Los & Heslenfeld, 2005; Los & Van den Heuvel, 2001) proposes that sequential effects would reflect the operation of a single automatic mechanism, unintentionally driven by stimulus sequence association from one trial to the next rather than by internal volitional expectations. According to the "dual-process" model proposed by Vallesi and collaborators (Vallesi, 2010; Vallesi & Shallice, 2007; Vallesi, Shallice, & Walsh, 2007), sequential effects would be instead the outcome of two processes: automatic arousal modulation by the previous interval, and voluntary preparation triggered by the conditional probability of target appearance (i.e., if the target did not occur at the short interval, the probability that it will occur at the long interval grows as a function of the elapsed time; see Coull, 2009; Niemi, & Näätänen, 1981, for reviews). That is, a previous long interval would decrease participants' arousal, while a previous short interval would increase arousal levels, thus lenghtening or speeding up RT, respectively. The arousal effect would occur regardless of the duration of the current interval, giving rise to symmetric sequential effects. The observed asymmetry would be instead determined by the controlled process computing the conditional probability of target appearance on the longest trials, with the result of counteracting the negative effect on RT of a previous (less arousing) long interval.

Despite the differences between the two models described above, a general consensus exists on the idea that sequential effects and temporal orienting would be mediated by dissociable cognitive and neural mechanisms. Los and Van den Heuvel (2001), for example, showed that sequential effects were stronger outside the attentional 'focus' of temporal orienting (i.e., on invalid conditions rather than on valid ones). Other authors have reported that temporal orienting effects could be elicited independently of sequential effects (Correa et al., 2004; Correa, Lupiáñez, & Tudela, 2006). This behavioural evidence is consistent with recent neuropsychological research showing that temporal orienting effects, triggered by simbolic cues, were diminished in patients with right prefrontal lesions relative to performance of control participants, whereas sequential effects were preserved (Triviño, Arnedo, Lupiáñez, Chirivella, & Correa, 2011; Triviño, Correa, Arnedo, & Lupiañez, 2010).

The neural substrates underlying temporal orienting effects have been widely investigated using event related potential measures (ERPs; e.g., Correa & Nobre, 2008, Correa, Lupiañez, Madrid, & Tudela, 2006; Doherty, Rao, Mesulam, & Nobre, 2005; Griffin, Miniussi, & Nobre, 2002; Lampar & Lange, 2011; Lange, 2011; Miniussi, Wilding, Coull, & Nobre, 1999; Sanders & Astheimer, 2008). Three major ERPs have been often associated to temporal orienting, namely, the contingent negative variation (CNV), the N2 and the P3. The CNV is a slow negative wave occurring during the preparatory interval between a warning signal and an impeding stimulus that requires a response (Walter, Cooper, Aldridge, McCallum, & Winter, 1964). The development of the CNV is sensitive to the temporal information provided by predictive cues, as demonstrated by enhanced negativity following an early expectany cue in relation to a late expectancy cue at the moment of likely early target onset (Los & Heslenfeld, 2005; Loveless & Sandford, 1974; Miniussi, Wilding, Coull, & Nobre, 1999; Trillenberg,

Verleger, Wascher, Wauschkuhn, & Wessel, 2000). This finding shows that temporal orienting may increase participant's readiness to respond around the time of the expected event. Temporal orienting also modulates brain potentials linked to cognitive control

and motor response, such as the N2 and the P3 (see Folstein & Van Petten, 2008; Polich, 2007, for reviews on the N2 and P3 potentials, respectively). The N2 amplitude is attenuated and the P3 latency is reduced for expected, validly cued, targets as compared to unexpected, invalidly cued, targets (Correa & Nobre, 2008; Correa et al., 2006; Doherty et al., 2005; Griffin et al., 2002). The N2 attenuation may reflect "the temporal maintenance of response inhibition to prevent responding at inappropriate times" (Correa & Nobre, 2008, p. 1654), while the reduced P3 latency would reflect the synchronization and preparation of fast responses to the upcoming event (Griffin et al., 2002; Miniussi et al., 1999). Alternatively, no modulation of early visual processing stages, indexed by the P1 and N1 potentials, is usually observed for targets presented at the expected moment in time, at least when the task does not involve high discriminative demands (see Correa, 2010; Correa et al., 2006, for reviews).

In contrast to temporal orienting, little attention has been paid to the neural correlates of sequential effects as well as to the interrelations between temporal orienting and sequential effects. A noticeable exception is the electrophysiological study by Los and Heslenfeld (2005; see also Van der Lubbe et al., 2004). The authors followed a temporal orienting procedure, in which the cue conveyed either no information (neutral condition) or valid information (valid condition) about the possible moment (early versus late) of target onset. The CNV was measured as an index of temporal preparation. They found that the CNV amplitude was more negative before an early target onset when the previous interval had been short rather than long on both

neutral and valid conditions. Interestingly, this effect by the previous interval was not eliminated at the early moment even when participants had been validly cued to a late target onset. That is, the contribution of sequential effects on the modulation of the CNV was additive to that of temporal orienting, which confirmed that sequential effects may contribute to the development of temporal preparation independently of temporal orienting.

Unfortunately, however, Los and Heslenfeld (2005) only measured brain activity related to the warning (cue) signal, while ERPs associated to target processing were not taken into account, thus precluding a direct comparison between the consequences of temporal orienting and sequential effects on stimulus analysis. To the best of our knowledge, sequential effects of temporal preparation over target processing have not been previously investigated with measures of brain activity.

In the present study, we explored the electrophysiological correlates of both temporal orienting and sequential effects in a dual-task experiment. The starting point of this work was a behavioural research (Capizzi, Sanabria, & Correa, 2012), in which we tested the controlled versus the automatic nature of temporal orienting and sequential effects (cf. Logan, 1979; Posner & Snyder, 1975). In our study, participants performed the temporal orienting task either alone (single-task condition) or simultaneously with a working memory updating task (dual-task condition). In the single-task condition, a coloured cue (a short versus a long line) predicted on a trial-by-trial basis the most likely moment of target onset to which participants had to respond. In the dual-task condition, working memory demands were manipulated by instructing participants to mentally update and report the final count of temporal cue colours at the end of each block.

The use of concurrent updating representations in working memory as secondary task was motivated by two main findings. First, dual-task studies that employed a working memory task have shown interference between working memory and time estimation of intervals in the range of seconds, which suggests that these two tasks may compete for common executive resources (e.g., Brown, 2006; Fortin & Breton, 1995). Second, working memory and timing tasks additionally share prefrontal structures (see Lewis & Miall, 2006, for a review), which are also related to temporal orienting of attention (Triviño et al., 2011; 2010). Hence, our premise was that the introduction of a concurrent working memory task would interfere selectively with the timing processes underlying controlled temporal preparation (i.e., temporal orienting effects), while leaving the automatic component (i.e., sequential effects) unaffected. Consistent with this prediction, our results (Capizzi et al., 2012) reported reduced validity effects in the dual-task condition as compared to the single-task condition. In contrast to temporal orienting, sequential effects survived to dual-task interference, as they were neither eliminated nor reduced by concurrent task demands.

