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Testing the domain-general nature of monitoring in the spatial and verbal cognitive domains

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ABSTRACT

While it is well-established that monitoring the environment for the occurrence of relevant events represents a key executive function, it is still unclear whether such a function is mediated by domain-general or domain-specific mechanisms. We investigated this issue by combining event-related potentials (ERPs) with a behavioral paradigm in which monitoring processes (non-monitoring vs. monitoring) and cognitive domains (spatial vs. verbal) were orthogonally manipulated in the same group of participants. They had to categorize 3-dimensional visually presented words on the basis of either spatial or verbal rules. In monitoring blocks, they additionally had to check whether the word displayed a specific spatial configuration or whether it contained a certain consonant. The behavioral results showed slower responses for both spatial and verbal monitoring trials compared to non-monitoring trials. The ERP results revealed that monitoring did not interact with domain, thus suggesting the involvement of common underlying mechanisms. Specifically, monitoring acted on low-level perceptual processes (as expressed by an enhanced visual N1 wave and a sustained posterior negativity for monitoring trials) and on higher-level cognitive processes (involving larger positive modulations by monitoring trials over frontal and parietal scalp regions). The source reconstruction analysis of the ERP data confirmed that monitoring was associated with increased activity in visual areas and in right prefrontal and parietal regions (i.e., superior and inferior frontal gyri and posterior parietal cortex), which previous studies have linked to spatial and temporal monitoring. Our findings extend this research by supporting the domain-general nature of monitoring in the spatial and verbal domains.

1. Introduction

Imagine that you get a copy-editor position at a famous publishing house. Your main duty is to check the manuscripts before publication to make sure that the final proofs are devoid of errors. In order to be successful at it, you must have good monitoring skills that allow detection of any typos or misspelled words. Though your job deals with verbal material, it may also happen that you need to monitor the text for words that are spatially misaligned with respect to the page settings. Are these two kinds of verbal and spatial monitoring skills mediated by domain-general or domain-specific mechanisms? The present study addresses this question by combining event-related potentials (ERPs), and source reconstruction of the electrophysiological data, with a behavioral paradigm that orthogonally manipulated monitoring processes (non-monitoring vs. monitoring) and cognitive domains (spatial vs. verbal) in the same group of participants.

The concept of monitoring has been commonly tied to the ability to evaluate goal-directed actions and detect errors, that is, “performance monitoring” (see Ullsperger et al. (2014) for a review). Beyond this, however, monitoring represents a multifaceted executive function strongly required in so many cognitive tasks that it is hard to encompass it in a single operational definition (e.g., Benn et al., 2014; see also Henson et al. (1999), Rugg et al. (1996), Shallice et al. (1994), Vallesi (2012), Vallesi and Shallice (2006)). According to the ROtman-Baycrest Battery for Investigating Attention (ROBBIA) model proposed by Stuss and colleagues (Stuss and Alexander, 2007; Stuss et al., 2005), monitoring can be defined as a “quality control” process, the goal of which is to strategically optimize behavior.

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To give an idea of the different levels at which monitoring may occur (cf. Stuss and Alexander, 2007), in the following we briefly review some of the tasks that require monitoring functions. Monitoring has been shown to play a role in temporal preparation tasks in which the time interval between a warning and target stimulus changes randomly and equiprobably across trials (e.g., Capizzi et al., 2015; Correa and Nobre, 2008; Coull, 2009; Elithorn and Lawrence, 1955; Mento and Tarantino, 2015; Niemi and Näätänen, 1981; Steinborn and Langner, 2011, 2012; Vallesi et al., 2013, 2014). Monitoring is also involved during both visuo-spatial tasks which require tracking regular predictable spatial trajectories compared to random irregular ones (Vallesi and Crescentini, 2011) and during visual search tasks which require detecting the presence of a non-salient target with respect to a target that pops out and attracts attention in a bottom-up fashion (Vallesi, 2014).

Further examples of tasks that may entail monitoring include vigilant attention and prospective memory tasks. In the former, participants must maintain attention over time in order to "monitor their environment for a (more or less frequently occurring) prespecified target" (Langner and Eickhoff, 2013, p. 872). In the latter, participants have to maintain and retrieve from memory a particular intention to perform an action when a given prospective memory cue is encountered (Brandimonte et al., 1996). According to some prospective memory models (e.g., McDaniel and Einstein, 2007), monitoring the environment for detection of the prospective memory cue is one of the main cognitive processes needed to complete the prospective memory task.

The above-mentioned studies suggest that monitoring processes can be divided into two broad classes according to whether they involve a more sustained and continuous type of activity (i.e., constantly tracking the spatial trajectory of a moving car; e.g., Vallesi and Crescentini, 2011) or a more transient event-related activity (i.e., trial-to-trial searching for a specific target embedded among distractors; e.g., Vallesi, 2014). In the present study, we focus on the latter type of monitoring that is framed here as that process in charge of checking each presented stimulus for the occurrence of a specific (spatial or verbal) target. Notably, since our monitoring condition contained a low number of targets, which were discarded from all the analyses, the key comparison was between target-absent trials in monitoring blocks and non-monitoring trials in both the behavioral and ERP data. This allowed us to make sure that any difference found between the monitoring and non-monitoring condition could be confidently attributed to the monitoring requests of the task and not to the detection of the target stimuli per se, which could engender other types of attentional processes outside monitoring (e.g., Hillyard and Anllo-Vento, 1998).

It seems likely that a successful event-related monitoring task should entail the orchestration of more elementary cognitive processes including the participants' ability to selectively discriminate whether each stimulus is a target or not and the ability to maintain the focus of attention on the specific monitoring requirements. In other words, monitoring could be mediated by temporally distinct processing stages, ranging from low-level visual processes to higher-level cognitive ones. However, a full understanding of the exact temporal dynamics underlying monitoring is still missing. This is partly because most of the previous studies on monitoring used methods that lacked temporal resolution, such as functional magnetic resonance imaging (fMRI) or neuropsychological approaches. These studies suggest that monitoring depends upon the functioning of right fronto-parietal areas and, in particular, of the right prefrontal cortex (see Vallesi (2012), for an overview). Critically, the involvement of right-lateralized brain areas seems to be independent of the continuous or transient nature of monitoring processes and the specific task requirements. For instance, a key role of right prefrontal regions has been demonstrated when monitoring for temporal contingencies (Stuss et al., 2005; Vallesi et al., 2009; Vallesi et al., 2007) as well as when monitoring for spatial regularities (Vallesi and Crescentini, 2011). Recent meta-analyses of both vigilant attention and prospective memory neuroimaging studies also showed monitoring in these paradigms to be mainly mediated by right fronto-parietal areas (see Langner and Eickhoff (2013) and Cona et al. (2015), respectively). Defining whether monitoring draws on domain-general right-lateralized neural mechanisms is important in order to gain a better understanding of the hemispheric organization of executive functions in the brain. Indeed, such an issue has been poorly explored as compared to other cognitive functions like, for instance, the processing of language or visuo-spatial attention (left-hemispheric vs. right-hemispheric dominance, respectively).

To date, the conclusion that monitoring is mediated by right domain-general mechanisms is mostly based on the outcomes of multiple independent studies that used different tasks and participants. It is also worth noting that some of the previous monitoring tasks reviewed above implemented material with an already strong right-hemispheric dominance, such as the spatial one, making it difficult to tell whether the right-prefrontal activation observed during monitoring was also driven by the spatial nature of the task. Taking these issues into account, a more direct test of the domain-general basis of monitoring is to implement two monitoring tasks that have a different hemispheric dominance with the same stimulus material and participants within a single experimental session. This kind of design allows the investigation of whether monitoring is a domain-general or a domain-specific function while avoiding any potential material-, sample-, or session-specific effects. Furthermore, it enables the control of inter-individual variability, which is a common constraint when relying on the results drawn from different studies. To our knowledge, such a manipulation is still missing in the literature (but see Benn et al. (2014), for a partial attempt in this direction).

To fill this gap, we devised a within-subject experiment in which participants were administered verbal and spatial monitoring tasks that differed from the non-monitoring ones only in the additional request to evaluate specific verbal or spatial features of the same set of stimuli. The verbal monitoring task consisted of deciding whether a particular consonant belonged to a visually presented word. Such a linguistic process has been shown to require left-lateralized reading abilities as demonstrated by the so-called "word superiority effect", according to which detecting a letter is faster and more accurate if the letter is present in a word than a pseudo-word (e.g., Grainger and Jacobs, 1994; Ziegler et al., 1997; see also Proverbio et al. (2013)). Conversely, in the spatial monitoring task participants had to evaluate a specific visuo-spatial configuration of the words, a process that involves more right-lateralized brain areas (e.g., Boulinguez et al., 2003; Corbetta and Shulman, 2011). Both monitoring tasks were performed in the context of ongoing verbal and spatial tasks, which required access to semantic and visuo-spatial information, respectively.

Building upon the studies reviewed earlier, we hypothesized the involvement of common, right-lateralized, mechanisms comprising visual discrimination and higher-level cognitive processes for both the spatial and verbal types of monitoring. This should be reflected by the finding of similar electrophysiological modulations and right prefrontal source activations for the spatial and verbal monitoring conditions compared to the non-monitoring ones.

2. Method

2.1. Participants

Fifty-four university students took part in the study. They were reimbursed 20 Euros for their participation. All participants were native Italian-speakers, with normal or corrected-to-normal visual acuity and color vision. Written informed consent was obtained from all of them before the experiment, which was approved by the Bioethical Committee of the Azienda Ospedaliera di Padova and was conducted according to the guidelines of the Declaration of Helsinki. All participants reported no history of neurological or psychiatric disorders. Data from two participants were discarded due to poor ERP data quality (<30 artifact-free trials on at least one condition). We also rejected data from two additional participants for low target hit rate ($<40\%$ accuracy in identifying target stimuli), which showed that they were not properly engaged in the monitoring task, and from four additional participants because of low performance in the non-monitoring tasks (accuracy level >3 standard deviations from the group mean on at least one condition). The data from the remaining 46 participants (mean age: 23 years, age range: 21–29 years, 12 men) were used for both behavioral and ERP analyses. All participants were right-handed according to the Edinburgh Handedness Inventory (Oldfield, 1971) with an average score of 80.3 (SD=16.5).

2.2. Apparatus and stimuli

Two Intel Core laptop computers with 17 inch screens were interconnected to run the experiment and to simultaneously record continuous electroencephalographic (EEG) activity. Stimulus presentation and data recording were controlled by E-prime 2 software (Schneider et al., 2002).

A detailed description of the stimuli can be found in our previous studies (Capizzi et al., 2016; Vallesi et al., 2015).

Briefly, a total of 36 words, divided into 18 proper nouns (9 males and 9 females) and 18 common nouns (9 males and 9 females), were selected from Bertinetto et al. (2005; http://linguistica.sns.it/CoLFIS/Home.htm). The proper nouns consisted of personal names (e.g., "sara") and names of states (e.g., "libia", the Italian name for Libya), whereas the common nouns included generic terms denoting non-living things (e.g., "mais", the Italian word for corn) and generic terms referring to people (e.g., "mago", the Italian word for wizard). All the words were created with 3-D effects and 3-D rotations that conferred upon them either a clockwise or counterclockwise rotation (i.e., roll) and an upward or a downward rotation (i.e., pitch). For example, in Fig. 1, the words "taxi" and "mago" show clockwise and upward rotations, whereas the words "libia" and "sara" display counterclockwise and downward rotations. Each word, including the proper nouns, was presented in lowercase letters and was colored either green or brown, though the specific color had no bearing on the task to be completed (cf., Capizzi et al., 2016; Vallesi et al., 2015).

2.3. Procedure and task

The testing session was performed in a quiet and normally illuminated room. Participants were seated at a distance of approximately 60 cm from the computer screen. Prior to the experimental session they were given both written and oral instructions. A trial started with the fixed presentation of a 400 ms blank gray screen, which contained a gray frame lighter than the background color. After that time elapsed, the word stimulus, which was embedded inside the frame, was displayed for 2000 ms. The next trial began after a 1400 ms inter-trial interval, during which the same screen as that used at the beginning of the trial was presented (see Fig. 1).

The experiment included a verbal session and a spatial session, which were administered serially and in a counterbalanced order across participants. Moreover, the monitoring blocks were intermixed (in a counterbalanced order) with other task-switching blocks, the results of which have been reported elsewhere (Capizzi et al., 2016).