These findings were taken as evidence that, differently from sequential effects, temporal orienting relies on controlled processing, so that when cognitive demands were increased by the secondary working memory task with respect to the single-task condition, participants did not longer benefit from the predictive information provided by the temporal cue. However, the specific locus of interference between temporal orienting and concurrent dual-task demands cannot be established by a purely behavioural approach. One might wonder, for instance, whether the disruption of temporal orienting effects shown by Capizzi et al. (2012) arose at response stages, which have been selectively linked to temporal orienting of attention (Nobre, 2001), or whether dual-task interference acted unspecifically on perceptual levels since temporal

orienting and working memory tasks shared the same visual modality. In addition, it makes sense to wonder whether the presence of a dual-task context might already interfere with preparatory activity preceding the onset of the target, as indexed by the CNV potential. To address these questions, the current study exploited the high temporal resolution of ERPs with the main aim of identifying at which stages of information processing the concurrent performance of a working memory task would interfere with temporal orienting of attention. In addition, we tested whether temporal orienting and sequential effects would act on similar or different levels of target processing.

Our predictions were as follows. With respect to temporal orienting effects, we reasoned that if the dual-task manipulation would interfere selectively with temporal orienting, then such interference should be reflected in a lower modulation of the CNV amplitude under dual-task relative to single-task conditions. Moreover, we expected to observe a significant impairment of the typical neural correlates of temporal orienting, with no attenuation of the N2 amplitude and P3 latency by temporal expectancy under dual-task relative to single-task conditions.

Regarding sequential effects, we sought to replicate Los and Heslenfeld's (2005) results of a more negative CNV when the previous interval was short as compared to when it was long. Building on this study which revealed additive influences of temporal orienting and sequential effects on preparatory processes, we also predicted a similar modulation of late target processing stages for the two temporal effects. Importantly, however, only the ERP pattern associated to sequential effects (but not to temporal orienting) should be unaffected by dual-task demands.

*2.1. Participants.* Twenty-two students from the University of Granada took part in the experiment in exchange for course credits or cash payment of 15 Euro. All participants gave informed consent prior to their inclusion in the study. They had normal or corrected-to-normal visual acuity and reported having normal colour vision. The study was approved by the local ethics committee and was conducted according to the guidelines of the Declaration of Helsinki. Data from six participants were discarded because of excessive eye-movements or other artefacts. The remaining 16 participants (age range: 22-35 years, 2 men) were used for both behavioural and ERP analyses. All but three participants were right-handed.

*2.2. Stimuli and task.* Stimulus presentation and response collection were controlled by an Intel Core 2 Duo personal computer connected to a 17" LCD monitor. This computer, running Biological E-prime software (Schneider, Eschman, & Zuccolotto, 2002), was connected to a Macintosh computer (Power PC G5) that recorded continuous EEG. All stimuli were presented centrally against a black background. The temporal cue consisted of a short  $(3.4^{\circ} \times 1.3^{\circ} \text{ visual angle})$  or long  $(7.5^{\circ} \times 1.3^{\circ})$  line displayed either in red, green or blue. The short line indicated that the target would probably appear early (after 1000 ms) and the long line indicated that the target would probably appear late (after 2000 ms). The target stimulus was a white dot (diameter:  $1.5^{\circ}$ ).

Participants were tested in a silent, dimly illuminated and electrically shielded room. Each trial began with the presentation of a blank screen for a random duration between 500 and 1000 ms (see Figure 1-A). The temporal cue, displayed in one of three

colours (red, green, or blue), was then presented for 750 ms. Each colour was randomly generated at the beginning of each trial with the same probability of appearance. In the first experimental session (i.e., single-task condition), participants were told that the colour of the temporal cue was task-irrelevant and should therefore ignore it. Following the temporal cue, the screen remained blank for a variable delay of either 1000 or 2000 ms, depending on the time interval for that trial. After the time interval elapsed, the target stimulus was presented for 100 ms and then disappeared. Participants had to respond to every target onset as quickly as possible by pressing either the leftmost or rightmost key on a 4-key numeric keypad with their left or right index finger, respectively. The assignment of the target to response keys was counterbalanced across blocks. A visual feedback message was displayed for 500 ms either in case of an anticipated response ("wait for the target") or if no response to the target, or after 1100 ms in case of a missed response, the next trial began.

#### PLEASE INSERT FIGURE 1.A AND 1.B

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In the dual-task condition, the temporal orienting task remained the same as that described above. The only difference with respect to the single-task condition was the addition of the concurrent working memory task. The working memory task required participants to count and remember how many times each temporal cue colour appeared during a block of trials. At the end of the block, one of the three colours was randomly chosen (e.g., "*red*") and participants said aloud how many times that colour had been

presented. The experimenter then typed the response. Each colour was equally probable to be selected for the memory test. This task encouraged participants to update their working memory contents on every trial, in order to maintain the final count of each colour until the end of the block. Feedback about memory accuracy (the word "correct" or "incorrect" in white for 1500 ms) was provided after the response in each block to engage participants in the working memory task. Participants' instructions, however, emphasised equal priority to temporal orienting and working memory tasks.

At the beginning of the experiment, participants were given a short training session to learn the cue-time interval contingency, which consisted of two blocks of 16 trials each (100% valid; cf. Correa et al., 2006). Participants were explicitly informed that the temporal cue would help them to predict the occurrence of the upcoming target. After the training session, participants completed thirty-one blocks of 16 trials each of the single-task condition, followed by thirty-one blocks of the dual-task condition. Presentation of the single-task condition took place before the dual-task condition, which was separated from the previous session by 1 or 2 days. The goal of this procedure was to familiarise participants with the temporal orienting task before performing the working memory task. In this way, we aimed to strengthen the processing of the temporal cues in the first (single-task) session in order to consolidate them for the second (dual-task) session.

The first block of each task condition was considered as practice. Each experimental block consisted of 8 early-cue trials and 8 late-cue trials. On early-cue trials, 6 were valid trials, in which the target appeared after 1000 ms, and 2 were invalid trials, in which the target appeared after 2000 ms (cue validity: 75%). Likewise, on late-cue trials, 6 were valid trials, in which the target appeared after 1000 ms, and 2 were invalid trials, in which the target appeared after 2000 ms (cue validity: 75%). Likewise, on late-cue trials, 6 were valid trials, in which the target appeared after 1000 ms. Participants received feedback

on RT performance only during practice trials. A rest between blocks of trials was allowed. The whole experimental session lasted about 90 minutes.