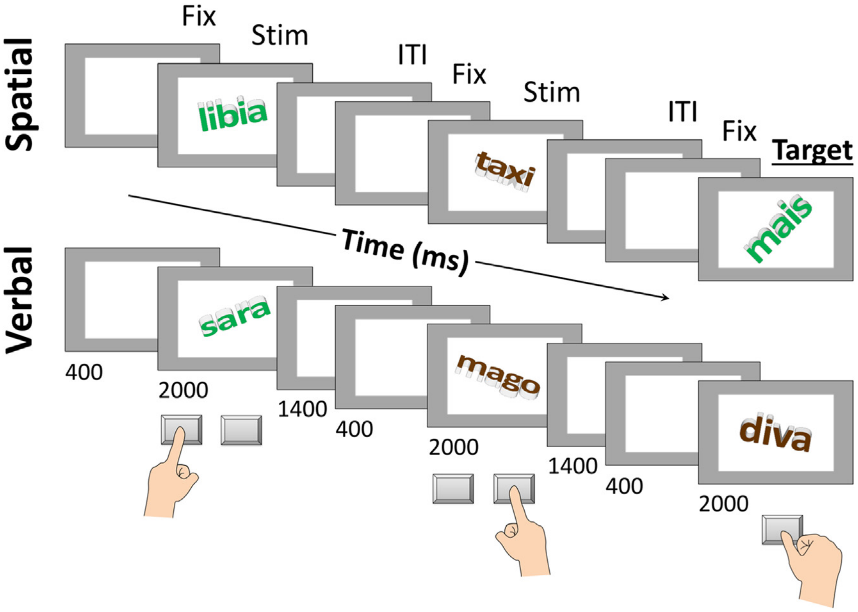

Fig. 1. Trial structure. Schematic representations of events and responses during the spatial and verbal monitoring tasks. "Libia" is the Italian name for "Libya", "mago" is the Italian word for "wizard", "mais" is the Italian word for "corn". Fix stands for fixed, ITI for inter-stimulus interval, Stim for stimulus. On spatial trials, participants had to classify 3-dimensional visually presented words according to either their roll (clockwise or counterclockwise) or pitch (upward or downward) orientation by pressing a specific left-sided or right-sided response key (counterbalanced across participants). Moreover, they were instructed to exclusively press a different response key and not to implement the ongoing spatial task-rules in case the word displayed a 45° rotation. Similarly, on verbal trials, participants were required to classify the words on the basis of their female/male gender status or proper/common name status and to use a different response key when the word contained the consonant "v". (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

In the verbal session, there were two non-monitoring blocks (with gender- and name-type subtasks) and two monitoring blocks (again comprising gender and name subtasks) that were presented according to the following order: non-monitoring subtask 1, monitoring subtask 1, non-monitoring subtask 2 and monitoring subtask 2. The first non-monitoring block always preceded the first monitoring block in order to avoid any potential interference between monitoring instructions and non-monitoring performance (e.g., Cona et al., 2012).

The non-monitoring gender subtask required participants to press the "f" key on the computer keyboard with the index finger of their left hand if the word was a female noun and the "k" key with the index finger of their right hand if the word referred to a male noun. In the non-monitoring name subtask, they had to press the "f" key for a proper noun and the "k" key for a common noun (see Fig. 1 for an illustration of the these stimulus-response arrangements). The assignment of categories to response keys was counterbalanced across participants. In the monitoring blocks, participants had to comply with either the gender or name subtask instructions, as stated above, depending on whether the monitoring block followed the non-monitoring gender or name subtask, respectively. However, participants had also to monitor whether the word contained the consonant "v". If this were the case, they had to refrain from implementing the gender or name subtask rules and instead press the spacebar with the thumb of their right hand (see Fig. 1).

The spatial session was similar to the verbal one and included the same word stimuli. The spatial non-monitoring subtasks comprised a roll-type subtask in which participants had to classify the words according to their roll rotation, and a pitch-type subtask in which they had to respond to their pitch rotation. The keys for responses were "f" or "k" on the computer keyboard (for example, in Fig. 1, participants had to press the "f" key for counterclockwise and downward rotations, whereas the "k" key for clockwise and upward rotations). The assignment of rotation direction to response keys was counterbalanced across participants. In the two monitoring blocks, participants had to press the spacebar with the thumb of their right hand if the word was rotated to 45° in either a clockwise or counterclockwise direction (see Fig. 1) and irrespective of whether they were performing the roll or the pitch subtask. Otherwise, they had to keep following the roll or the pitch subtask instructions. The presentation order of the non-monitoring and monitoring spatial blocks was the same as for the verbal session.

Each experimental block included 32 trials. Of these, only 4 or 5 trials in each monitoring block contained a noun with the consonant "v" or with a rotation of 45°. These words constituted the targets for the verbal and the spatial monitoring tasks, respectively. Of note for the verbal monitoring task, the consonant "v" was never the first letter. This was done to force participants to silently read each presented word before deciding whether or not it was a target. As mentioned in the Introduction, target trials were excluded from all the analyses. To increase the signal-to-noise ratio of the ERP data and considering that we were not interested in the difference per se between the two non-monitoring and the two monitoring subtasks, they were collapsed for both the verbal and the spatial sessions (i.e., the gender and the name subtasks for the verbal session and the roll and the pitch subtasks for the spatial one, respectively). The same was done for the behavioral analyses.

Before the EEG recording, participants practiced both the verbal and spatial tasks. Each practice block comprised 10 trials. Participants received a feedback message (the Italian word for "wrong" displayed in red or the Italian expression for "well done" in blue) for a duration of 1500 ms after their response on each trial. In order to encourage participants to fully process both the verbal and spatial word features, only in the practice session the stimulus was presented until a key-response was detected. However, if participants' accuracy was below 80% after the first block of practice trials, they repeated the practice block until they reached this criterion. Additionally, the stimulus duration was set to 2000 ms, like in the proper experimental sessions, in these further practice blocks. Moreover, the experiment was automatically interrupted by the program if participants' accuracy was still below 80% after 5 consecutive blocks of practice trials. All participants met this criterion and proceeded to the subsequent EEG session. The experiment lasted about 2 h including the EEG set-up.

2.4. *EEG recording*

Participants were seated in front of the computer monitor and were instructed to avoid as much as possible eye blinks and movements during stimulus presentation. The EEG was recorded using BrainAmp amplifiers (Brain Products, Munich, Germany) from 64 Ag/AgCl electrodes that were mounted on an elastic cap (EASYCAP GmbH, Germany) according to the extended 10–20 system. Electrooculographic (EOG) activity was recorded with an electrode placed under the left eye and was also monitored through the scalp electrodes placed in the proximity of both eyes. Impedances for each channel were measured and adjusted until they were kept below 10 kΩ before testing. All electrodes were referenced to FCz during the recording and were re-referenced offline to the average of all of the electrodes. An electrode positioned at AFz served as the ground electrode. Raw data were band-pass filtered between .1 and 100 Hz and digitized at a sampling rate of 500 Hz.

2.5. *Data analysis*

2.5.1. *Behavioral data analysis*

Data from practice trials, errors, trials without responses and trials corresponding to the target in the monitoring blocks were discarded from all subsequent analyses. Anticipated responses (RTs < 150 ms) were absent. Accuracy data (percentage of correct responses) and mean RTs for correct responses were analyzed separately through a repeated-measures ANOVA with Process (non-monitoring, monitoring) and Domain (spatial, verbal) as within-participant factors. Since accuracy data were not normally distributed (Shapiro-Wilk test, all *ps* < .001), the raw values were arcsine-transformed before being entered into the ANOVA. For both RT and accuracy analyses, two-tailed paired *t*-tests were conducted to further investigate significant interactions.

2.5.2. *Electrophysiological data analysis*

Signal pre-processing was performed using BrainVision Analyzer 2.0 (Brain Products GmbH). Raw data were first filtered offline with a 30-Hz low-pass filter (Butterworth zero phase, 48 dB/oct). An ocular correction algorithm based on independent component analysis (ICA) was performed on the continuous data to correct for eye movements and blink activity. Electrodes that were consistently bad according to the epoch rejection criteria described below were replaced through spherical spline interpolation (Perrin et al., 1989). Overall, only two electrodes were interpolated for two different participants (AF8 for one participant and FP2 for another one). The data were then re-referenced to the average of all of the electrodes. They were finally segmented into epochs [−200, 1000 ms] with respect to the word onset. The period of 200 ms preceding the word onset was used to calculate the baseline.

Epochs were discarded if, on any channel, the absolute difference between two consecutive sampling points exceeded 30 μV/ms, if peak-to-peak deflections in a segment exceeded ±80 μV within intervals of 200 ms, if the amplitude exceeded a value of

± 80 μV and if the activity was lower than .1 μV within intervals of 200 ms. Furthermore, each epoch was visually inspected and epochs containing any residual artifact were manually removed. A minimum of 30 trials per condition and participant was chosen as the criterion to ensure a sufficient signal-to-noise ratio. Only trials with correct behavioral responses were analyzed. In addition, practice trials and trials corresponding to the target in the monitoring blocks were excluded from further analyses. Four separate grand average waveforms were constructed relative to our main experimental conditions: spatial non-monitoring, spatial monitoring, verbal non-monitoring and verbal monitoring. The mean number of trials per participant (with ranges in parentheses) contributing to each grand average was: 57 (43 – 64) for spatial non-monitoring, 47 (34 – 54) for spatial monitoring, 57 (44 – 64) for verbal non-monitoring and 49 (30 – 54) for verbal monitoring.

Differences in the ERPs between the experimental conditions were tested for statistical significance through two-tailed non-parametric permutation tests based on the $t_{\max}$ statistic (Blair and Karniski, 1993). The analysis was performed using the Mass Univariate ERP toolbox (Groppe et al., 2011a, 2011b) written in Matlab with a family-wise alpha level of .05. This statistical approach has the advantage of avoiding the a priori definition of time windows and/or scalp regions of interest, since the relevant univariate test comparing participants' ERP amplitudes in different conditions (e.g., a paired t-test contrasting non-monitoring and monitoring trials) is performed for each (channel, time)-pair. In our case, 32,000 total comparisons were performed, corresponding to the combination of the 64 channels used for the EEG recording and the 500 time points included between 0 and 1000 ms post-stimulus (i.e., the length of our segmentation). Each comparison was repeated 2500 times. Therefore, the most extreme t-value (i.e., the $t_{\max}$) in each of the 2500 permutations was used to estimate the $t_{\max}$ distribution of the null hypothesis against which to compare the 32,000 observed t-values. A particular advantage of using the $t_{\max}$ statistic is that it provides a strong control of the family-wise error rate and thus a great degree of certainty that both the sign and the spatio-temporal localization of a given effect are reliable (Groppe et al., 2011a, 2011b).

2.5.3. *ERP-behavior correlation analysis*

Next, we investigated whether the ERP components identified by the electrophysiological analysis were related to the behavioral performance in the monitoring task. To this aim, we carried out a series of correlation analyses between the behavioral and the electrophysiological measures of the monitoring effect, computed as the difference between monitoring and non-monitoring conditions in either the RTs or the ERP amplitudes (i.e., the RT and ERP monitoring effects). In particular, for each of the 5416 (channel, time)-pairs that exhibited a significant ERP monitoring effect in the $t_{\max}$ permutation test (see Section 3.2), we computed a Pearson's correlation between the RT monitoring effect and the ERP monitoring effect and conducted null hypothesis statistical significance testing by using a non-parametric percentile bootstrap test (2000 resamples; two-sided 95% bootstrap-confidence interval (B-$CI_{95\%}$), corresponding to an alpha level of.05), which is more robust against heteroscedasticity compared to traditional t-tests (Pernet et al., 2013). The results were then corrected for multiple comparisons by using an FDR correction (Benjamini and Hochberg, 1995) at a .05 alpha level. Significant correlations that involved less than five consecutive time-points (i.e., significant effects that lasted < 10 ms) were not reported.

2.5.4. *Source estimation*

Finally, to investigate the spatial dynamics of the brain activity underlying monitoring, we performed cortical EEG source imaging on the individual EEG data in the monitoring and non-monitoring conditions by using Brainstorm (Tadel et al., 2011). In particular, we estimated the current strength dynamics of the EEG cortical sources using the depth-weighted minimum norm estimation approach (Baillet, Riera et al., 2001) and a boundary element methods (BEM) conductive head model (Gramfort et al., 2010; Kybic et al., 2005). The solution space was constrained to the cerebral cortex, which was modeled as a three-dimensional grid of 15002 elementary current dipoles oriented normally to the surface of the cortex. The FreeSurfer brain template (FSAverage; see Fischl et al. (1999)) was used as the brain model. A diagonal noise covariance matrix computed for each participant on pre-stimulus time points was used as an estimate of sensors variance.

Participants' EEG time series in the monitoring and non-monitoring conditions were transformed into absolute baseline-normalized (Z-scored) dipole strengths and compared by performing whole-brain two-tailed paired-sample t-tests for each time point. The results were then corrected for multiple comparisons by using an FDR correction (Benjamini and Hochberg, 1995) at a .05 alpha level.

3. Results

3.1. *Behavioral results*

3.1.1. *Accuracy*

Participants showed a reasonable level of accuracy in both the spatial and verbal monitoring tasks (correct responses to the target: 83% and 94%, respectively), which confirms that they were attending to the monitoring instructions. As outlined above, target responses were excluded from the subsequent accuracy analysis.