2.3. EEG recording. Participants seated in front of the computer monitor and were instructed to avoid eye blinks and movements during stimulus presentation. The EEG recording was performed using a 128-channel Geodesic Sensor Net<sup>TM</sup> (Tucker, Liotti, Potts, Russell, & Posner, 1994; see Figure 1-B), connected to an AC-coupled high-input impedance amplifier (200 M $\Omega$ , Net Amps<sup>TM</sup>, Electrical Geodesics, Eugene, Oregon). The head-coverage included sensors lateral to and below both eyes to monitor horizontal and vertical eye movements (electrooculogram, EOG electrodes). Impedances for each channel were measured and adjusted until they were kept below 50 k $\Omega$  before testing, as recommended for the Electrical Geodesics high-input impedance amplifiers. Gain and zero calibration were performed prior to the start of every recording. All electrodes were referenced to the vertex (Cz) during the recording and were algebraically re-referenced off-line to calculate the average reference. The EEG was amplified with a band pass of 0.1-100 Hz (elliptic filter) and digitized at a sampling rate of 250 Hz.

*2.4. ERP analysis.* Continuous raw data were filtered offline using a 30-Hz lowpass filter. Separate epochs were constructed for cues (between -100 and 1750 ms relative to cue onset) and targets (between -200 and 600 ms relative to target onset). The period of 100 ms preceding cue onset was used to calculate the baseline for the cue analysis. A strict baseline correction was instead performed for the target analysis, [-200, 50] ms, in order to minimize distortion of the ERP averages due to the overlap from previous events (see Woldorff, 1993). The segmented epochs were then submitted

to software algorithms for identification of artefacts (Eye blink and Eye movement threshold: deflections exceeding  $\pm 70 \ \mu$ V relative to baseline in EOG channels; other artifacts threshold: deflections exceeding  $\pm 80 \ \mu$ V relative to baseline in any channel). Individual bad channels were replaced on a trial-by-trial basis with a spherical spline algorithm (Perrin, Pernier, Bertrand, & Echallier, 1989), but trials were discarded if more than ten channels were bad. In addition, trials that did not meet the criteria set for behavioural analyses were rejected. A minimum of 30 trials per condition was required to ensure a sufficient signal-to-noise ratio.

Artefact-free epochs were then re-referenced off-line to the average in order to eliminate the effects of reference-site activity and to generate an accurate estimation of the scalp topography of the recorded electrical fields (Tucker, Liotti, Potts, Russell, & Posner, 1994). Separate grand average waveforms were constructed according to both cues and targets categories. ERP waves elicited by the cue gave rise to four conditions: previous short – early cue, previous long – early cue, previous short–late cue, previous long – late cue, according to whether early and late cue trials were preceded by a short or long interval. Cue validity was not taken into account since this was not relevant until the appearance of the target.

ERPs evoked by targets were separated into two categories: 1) valid and invalid trials, regardless of the previous interval condition; and 2) previous short and previous long interval trials, regardless of the validity condition (note that the small number of invalid trials did not allow combining the two conditions into a single analysis).

Given that all analyses were restricted to targets appearing at the short time interval in order to avoid any influence from foreperiod effects at the long time interval (i.e., if the target does not appear after the short interval, it would appear after the long interval with full probability; Coull, 2009; Niemi, & Näätänen, 1981), the valid

condition included trials in which the cue was 'early' and the target appeared at the short interval, whereas the invalid condition included trials in which the cue was 'late' and the target appeared at the short interval. Following the same criteria for the sequential effects analysis, the previous short interval condition included trials in which the previous interval was 'short' and the target appeared at the short interval, while the previous long interval condition included trials in which the previous interval condition included trials in which the previous long interval condition included trials in which the previous interval condition included trials in which the previous long interval condition included trials in which the previous interval was 'long' and the target appeared at the short interval.

For all analyses, amplitude was calculated as the mean voltage in a specificied temporal window and electrodes site. Such windows and sites were chosen on the basis of visual inspection of the grand average waveforms and according to prior literature. The latency associated to the maximum peak was analysed only for the P3 potential within the same temporal window and electrodes site as those used for the P3 amplitude. The Greenhouse-Geisser correction was applied when sphericity was violated (Jennings and Wood 1976). Corrected probability values are reported.

*2.4.1.Cue-locked ERPs.* The mean CNV amplitude was analysed after cue offset (note that the temporal cue was presented for 750 ms) over frontal and central regions (*left*: 7, 13, C1, 32; *midline*: FCz, Cz; *right*: 107, 113, C2, 81). Five time bins of 200 ms each were selected for statistical analysis: (1) 750–950 ms, (2) 950–1150 ms, (3) 1150-1350, (4) 1350-1550, and (5) 1550-1750 ms. Amplitude differences were tested using a five-way ANOVA with the within-participants factors of Time bin (1, 2, 3, 4, 5), Task (single-task, dual-task), Cue (early, late), Previous interval (short, long) and Electrodes site (left, midline, right). Significant effects of Electrodes site were reported only if they interacted with either Cue, Previous interval, or both.

2.4.2. Target-locked ERPs.

*2.4.2.1.Temporal orienting.* The P1 and N1 potentials were measured over posterior electrodes (*left:* P1, PO3, PO7, O1, 67; *midline:* Pz, POz, 73; *right:* P2, PO4, PO8, O2, 78) beetween 110-150 ms and 160-200 ms, respectively.

The N2 potential was measured over parietal regions (*left*: 54, P3, P1; *midline*: CPz, Pz, POz; *right*: 80, P4, P2) between 240-280 ms. The P3 was analysed over central and parietal electrodes sites (*left*: 7, C1, CP1, 54, 32; *midline*: Cz, CPz, Pz; *right*: 107, C2, CP2, 80, 81) between 340-430 ms.

Separate repeated-measures ANOVAs were conducted on the mean amplitude of each target-locked ERP and on the latency of the P3 with Task (single-task, dual-task), Validity (valid, invalid) and Electrodes site (left, midline, right) as within-participants factors. Significant effects of Electrodes site were reported only if they interacted with Validity.

*2.4.2.2. Sequential effects.* The analysis of sequential effects was conducted on the same ERPs, including the same temporal windows and electrodes sites as those employed in the temporal orienting analysis. Separate repeated-measures ANOVAs were conducted on the mean amplitude of each target-locked ERP and on the latency of the P3 with Task (single-task, dual-task), Previous interval (short, long) and Electrodes site (left, midline, right) as within-participants factors. Significant effects of Electrodes site were reported only if they interacted with Previous interval. 

#### 3. Results

*3.1. Behavioural results.* The overall accuracy (i.e., proportion of correct responses) across participants to the colour memory test was 0.74.

In the temporal orienting task, data from practice trials, the first trial of each block, trials involving premature responses (i.e., responses before target onset: 1.7%), trials with RTs below 150 ms (0.5%) and above 1000 ms (0.1%), and trials without responses (0.6%) were rejected from the analysis. A repeated-measures ANOVA was conducted on the RTs to respond to the target with Task (single-task, dual-task), Validity (valid, invalid), Previous interval (short, long) and Interval (short, long) as within-participants factors.