The ANOVA conducted on the arcsine-transformed accuracy data showed significant main effects of both Process and Domain factors [$F(1,45)=7.81$, $p=.008$, partial $\eta^2=.15$, and $F(1,45)=21.71$, $p<.001$, partial $\eta^2=.33$, respectively], demonstrating that participants were less accurate on monitoring trials compared to non-monitoring trials and on spatial trials compared to verbal trials. The Process by Domain interaction was also significant [$F(1,45)=11.67$, $p=.001$, partial $\eta^2=.21$]. As shown in Fig. 2, this interaction was explained by the fact that the monitoring cost for the spatial domain was significantly higher [$M=.120$, $SD=.187$, $t(45)=4.37$, $p<.001$, Cohen's $d=.644$] than that found for the verbal domain [$M=-.028$, $SD=.183$, $t(45)=-1.05$, $p>.298$, $d=-.155$]. Please note that the ANOVA results were fully confirmed by non-parametric tests on raw accuracy scores (not reported here).

3.1.2. *RTs*

The significant main effect of Process [$F(1,45)=187.20$, $p<.001$, partial $\eta^2=.81$] showed that RTs were longer on monitoring trials compared to non-monitoring trials, further confirming that our

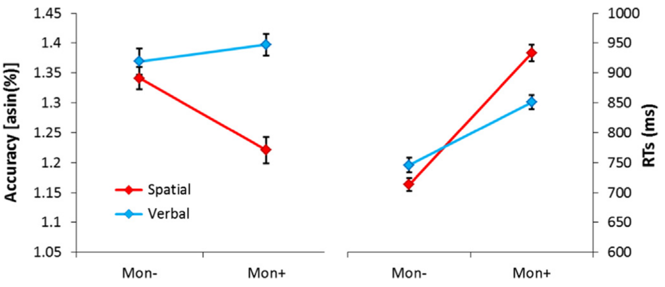

Fig. 2. Behavioral results. Accuracy (arcsin-transformed percentage of correct responses) and mean response times (RTs) in milliseconds (ms) as a function of Domain (spatial, verbal) and Process (non-monitoring, Mon–, monitoring, Mon+). Vertical bars represent the within-subjects standard errors of the mean (Morey, 2008).

manipulation regarding monitoring was effective. The main effect of Domain was not significant [$F(1,45)=2.67$, $p=.109$, partial $\eta^2=.06$]. There was instead a significant Process by Domain interaction [$F(1,45)=43.79$, $p<.001$, partial $\eta^2=.49$]. As shown in Fig. 2, this interaction was explained by the fact that the monitoring cost for the spatial domain was significantly higher [$M=220$ ms, $SD=104$ ms, $t(45)=14.33$, $p<.001$, $d=2.11$] than that found for the verbal domain [$M=105$ ms, $SD=95$ ms, $t(45)=7.50$, $p<.001$, $d=1.11$], although it reached statistical significance in both domains.

While the behavioral monitoring effect was modulated by the cognitive domain, we performed additional analyses to further investigate the hypothesis of domain-general monitoring mechanisms. Assuming that there are common underlying mechanisms for spatial and verbal monitoring costs, there should also be shared variance between the monitoring costs in the two domains. This prediction was confirmed by a robust correlation analysis, in which the statistical significance of the correlation between the two monitoring costs was assessed by using a non-parametric percentile bootstrap test (Pernet et al., 2013; see Section 2.5.3). This analysis showed a significant correlation between the spatial and verbal monitoring costs (Pearson's $r=.620$, $B\text{-}CI_{95\%}=.447\text{–}.779$, proportion of shared variance=38.46%), thus supporting the idea of domain-general monitoring mechanisms.

3.2. Electrophysiological results

We first tested for the statistical significance of the Process by Domain interaction by carrying out a $t_{\max}$ permutation test contrasting the monitoring − non-monitoring difference waves (i.e., the ERP monitoring effect) in the spatial and verbal cognitive domains. This analysis revealed no significant differences between the two conditions (all $ps \geq .08$; critical t value$=\pm 4.86$, $df=45$, test-wise α level$=.000014$), thus showing that the ERP monitoring effect was not modulated by the cognitive domain of the task to be monitored.[1] Consequently, we then assessed the statistical significance of the Process and Domain main effects. To this end, we carried out a series of $t_{\max}$ permutation tests contrasting, respectively, the ERPs for the monitoring and non-monitoring conditions averaged across the two domains and the ERPs for the spatial and verbal domains averaged across the two process conditions. For the sake of brevity, we report the analysis on the Domain main effect in the Supplementary materials as it is beyond the scope of the present study.

The mass univariate analysis of the Process main effect revealed a number of significant differences (critical t value$=\pm 4.83$, $df=45$, test-wise $\alpha=.000016$) between monitoring and non-monitoring ERPs. Based on their distinct spatio-temporal characteristics, these significant condition-dependent ERP differences were grouped into two negative and two positive ERP monitoring effects, as detailed in what follows (see Fig. 3). We shall not describe significant differences that involve less than five consecutive time-points (i.e., significant effects lasting <10 ms), which would be too quick to tap long-lasting monitoring processes and possibly due to random noise.

The first significant ERP effect differentiating between monitoring and non-monitoring conditions concerns an early negative ERP component distributed over posterior scalp sites. In particular, ERP amplitudes were significantly more negative for the monitoring as compared to the non-monitoring condition in the 130–202 ms time window over bilateral occipito-parietal electrodes (P4–8, PO4, PO7–8, O1–2, Oz), with a slight right lateralization (see Figs. 3 and 4A). Fig. 4D shows the corresponding topographic map for this result. Based on its spatio-temporal pattern, this ERP monitoring effect can be described as a stronger visual N1 component for monitoring trials. In addition, the $t_{\max}$ permutation test revealed a further effect with a similar negative polarity that relates to a sustained, negative-going ERP component distributed over posterior electrodes and present during a long-lasting, continuous time window spanning from 230 ms to the end of the epoch (see Fig. 3). In particular, significantly more negative ERP amplitudes for monitoring as compared to non-monitoring trials were found in the 230–460 ms time window over bilateral parieto-occipital (P5–6, PO3–4, POz) and occipito-temporal electrodes (P7–8, O1–2, Oz, TP9–10) (see Fig. 4E), which also showed an ERP monitoring effect in a time window extending from 474 ms to the end of the epoch (see Fig. 4F).

Turning to the positive ERP monitoring effects, the $t_{\max}$ permutation test showed a first significant modulation in the 242–462 ms time window (see Fig. 3). This ERP effect was characterized by significantly more positive ERP amplitudes for the monitoring as compared to the non-monitoring condition over bilateral frontal and central electrodes (AF3, F1,3–5, FC1–5, FCz, C1–4, Cz, CP1) with a slight left scalp lateralization (see Figs. 4B and E). The $t_{\max}$ permutation test also revealed a further late sustained, positive-going ERP component in a time window spanning from 616 ms to the end of the epoch (see Fig. 3). This effect was characterized by more positive ERP amplitudes for the monitoring as compared to the non-monitoring condition. Such a modulation was widely distributed over bilateral fronto-centro-parietal electrodes (F1, F2, F4, FC2, FC4, C2, C4, C6, CP1–6, CPz, P1–2, Pz), with a clear right lateralization involving frontal and central electrodes (see Figs. 4C and F).

3.3. ERP-behavior correlation results

The ERP-behavior correlation analysis showed significant negative correlations for bilateral occipital electrodes (O1–2, Oz, PO7–8) in the 542–608 ms time window. Specifically, in this spatio-temporal window there were 115 significant correlations that survived the FDR correction (median $r=-.481$, range $=-.538$ to $-.438$; median lower bound of the $B\text{-}CI_{95\%}=-.632$, range $=-.677$ to $-.594$; median upper bound of the $B\text{-}CI_{95\%}=-.312$, range $=-.403$ to $-.235$; all $p<.002$). This result shows that participants who had larger monitoring vs. non-monitoring differences in this occipital ERP component (i.e., those who showed more negative ERP amplitudes in the monitoring as compared to the non-monitoring condition) exhibited a smaller RT monitoring effect, that is, were more efficient (i.e., quicker) in classifying the words according to the verbal or spatial rules while performing the additional monitoring tasks.

3.4. Source estimation results

The mass univariate analysis contrasting the source activation z-maps for the monitoring and non-monitoring conditions revealed several significant differences that survived the FDR correction for multiple comparisons (in this case, ≈ 9 millions). These significant condition-dependent differences in source activity were grouped as detailed in what follows on the basis of their distinct spatio-temporal characteristics and in relation to the results of the mass univariate analysis of the ERP data. Please note that we do not describe significant differences that involve less than five consecutive time-points (i.e., significant effects that last

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[1] To further verify the non-significant Process by Domain interaction, we performed additional $t_{\max}$ permutation tests contrasting the spatial and verbal domains in both the non-monitoring and monitoring conditions. Importantly, we also contrasted monitoring and non-monitoring conditions separately for both domains and performed an intersection analysis, which provided further support for the domain-general nature of monitoring. The results of these analyses are presented in the Supplementary materials.

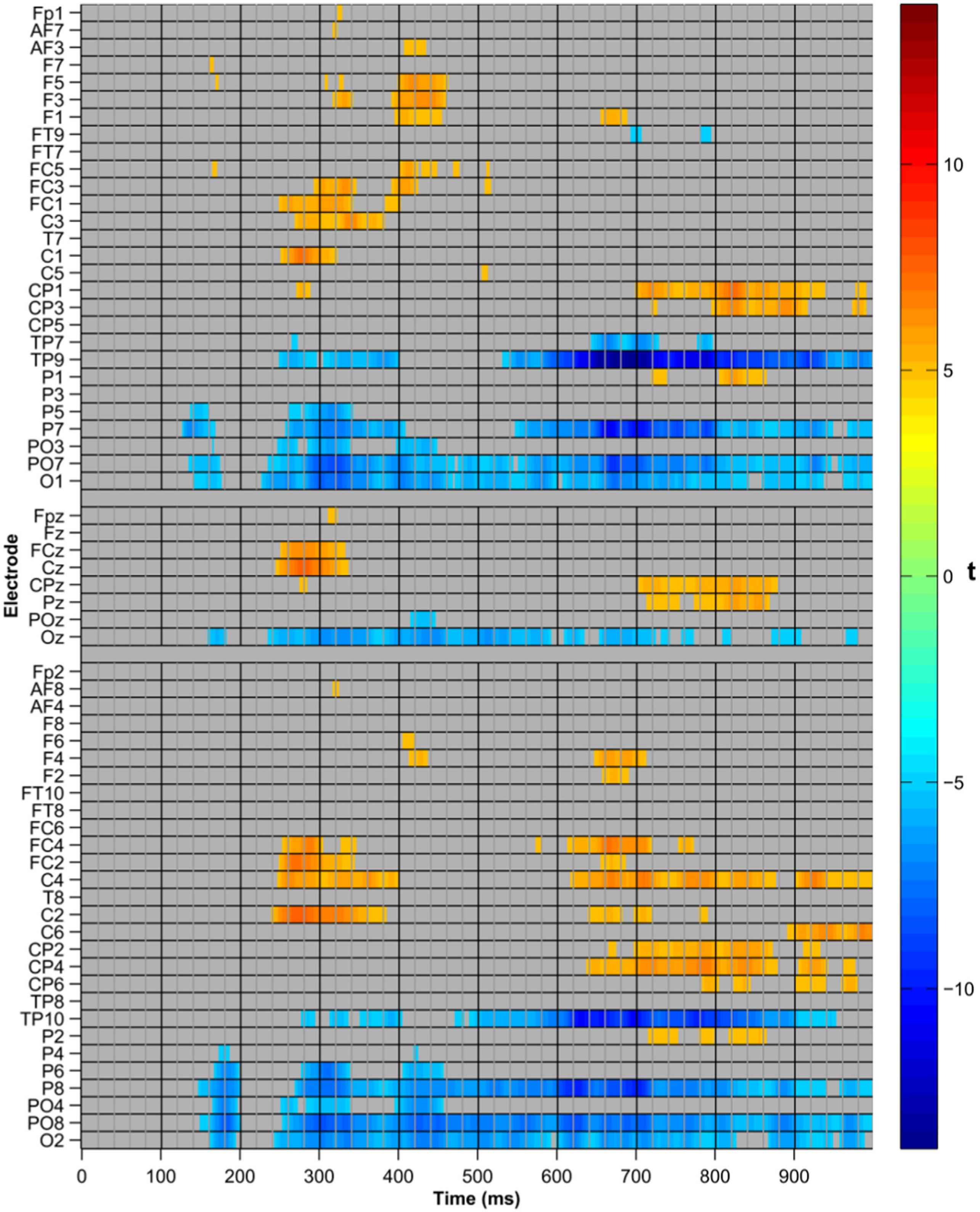

Fig. 3. Electrophysiological results, main effect of Process factor. Raster diagram showing significant differences between ERPs elicited by monitoring and non-monitoring trials (i.e., the ERP monitoring effect) according to the t_{max} permutation test. Rectangles in warm and cold colors indicate electrodes/time points in which the ERPs to monitoring trials are more positive and negative, respectively, as compared to those in non-monitoring trials. The colorbar on the right indicates t values. Gray rectangles indicate electrodes/time points at which no significant differences were found. Note that the electrodes are organized along the y-axis somewhat topographically (Groppe et al., 2011a, 2011b). Electrodes on the left and right sides of the head are grouped on the top and bottom part of the diagram, respectively, while midline electrodes are shown in the middle. Within those three groupings, the y-axis top-to-bottom corresponds to scalp anterior-to-posterior. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