The main effect of Task was significant, F(1, 15) = 6.64, p = .02,  $\eta p^2 = .3$ , indicating that participants were slower in the dual-task condition as compared to the single-task condition. The main effect of Validity and the interaction between Validity and Interval also reached significance, F(1, 15) = 14.72, p = .001,  $\eta p^2 = .4$ , and F(1, 15)= 14.44, p = .001,  $\eta p^2 = .4$ , respectively. Importantly, validity effects were modulated by Task condition, as revealed by a significant Task x Validity interaction, F(1, 15) =22.57, p < .001,  $\eta p^2 = .6$ . Planned comparisons for this interaction showed that participants were faster on valid trials as compared to invalid trials in the single-task condition, F(1, 15) = 26.47, p < .001, but not in the dual-task condition, F < 1 (see Figure 2). This finding was also supported by a significant Task x Validity x Interval interaction, F(1, 15) = 32.64, p < .001,  $\eta p^2 = .6$ , revealing that the interaction between Task and Validity was significant at the short interval, F(1, 15) = 36.26, p < .001, and marginally significant at the long interval, F(1, 15) = 3.53, p = .07. In particular, at the short interval validity effects were significant only in the single-task condition, F(1, 15) = 39.76, p < .001, but not in the dual-task condition, F < 1. At the long interval, no validity effects were observed in either the single-task, F(1, 15) = 1.40, p = .2, or in the dual-task condition, F(1, 15) = 1.45, p = .2.

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The main effect of Previous interval was significant, F(1, 15) = 110.73, p < .001,  $\eta p^2 = .8$ , as participants responded faster after a previous short interval than after a previous long interval. The asymmetry of sequential effects was indexed by a significant Previous interval x Interval interaction, F(1,15) = 46.47, p < .001,  $\eta p^2 = .7$ , with a larger effect of the previous interval at the current short interval than at the current long interval, although it reached statistical significance in both time intervals [F(1,15) = 84.42, p < .001, and F(1,15) = 16.58, p = .001, for the short and the longinterval, respectively]. Crucially, sequential effects were not modulated by Task condition (see Figure 3), since the interactions involving Task and Previous interval factors were not statistically significant ( $F_{s} < 1$  for both Task x Previous interval and Task x Previous interval x Interval interactions). Moreover, there were no significant interactions involving Validity and Previous interval (ps>.1 for both Validity x Previous interval and Validity x Previous interval x Interval interactions). Further a priori planned comparisons showed that validity effects were significant for both previous short and previous long intervals [F(1,15) = 8.14, p = .01, and F(1,15) = 5.16, p = .03, for the previous short and the previous long interval, respectively], as well as sequential effects were significant for both valid and invalid short-trials [F(1,15) = 63.69, p < .001,

and F(1,15) = 33.23, p < .001, for the short-valid and the short-invalid trial, respectively].

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Finally, there was a significant main effect of Interval, F(1,15) = 124.95, p < .001,  $\eta p^2 = .8$ , with participants responding faster at the long interval as compared to the short interval, and a significant Task x Interval interaction, F(1,15) = 20.01, p < .001,  $\eta p^2 = .5$ , with a larger difference in participants' RTs between the single-task and the dual-task condition at the short interval as compared to the long interval [F(1,15) = 9.88, p = .006, and F(1,15) = 3.13, p = .09, for the short and the long interval, respectively].

#### 3.2. Electrophysiological results.

*3.2.1. Cue-locked ERPs.* The CNV analysis revealed a significant main effect of Time bin, F(4,60)=4.96, p=.01,  $\eta p^2 =.2$ . Trend analyses showed that the time course of the CNV followed a significant linear trend, F(1,15)=7.19, p=.01 (i.e., it became more negative across the preparatory interval) rather than a quadratic trend, F<1. The main effect of Task was marginally significant, F(1,15)=3.61, p=.07,  $\eta p^2 =.1$ , revealing attenuated CNV amplitude (i.e., less negative) in the dual-task condition (-0.47  $\mu v$ ) as compared to the single-task condition (-0.82  $\mu v$ ). This Task effect was better qualified by a significant Task x Cue interaction, F(1,15)=7.63, p=.01,  $\eta p^2 =.3$ , showing that the CNV amplitude was more negative for early cue than for late cue in the single-task

condition [-0.99  $\mu$ v versus -0.65  $\mu$ v, *F*(1,15)= 12.79, *p*=.002], but not in the dual-task condition [-0.45  $\mu$ v versus -0.50  $\mu$ v, *F*<1].

There was a significant main effect of Previous interval, F(1,15)=6.67, p=.02,  $\eta p^2 = .3$ , with more negative CNV amplitude when the previous interval was short (-0.76 µv) as compared to when it was long (-0.53 µv). This effect interacted with Time bin, F(4,60)=4.75, p=.002,  $\eta p^2 = .2$ . Bonferroni corrected comparisons ( $\alpha$ =.01) for this interaction showed that the effect of Previous interval was significant for each of the last two time bins [F(1,15)=9.21, p=.008, and F(1,15)=8.97, p=.009, respectively], while it was not significant for the first, F(1,15)=1.59, p=.2, the second, F(1,15)=4.53, p=.05, and the third time bin, F(1,15)=4.4, p=.05.

The interaction between Task and Previous interval was marginally significant, F(1,15)=4.3, p=.055,  $\eta p^2 = .2$ . Subsequent planned comparisons revealed that the CNV amplitude was more negative when the previous interval was short rather than long in the single-task condition [-1.02 µv versus -0.61 µv, F(1,15)=14.73, p=.001], but not in the dual-task condition [-0.49 µv versus -0.45 µv, F<1].

In order to test whether our results replicated Los and Heslenfeld's (2005) study in the single-task condition, separate ANOVAs were conducted on each task condition over the final part of the CNV (i.e., at the last 200 ms before early target onset) with Cue, Previous interval and Electrodes site as factors. The ANOVA on the single-task condition showed significant main effects of both Cue, F(1,15)=9.27, p=.008,  $\eta p^2 =.3$ , and Previous interval, F(1,15)=13.43, p=.002,  $\eta p^2 =.4$ . Although the interaction between the two factors was not significant, F(1,15)=2.8, p=.1,  $\eta p^2 =.1$ , further planned comparisons revealed that the effect of previous interval was significant only when the cue was early, F(1,15)=11.89, p=.003, but not when it was late, F(1,15)=2.63, p=.1 (see Figure 4). The ANOVA on the dual-task condition revealed no significant main effects or interactions (all  $p_{s>.5}$ ).

In sum, the analysis of cue-related activity revealed significant effects of cueing and previous interval, that seemed to interact, on the modulation of the CNV amplitude in the single-task condition. Both effects were eliminated in the dual-task condition.