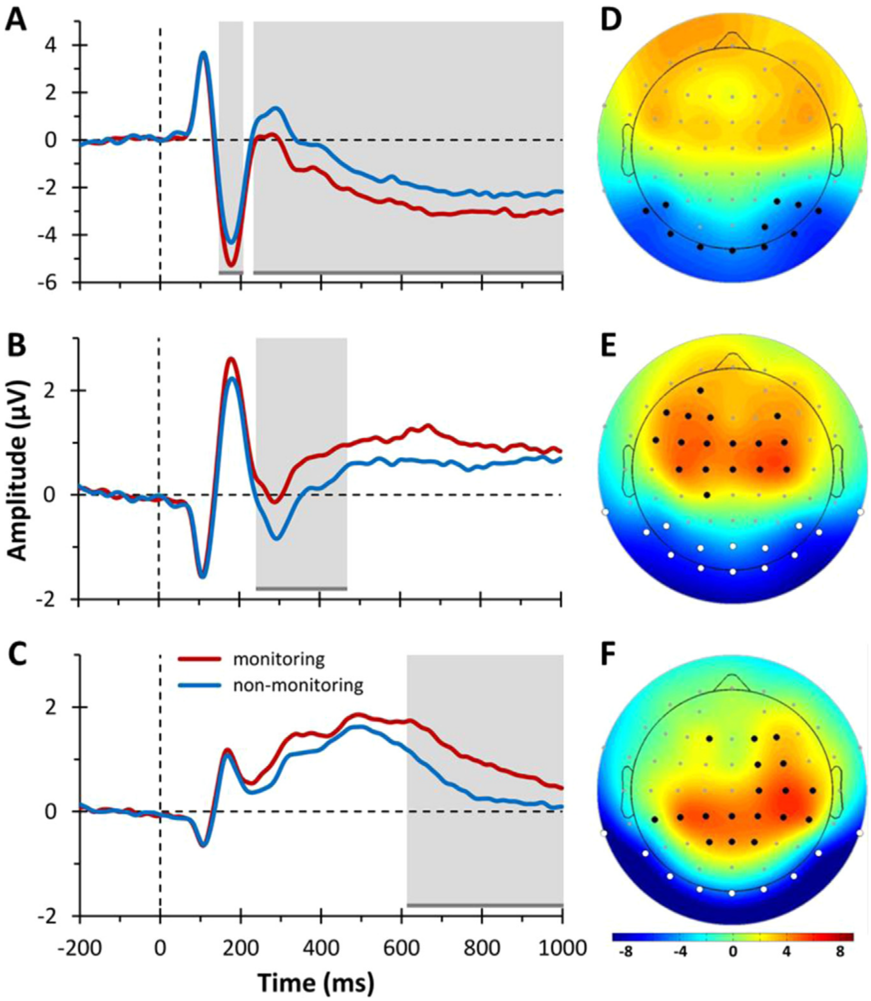

Fig. 4. Electrophysiological results, ERP monitoring effects. The trace plots on the left depict the grand average ERPs elicited by monitoring and non-monitoring trials averaged across the electrodes showing significant ERP monitoring effects (indicated as black circles in the topoplots on the right). The topoplots on the right show the *t* values for the significant ERP monitoring effects averaged in the time window in which these effects were significant (indicated by the gray shaded region in the trace plots). The colorbar indicates t values. (A, D) The trace plot in (A) shows the ERPs for both the early and the sustained negative ERP monitoring effects; the topoplot in (D) corresponds to the early effect. (B, E) The trace plot in (B) shows the ERPs for the first positive ERP monitoring effects distributed over fronto-central electrodes (E). (C, F) The trace plot in (C) shows the ERPs for the late positive ERP monitoring effects distributed over bilateral parietal and right fronto-central electrodes (F). White circles in E and F indicate electrodes showing a significant sustained negative ERP monitoring effect. See Section 3.2 for details.

<10 ms) and less than five contiguous cortical vertices in the distributed sources model.

The source analysis showed that the monitoring condition led to significantly stronger activations in the right ventral occipito-temporal cortex, including the fusiform gyrus (FuG) and the collateral sulcus (CollS), in the 180–220 ms time window.[2] Based on its spatio-temporal characteristics, this activation seems to involve the cortical sources of the N1 ERP monitoring effect we found in the mass univariate analysis of electrophysiological data (Figs. 5 and 6).

The analysis of the monitoring effect on source activation also revealed the putative cortical sources of the sustained negative ERP monitoring effect observed over posterior scalp regions. In fact, significantly stronger activations for the monitoring as compared to the non-monitoring condition were found in different time windows starting at 220 ms and spanning the entire epoch. A first time window (220–404 ms) involved bilateral ventromedial occipito-temporal cortices, including the CollS, lingual gyrus (LingG) and other extrastriate regions, also comprising bilateral lateral temporal cortices in the 300–320 ms time window (Figs. 5 and 6). Furthermore, significant monitoring effects were found in a later, sustained time window spanning from 440 ms to the end of the epoch and involving vast bilateral regions of the ventral occipital cortex and the temporal lobes (see Supplementary Fig. S5).

Turning to the putative sources of the positive ERP monitoring effects, the analysis revealed a number of significant monitoring effects on source activity in right parietal and prefrontal regions in time windows corresponding to the first positive ERP monitoring effect. In particular, significant effects were found in the right posterior parietal cortex (PPC) including the horizontal portion of the intraparietal sulcus (hIPS) and the medial and lateral superior parietal lobule (SPL) at 250–360 ms (Figs. 5 and 6). This temporal

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[2] The analysis also revealed a set of significant differences between the source activity for the monitoring and non-monitoring conditions in some earlier, contiguous time windows that preceded the first significant ERP effect reported in the electrophysiological data analysis. During the 92–114 ms time-window, significant monitoring effects were found in right lateral and medial regions of the posterior parietal cortex (PPC), including the horizontal portion of the intraparietal sulcus (hIPS) and the precuneus (preCUN), and in bilateral ventromedial and left ventrolateral regions of the prefrontal cortex, including the anterior cingulate cortex (ACC) and the orbital gyrus (OG). Following this first activation (116–166 ms), significant differences between the two monitoring conditions were found in the right preCUN.