#### PLEASE INSERT FIGURE 4

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3.2.2. Target-locked ERPs.

*3.2.2.1. Temporal orienting.* There were no significant main effects or interactions between Task and Validity for either P1 or N1 amplitudes (all *p*s>.16).

The ANOVA on the N2 amplitude revealed a significant main effect of Task, F(1,15)=15.22, p=.001,  $\eta p^2 = .5$ , such that the amplitude of the N2 was larger in the dual-task condition (1.06  $\mu$ v) as compared to the single-task condition (2.12  $\mu$ v; see Figure 5). Importantly, validity effects were modulated by Task condition as revealed by a significant Task x Validity interaction, F(1,15)=7.83, p=.01,  $\eta p^2 = .3$ . Planned comparisons for this interaction showed that the N2 was attenuated for valid trials as compared to invalid trials in the single-task condition [2.48  $\mu$ v versus 1.76  $\mu$ v, F(1,15)= 8.9, p=.009], but not in the dual-task condition [1.01  $\mu$ v versus 1.11  $\mu$ v, F<1]. There was also a significant Validity x Electrodes site interaction, F(2,30)=4.38, p=.02,  $\eta p^2=.2$ . This interaction was due to larger validity effects at the right site than at the other two sites, although Bonferroni corrected ( $\alpha=.017$ ) comparisons showed that

validity effects were not significant in any of the three sites [F(1,15)= 1.16, p=.2, for the left site, F(1,15)= 2.84, p=.1, for the midline site, and F(1,15)= 5.66, p=.03, for the right site]. None of the other terms in the ANOVA reached statistical significance (all ps>.1).

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PLEASE INSERT FIGURE 5

The ANOVA on the P3 amplitude revealed a significant main effect of Task, F(1,15)=12.83, p=.003,  $\eta p^2 =.4$ , with a larger amplitude in the single-task condition (2.68 µv) as compared to the dual-task condition (1.67 µv). There was a significant Validity x Electrodes site interaction, F(2,30)=9.51, p<.001,  $\eta p^2 =.3$ . Bonferroni corrected comparisons ( $\alpha$ =.017) for this interaction showed that validity effects were marginally significant for the right site, F(1,15)=6.26, p=.02, but not for the left and the midline sites [F(1,15)=1.01, p=.3, and F(1,15)=2.15, p=.1, for the left and the midline site, respectively]. Although the Task x Validity interaction failed to reach statistical significance, F(1,15)=1.60, p=.2,  $\eta p^2=.09$ , hypothesis-driven planned comparisons revealead that validity effects were marginally significant in the single-task condition, F(1,15)=3.8, p=.07, but not significant in the dual-task condition, F<1.

The ANOVA on the P3 latency displayed only a significant Task x Validity x Electrodes site interaction, F(2,30)=4.44, p=.02,  $\eta p^2=.2$  (ps>.22 for all the other main effects and interactions). Separate ANOVAs for each electrode site showed that the Task x Validity interaction was only significant for the left site, F(1,15)=5.01, p=.04,  $\eta p^2=.2$ , but not for the midline and the right sites [F<1 for both sites]. Specifically, for

the left site the P3 following a valid trial peaked earlier as compared to the P3 following an invalid trial in the single-task condition [387 ms versus 399 ms, F(1,15)=14.96, p=.001] as compared to the dual-task condition [396 ms versus 394 ms, F<1; see Figure 6]<sup>1</sup>. There were no significant validity effects in either the single-task or the dual-task condition for the midline and the right sites (all ps>.1).

<sup>1</sup> As can be observed in Figure 6, the P3 was preceded by another positive deflection (P3<sub>1</sub>) peaking at around 280-340 ms. Separate repeated-measures ANOVAs were conducted on the mean amplitude and latency of this ERP with Task (single-task, dual-task), Validity (valid, invalid) and Electrodes site (left, midline, right) as factors. The ANOVA on the P3<sub>1</sub> amplitude elicited a significant main effect of Task, F(1,15)=24.91, p < .001,  $\eta p^2 = .6$ , indicating that the P3<sub>1</sub> amplitude was smaller in the dual-task condition (0.73  $\mu$ v) than in the single-task condition (1.93  $\mu$ v). Validity effects were modulated by Task condition, as indexed by a significant Task x Validity interaction, F(1,15) = 5.15, p = .03,  $\eta p^2 = .2$ , with validity effects being significant in the single-task condition, F(1,15) = 6.18, p = .02, but not in the dual-task condition, F < 1. The main effect of Validity was only marginally significant, F(1,15)=3.83, p=.06,  $\eta p^2=.2$ , and interacted with Electrodes site, F(2,30) = 4.52, p = .01,  $\eta p^2 = .2$ . Planned comparisons for this interaction showed that validity effects were marginally significant for the right site, F(1,15) = 5.85, p=.02 (Bonferroni corrected,  $\alpha = .017$ ), but not for the left and the midline sites [F(1,15)=2.14, p=.1, and F(1,15)=3.22, p=.09, for the left and the midline site, respectively]. The ANOVA on the P31 latency did not reveal any significant main effects or interactions (all *ps*>.065).

To sum up, activity related to temporally expected targets, with respect to unexpected targets, attenuated the N2 amplitude and reduced the P3 latency only in the single-task condition. In contrast, temporal orienting of attention did not result in any effect on target processing at the P1 and N1 potentials in either the single-task or the dual-task condition.

PLEASE INSERT FIGURE 6

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*3.2.2.1. Sequential effects.* The ANOVA on the P1 amplitude showed a significant Previous interval x Electrodes site interaction, F(2,30)=3.68, p=.03,  $\eta p^2 =.1$ . Bonferroni corrected ( $\alpha$ =.017) comparisons for this interaction showed that the P1 amplitude was larger when the previous interval was short as compared to when it was long in the right site [1.24 µv versus 0.96 µv, F(1,15)=7.56, p=.015], while it did not reach statistical significance in either the left [0.98 µv versus 0.89 µv, F<7] or the midline site [1.41 µv versus 1.24 µv, F(1,15)=2.01, p=.1]. The main effect of Previous interval was not modulated by Task condition since both the Task x Previous interval x Electrodes site interaction were not significant (both Fs <1; see Figure 7).

The ANOVA on the N1 amplitude showed a significant Task x Previous interval interaction, F(1,15)=6.75, p=.02,  $\eta p^2 = .3$ , such that the N1 was attenuated when the previous interval was short than when it was long in the single-task condition [-0.61  $\mu v$  versus -0.94  $\mu v F(1,15)=3.52$ , p=.07] as compared to the dual-tak condition [-0.39  $\mu v$ 

versus -0.31  $\mu$ v, *F*<1; see Figure 7]. None of the remaining terms of the ANOVA reached statistical significance (all *p*s>. 13).

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PLEASE INSERT FIGURE 7

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The ANOVA on the N2 amplitude showed a significant main effect of Task, F(1,15)=20.44, p<.001,  $\eta p^2=.5$ , such that the amplitude of the N2 was larger in the dual-task condition (1.02  $\mu$ v) as compared to the single-task condition (2.30  $\mu$ v; see Figure 8). The main effect of Previous interval was significant, F(1,15) = 21.83, p < .001,  $\eta p^2 = .5$ , such that the N2 amplitude was attenuated when the previous interval was short  $(1.89 \,\mu v)$  rather than long  $(1.43 \,\mu v)$ . The effect of Previous interval interacted with Task condition as revealed by a significant Task x Previous interval interaction, F(1,15) = 10.86, p = .004,  $np^2 = .4$ . Planned comparisons for this interaction showed that the N2 was attenuated when the previous interval was short as compared to when it was long in the single-task condition [2.69  $\mu$ v versus 1.91  $\mu$ v, F(1,15)= 38.81, p<.001], but not in the dual-task condition [1.08  $\mu$ v versus 0.95, F<1]. There was also a Previous interval x Electrodes site interaction, F(2,30) = 9.71, p < .001,  $np^2 = .3$ . This interaction was explained by a larger difference between previous short and previous long intervals in the right and midline sites [F(1,15)=43.9, p<.001, for the right site, and F(1,15)=22.74,  $p \le .001$ , for the midline site], as compared to the left site, F(1,15) = 4.95, p = .04(Bonferroni corrected,  $\alpha$ =.017).

PLEASE INSERT FIGURE 8

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The ANOVA on the P3 amplitude elicited a significant main effect of Task, F(1,15) = 13.82, p = .002,  $\eta p^2 = .4$ , indicating that the P3 amplitude was smaller in the dual-task condition (1.70  $\mu$ v) than in the single-task condition (2.74  $\mu$ v). The effect of Previous interval was significant, F(1,15) = 9.71, p = .007,  $\eta p^2 = .3$ , with larger P3 amplitude when the previous interval was short  $(2.40 \,\mu v)$  than long  $(2.05 \,\mu v)$ . Although the Task x Previous interval interaction failed to reach statistical significance (F < 1), hypothesis-driven planned comparisons revealead that the effect of previous interval was significant in the single-task condition, F(1,15) = 9.45, p = .007, and marginally significant in the dual-task condition, F(1,15)=3.95, p=.06 (see Figure 9).

The ANOVA on the P3 latency displayed only a significant Task x Previous interval x Electrodes site interaction, F(2,30) = 6.24, p=.005,  $\eta p^2 = .2$  ( $p_s > .4$  for all the other main effects and interactions). Separate ANOVAs for each site showed that the Task x Previous interval interaction was marginally significant for the right site, F(1,15)=3.98, p=.06,  $\eta p^2=.2$ , but not for the left and the midline sites (*ps*>.1 for both sites). Specifically, on the right site the difference between previous short (396 ms) and previous long interval (403) was larger in the single-task condition as compared to the dual-task condition (399 ms versus 397ms), although such a difference did not approach statistical significance in either task condition [F(1,15)=2.01, p=.1 and F<1, for the single-task and the dual-task condition, respectively] $^{2}$ .

<sup>2</sup> Similarly to temporal orienting, separate ANOVAs were conducted on the mean amplitude and latency of the P3<sub>1</sub> potential (see Figure 9) with Task (single-task,

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To sum up, target-related activity revealed sequential effects at the P1 and N1 potentials. The P1 amplitude was larger when the previous interval was short than when it was long over the right site in both the single-task and the dual-task condition. Conversely, the N1 and N2 potentials were attenuated following a previous short interval as compared to a previus long interval only in the single-task, but not in the

dual-task), Previous interval (short, long) and Electrodes site (left, midline, right) as factors. Analysis on the P3<sub>1</sub> amplitude elicited a significant main effect of Task, F(1,15)=25.98, p<.001,  $\eta p^2 =.6$ , indicating that the P3<sub>1</sub> amplitude was smaller in the dual-task condition (0.75  $\mu$ v) than in the single-task condition (2.04  $\mu$ v). The effect of Previous interval was significant, F(1,15)=17.65, p<.001,  $\eta p^2 =.5$ , with larger P3<sub>1</sub> amplitude when the previous interval was short (1.67  $\mu$ v) than long (1.12  $\mu$ v). There was a significant Previous interval x Electrodes site interaction, F(2,30)=3.43, p=.04,  $\eta p^2 =.1$ . Bonferroni corrected ( $\alpha$ =.017) comparisons for this interaction revealed a larger difference between previous short and previous long intervals in the right site than in the other two sites, although the effect reached statistical significance in the three sites [F(1,15)=21.37, p<.001, for the right site, F(1,15)=13.97, p=.001, for the left site, and F(1,15)=14.68, p=.001, for the midline site]. The interactions involving Task condition did not approach significance (all ps>.1). The ANOVA on the P3<sub>1</sub> latency displayed only a marginal significant effect of Task, F(1,15)=3.35, p=.08,  $\eta p^2 =.1$ .

dual-task condition. The amplitude of the P3 potential was larger when the previous interval was short versus long in both task conditions. In contrast, the latency of the P3 was modulated by dual-task demands.

#### 4. Discussion

In the present study, we explored the locus of interference between temporal preparation and working memory tasks by using a dual-task paradigm. Participants simply performed the temporal orienting task in the single-task session and in conjunction with a working memory updating task in the dual-task session. On the basis of prior findings (Capizzi et al., 2012), it was predicted that temporal orienting effects would be only obtained in single-task relative to dual-task conditions, while sequential effects would not be reduced by extra processing demands.

The behavioural results confirmed that the concurrent updating of colour information in working memory impaired participants' ability to voluntarily orient attention in time. The ERP results further corroborated the involvement of controlled processing in temporal orienting of attention by showing that working memory manipulation interfered in a selective way with neural activity linked to validity effects, as indexed by both preparatory CNV and late target-locked N2 and P3 potentials (cf., Nobre, 2001).

With respect to sequential effects, the behavioural data confirmed their resistance to working memory interference, as they were not reduced by concurrent dual-task demands. Interestingly, however, the behavioural dissociation between temporal orienting and sequential effects was supported only partially by the ERP findings. On the one hand, as expected on the basis of Los and Heslenfeld's (2005)

results, there was a significant effect of previous interval on the modulation of the CNV in addition to that of temporal orienting. On the other hand, however, both effects were eliminated by dual-task demands. Target-related activity also revealed some differences (at P1 and N1) as well as some similarities (at N2 and P3) between temporal orienting and sequential effects, which suggested a certain degree of neural overlap in the modulation of target processing at post-perceptual stages.

The interference between temporal orienting of attention and working memory tasks occurred at preparatory stages preceding the onset of the target. The effect of predictive temporal cues on preparatory processes has been reliably associated to the modulation of the amplitude of the CNV. Early cues lead to higher modulation of the CNV (i.e., more negative) before the moment of early target onset as compared to late cues (Los & Heslenfeld, 2005; Miniussi et al., 1999), which shows that preparatory processes are initiated by cue-based information in order to increase response readiness to the upcoming event. It has been recently reported (Zanto et al., 2011) that in contrast to younger adults, older adults revealed neither behavioural benefits from temporal cues nor CNV preparatory activity, suggesting an age-related failure to form temporal expectancies about the subsequent target stimulus. Our data add to these observations, indicating that the concurrent performance of a demanding working memory task may also interfere with the development of anticipatory processes related to temporal orienting, as reflected in the reduction of the CNV amplitude under dual-task relative to single-task conditions.

This finding shares some similarities with a recent EEG experiment (Gontier et al., 2007), which reported that task interference deteriorated performance and decreased amplitudes of CNV and P3 potentials in an explicit timing task requiring participants to discriminate between two durations. The fact that both explicit (Gontier et al., 2007)

and implicit (our experiment; see Coull and Nobre, 2008) timing tasks behaved similarly under augmented cognitive load is in agreement with the idea that the two tasks are supported by a common timing mechanism (see Piras & Coull, 2011, for similar conclusions). Along the same line, Triviño et al. (2011) recently showed that right frontal patients displayed a severe deficit in both time estimation (i.e., overestimation in the range of milliseconds and minutes) and temporal orienting tasks. Future research should test further the role of time perception in temporal preparation tasks, for example, by comparing explicit and implicit timing tasks under similar extra processing demands.

The CNV results replicated only partially the findings by Los and Heslenfeld (2005), as the CNV amplitude was more negative before the moment of early target onset when the previous interval was short rather than long. However, such an effect was reported only when the cue was directing attention to the early moment but not to the late moment. The difference between Los and Heslenfeld's (2005) study and the present findings suggests that there could be also interactive modulation of temporal orienting and sequential effects on the development of temporal preparation. In any case, one would expect that the CNV component associated to sequential effects should be resistant to working memory interference. Surprisingly, however, both temporal orienting and sequential effects on the CNV were eliminated by the working memory task. This result is difficult to explain from Los and colleagues' model (Los, 1996; Los & Heslenfeld, 2005; Los & Van den Heuvel, 2001) stating that sequential effects would reflect the operation of a single automatic mechanism since, if this were the case, there should not be any change of sequential effects over the CNV under dual-task conditions.

Otherwise, it might be possible that the disruption of sequential effects by dualtask interference was due to the fact that such effects, albeit automatic, could be modulated by endogenous factors (e.g., Ruz & Lupiañez, 2002; Fodor, 1983). In the field of temporal preparation, previous studies have already implied that sequential effects may be contingent on a particular attentional set. For example, Los and Van den Heuvel (2001) showed that sequential effects were larger when attention was not explicitly directed to a particular moment in time, that is, on invalid temporal orienting conditions, which suggested that endogenous strategic processes could modulate the magnitude of sequential effects. In a similar vein, it has been reported that sequential effects differed between high trait impulsivity as compared to low trait impulsivity groups (i.e., sequential effects facilitated response inhibition selectively in the low impulsivity group: Correa, Triviño, Pérez-Dueña, Acosta, & Lupiañez, 2010). As impulsivity is an index of attentional control (e.g., Rubia et al., 2003), Correa et al.'s (2010) results also suggest that sequential effects may be influenced by controlled factors. Lastly, sequential effects are larger in the context of a blocked-manipulation of temporal cues as compared to a within-trials design (Correa et al., 2004). Once again, since generating a new temporal expectancy on each trial is more demanding than generating a single temporal expectancy for a whole block, such findings suggest that the expression of sequential effects may be influenced in the context of controlled task sets.

But, if we assume that increased attention control in the dual-task condition might have affected the expression of sequential effects on the CNV potential, then the following question is in order: which are the electrophysiological correlates of sequential effects that contributed to the behavioural dual-task benefit? The analysis of target related activity was particularly important to answer to this question and elucidate

the mechanisms underlying the behavioural dissociation between temporal orienting and sequential effects.

In relation to temporal orienting effects, the results of target-locked ERPs closely paralleled the behavioural data in agreement with prior literature. Consistent with our predictions, we found the typical modulation of the N2 amplitude and P3 latency when participants were only engaged in the single-task condition (Correa et al. 2006; Doherty et al. 2005; Griffin et al. 2002), but not when they performed the working memory task concurrently with the temporal orienting task. Attenuation of the N2 by temporal expectancy has been reported as a common hallmark in temporal orienting research (see Correa et al., 2006, for a review). The functional processes underlying this modulation may be related to the fact that temporally anticipated targets benefit from a more efficient releasing of inhibitory control mechanisms that would be in charge of "prevent responding at inappropriate times" (cf. Correa & Nobre, 2008; see also Davranche et al., 2007). This explanation fits in well with lesion studies proposing a key role of the prefrontal cortex in inhibitory control during temporal preparation (Triviño et al., 2011; 2010; Vallesi et al., 2007; Narayanan et al. 2006). Our data showed that when attention was withdrawn from the temporal orienting task by focusing on concurrent working memory demands, there was no modulation of the N2 amplitude by temporal expectancy, suggesting a failure of temporal preparation to release inhibitory control under dual-task conditions.

The reduction of the P3 latency by temporal expectancy also replicated previous findings (Correa & Nobre, 2008; Doherty et al., 2005; Griffin et al. 2002; Miniussi et al., 1999), indicating that preparing on the basis of predictive temporal information speeds up late potentials related to target onset. Interestingly, the P3 latency modulation was abolished when the working memory task was introduced, indexing a competition

for resources between the two tasks being performed at critical late stages of information processing, which is in line with the idea that temporal orienting mainly modulates post-perceptual components (Nobre, 2001).

Regarding sequential effects, analysis of target-related activity showed an early effect by the duration of the previous trial on the P1 potential. The P1 amplitude increased when the previous interval was short rather than long under both the singletask and the dual-task condition. At first glance, this finding may seem counterintuitive since beneficial consequences of sequential effects on perceptual processing do not fit with the idea of their late motor locus (e.g., Los & Heslenfeld, 2005; Los & Van den Heuvel, 2001). As discussed above, motor-related ERP potentials, like the CNV, are sensitive to the duration of the previous trial. In addition to the CNV, Van der Lubbe et al. (2004) measured the lateralized readiness potential (LRP) as an index of motor preparation. The LRP is a waveform obtained by the difference between the EEG activity recorded above the primary motor areas contra- and ipsi-lateral to the response hand (Coles, 1989). Its amplitude mainly reflects the motor activation of the responding hand. Van der Lubbe et al.'s (2004) reults showed that the LRP amplitude was larger when the previous interval was short as compared to when it was long, suggesting that sequential effects influenced motor processes related to anticipation of the upcoming stimulus. However, since both Los and Heslenfeld's (2005) and Van Der Lubbe at al.'s (2004) studies did not consider target-related activity, the question of whether sequential effects would also involve different types of target modulation at perceptual or central stages of processing remained unanswered.

It is difficult to pinpoint the functional significance of the early modulation by sequential effects shown here as, to the best of our knowledge, it represents a novel finding. Moreover, one might argue that our P1 results were influenced by overlapping

activity from preceding events (see Woldorff, 1993). We were reassured that this was not the case since, on the one hand, a strict baseline correction was applied to the target analysis and, on the other hand, such an early effect should also be observed for temporal orienting, if it had been driven exclusively by activity from previous events.

A possible explanation considers that the P1 modulation could reflect some automatic processing of sensory information triggered by the participant's state of arousal. According to the dual-process model (Vallesi, 2010), repetition of a previous short interval would increase arousal levels as compared to alternation from a previous long interval. Other researchers (e.g., Vogel & Luck, 2000) have found a larger P1 amplitude for high levels versus low levels of arousal, thus supporting our claim The fact that this early effect resisted to dual-task interference could also be taken as further demonstration that the arousal process is a key component of sequential effects. Future studies are needed to corroborate these suggestions and to better clarify the functional meaning of this early P1 effect.

The second ERP deflection that was sensitive to the duration of the previous trial was the N1 potential. Less negativity was elicited by repetition of a previous short interval as compared to alternation from a previous long interval in the single-task condition, while this effect was absent in the dual-task condition. A reduced N1 amplitude for repetition of a short interval could be related to repetition-suppression effects, as neural activation for repeating trials (previous short interval) would be reduced as compared to alternating trials (previous long interval; see Grill-Spector et al., 2006, for a review).

Taken together, the results from the P1 and N1 potentials for sequential effects diverged from the findings on temporal orienting that revealed no modulation of early processing stages by valid trials as compared to invalid trials. In contrast, a similar

pattern for both temporal orienting and sequential effects was observed for the N2 and P3 potentials. The N2 was attenuated by a previous short interval as compared to a previous long interval in the single-task condition, while this modulation was absent in the dual-task condition. This finding could suggest a possible role for inhibition in the expression of sequential effects that would be similar to the functional meaning of the N2 for temporal orienting. According to Los (2010), inhibition could be indeed involved in sequential effects as it would be implemented during intertrial transitions to prevent participants from making a premature response.

However, the high similarity between the modulation of the N2 for both temporal orienting and sequential effects (see Figures 5 and 8) makes us cautious before drawing strong conclusions on the meaning of the N2 for sequential effects. As already pointed out above, it is likely that a controlled task set might have influenced the expression of sequential effects. This explanation is supported by the fact that the modulation of the N2 amplitude was disrupted by dual-task demands in a similar way for both temporal orienting and sequential effects. To control for this possibility, future research should include a neutral condition in which the predictive temporal cue should be replaced by a non-informative warning signal. If the N2 modulation by sequential effects would be replicated outside the context of a temporal orienting (endogenous) procedure, then it could be concluded that it truly reflected activity linked to the duration of the previous interval.

The last similarity between the two temporal preparation effects was observed at the P3 potential. A larger P3 amplitude was found for previous short as compared to previous long intervals, as well as for valid as compared to invalid trials. These findings suggest that, in addition to temporal orienting, sequential effects could also facilitate the synchronization and preparation of fast responses to target onsets. The fact that such a

facilitation by sequential effects survived to dual-task interference supports this argument. However, a puzzling aspect of these data is that the P3 latency was affected by dual-task demands for both temporal orienting and sequential effects, suggesting again a possible influence of controlled factors.

To conclude, the present ERP findings provided novel electrophysiological evidence of interference between performance of a concurrent working memory task and both temporal orienting and sequential effects at late processing stages. This result suggests that although the two temporal effects can be behaviourally dissociated in the context of a dual-task paradigm, they can be influenced in a similar way by simultaneous task demands. Such a pattern of data does not cast doubt on the automaticity of sequential effects, but it opens the possibility that they can be higly sensitive to modulation by controlled factors. The next research step would be to employ a neutral control condition to better isolate the pure modulation of sequential effects on target processing. On the contrary, the present ERP findings strengthened the involvement of controlled processing in the ability to voluntarily orient attention in time, by showing a selective dual-task interference with processing stages typically linked to temporal orienting of attention.

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#### FIGURE CAPTIONS

Figure 1. (A) Schematic representation of events in a trial. The colour of the temporal cue could be red, green or blue. (B) Sketch of the electrodes distribution around the scalp as viewed from above (the top of the figure represents the frontal area).

Figure 2. Mean reaction times (RTs) as a function of Task (single-task, dual-task), Validity (valid, invalid) and Interval (short, long). Vertical bars represent standard error of the mean.

Figure 3. Mean reaction times (RTs) as a function of Task (single-task, dual-task), Previous interval (short, long) and Interval (short, long). Vertical bars represent standard error of the mean.

Figure 4. Grand average waveforms and topographies (with the corresponding electrodes used for the statistical analysis) of the CNV as a function of Cue (early, late) and Previous interval (short, long) for the single-task condition (A) and the dual-task condition (B).

Figure 5. Grand average waveforms for the left, midline and right sites and topographies (with the corresponding electrodes used for the statistical analysis) of the N2 as a function of Validity (valid, invalid) for the single-task condition (A) and the dual-task condition (B).

Figure 6. Grand average waveforms for the left, midline and right sites and topographies (with the corresponding electrodes used for the statistical analysis) of the P3 as a function of Validity (valid, invalid) for the single-task condition (A) and the dual-task condition (B).

Figure 7. Grand average waveforms for the left, midline and right sites and topographies (with the corresponding electrodes used for the statistical analysis) of the P1 and N1 as a function of Previous interval (short, long) for the single-task condition (A) and the dual-task condition (B).

Figure 8. Grand average waveforms for the left, midline and right sites and topographies (with the corresponding electrodes used for the statistical analysis) of the N2 as a function of Previous interval (short, long) for the single-task condition (A) and the dual-task condition (B).

Figure 9. Grand average waveforms for the left, midline and right sites and topographies (with the corresponding electrodes used for the statistical analysis) of the P3 as a function of Previous interval (short, long) for the single-task condition (A) and the dual-task condition (B).

Figure 1.A



Figure 1.B



Figure 2



Figure 3



## A. Single-Task









Left

Valid — Invalid

Midline

Right





A. Single-Task





Valid — Invalid

Midline

Right









Left





- Previous short - Previous long





# A. Single-Task



Left

- Previous long

Midline

Right



## **B. Dual-Task**

Previous short



# A. Single-Task



Left

- Previous long

Midline

Right



## **B. Dual-Task**

Previous short