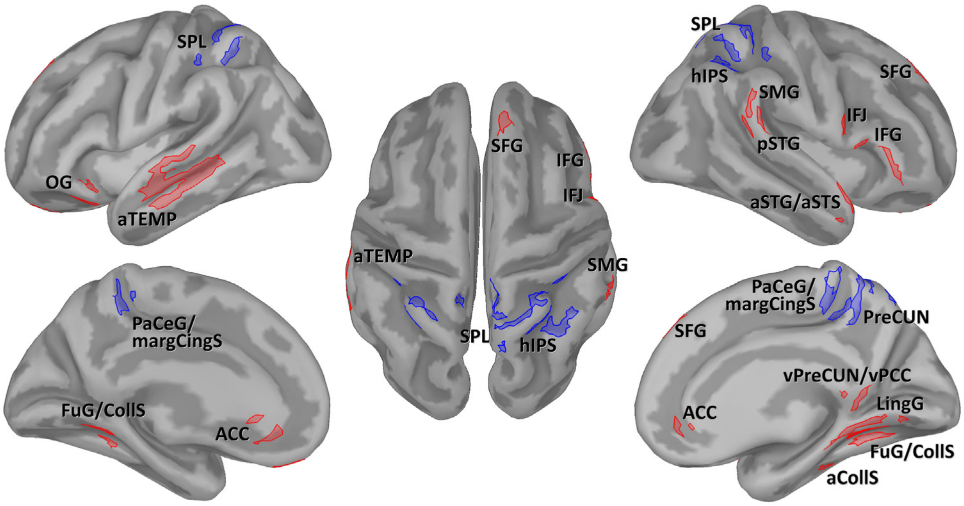

Fig. 5. Source estimation results. The figure shows the cortical sources identified by the FDR-corrected mass univariate analysis (see Sections 2.5.4 and 3.4) as showing a significant monitoring effect (blue: monitoring < non-monitoring; red: monitoring > non-monitoring). Spatially contiguous cortical sources showing a reliable monitoring effect were grouped in cortical regions based on anatomical criteria. For illustrative purpose, the vast bilateral regions of the ventral occipital cortex and the temporal lobes related to the sustained negative ERP monitoring effect are not shown here (see Supplementary Fig. S5). See Section 3.4 for explanation of abbreviations. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

window corresponds to the negative-going peak of the ERP component found in the ERP analysis (see Fig. 4B). Moreover, as compared to the non-monitoring condition, the monitoring condition led to significantly stronger activations in the right superior frontal gyrus (SFG) at 266–280 ms, as well as in the right ventrolateral prefrontal cortex including the right inferior frontal gyrus (IFG) in two time windows (306–318 ms and 404–424 ms) that correspond to the positive-going part of the same ERP component (see Fig. 4B) and in the right inferior frontal junction (IFJ) at 302–320 ms. A further monitoring effect was found at 412–456 ms in the medial SPL/precuneus (preCUN) region of both hemispheres, with a slight right lateralization (Figs. 5 and 6).

Finally, the analysis of the monitoring effects on source activity revealed the putative cortical sources of the later, more sustained positive ERP monitoring effect. Importantly, significantly stronger activations for the monitoring as compared to the non-monitoring condition were found in the right supramarginal gyrus (SMG) in several time windows (536–570 ms, 594–632 ms, 644–742 ms, 756–776 ms, 788–812 ms, and 902–912 ms) and, again, in the right IFG at 610–624 ms (Figs. 5 and 6). Moreover, significant monitoring effects were found in the left orbital gyrus (OG) at 726–748 ms and 832–850 ms.

In addition to the source analysis on the non-monitoring and monitoring conditions averaged across the two domains, we also tested for significant monitoring effects on source activity separately for the spatial and verbal domains. We then performed an intersection analysis to identify the cortical sources for which the monitoring effects were significant for both domains. This analysis confirmed the main brain source activations described above. Indeed, with the exception of the effects concerning the right SFG at 266–280 ms and the right IFG at 306–318 ms, all the other reported effects were replicated. However, the results of this new analysis did not survive correction for multiple comparisons, probably due to a reduction of the signal-to-noise ratio in the estimated source activity signals.

4. Discussion

A great deal of studies have investigated the neural underpinnings of monitoring across different cognitive domains (see Vallesi (2012), for an overview) but, to our knowledge, no one has adopted a within-subject approach manipulating both the process (non-monitoring vs. monitoring) and domain (spatial vs. verbal) in a full experimental design. By combining ERPs with such a paradigm, we aimed at directly assessing the cognitive processes and the neural mechanisms at the basis of different types of monitoring. Our working hypothesis was that monitoring is mediated by domain-general mechanisms that operate independently of the specific and lateralized cognitive domain of the tasks to be performed.

The behavioral data supported this prediction only in part as evidenced by the finding of a significant Process by Domain interaction. This interaction showed that participants were slower when engaged in the spatial monitoring tasks compared to the verbal tasks. The relative easiness of the verbal monitoring condition with respect to the spatial one was also reflected in the accuracy data, which showed a significant monitoring cost for the spatial tasks but not for the verbal tasks. Overall, the behavioral results thus suggest that participants found it easier to monitor for the presence of a specific consonant within the words than monitor for their spatial configuration. Two complementary explanations can be put forward to account for this finding. The first one considers that words represent highly familiar stimuli and that skilled readers are usually very fast and accurate at recognizing them. The automaticity of the word-reading system (e.g., Stroop, 1935) might thus justify the pattern of data found in the context of the verbal monitoring tasks. Automatic word reading, however, could have also been involved in spatial monitoring trials even if it was not necessary to accomplish the spatial tasks.

The second explanation takes into account that the degree of similarity between the task rules of monitoring and non-monitoring conditions differed across the spatial and verbal domains. Namely, whereas in the spatial domain non-monitoring and monitoring tasks both required participants to discriminate some visuo-spatial features of the words, the verbal monitoring requirements stressed a different linguistic processing level (i.e., letter recognition) than that needed in the verbal non-monitoring tasks (i.e., grammatical or semantic processing). Accordingly, it is reasonable to assume that the degree of interference between our non-monitoring and monitoring tasks was higher for the spatial domain than for the verbal domain, thereby explaining the finding of a greater spatial monitoring cost. Despite such differences

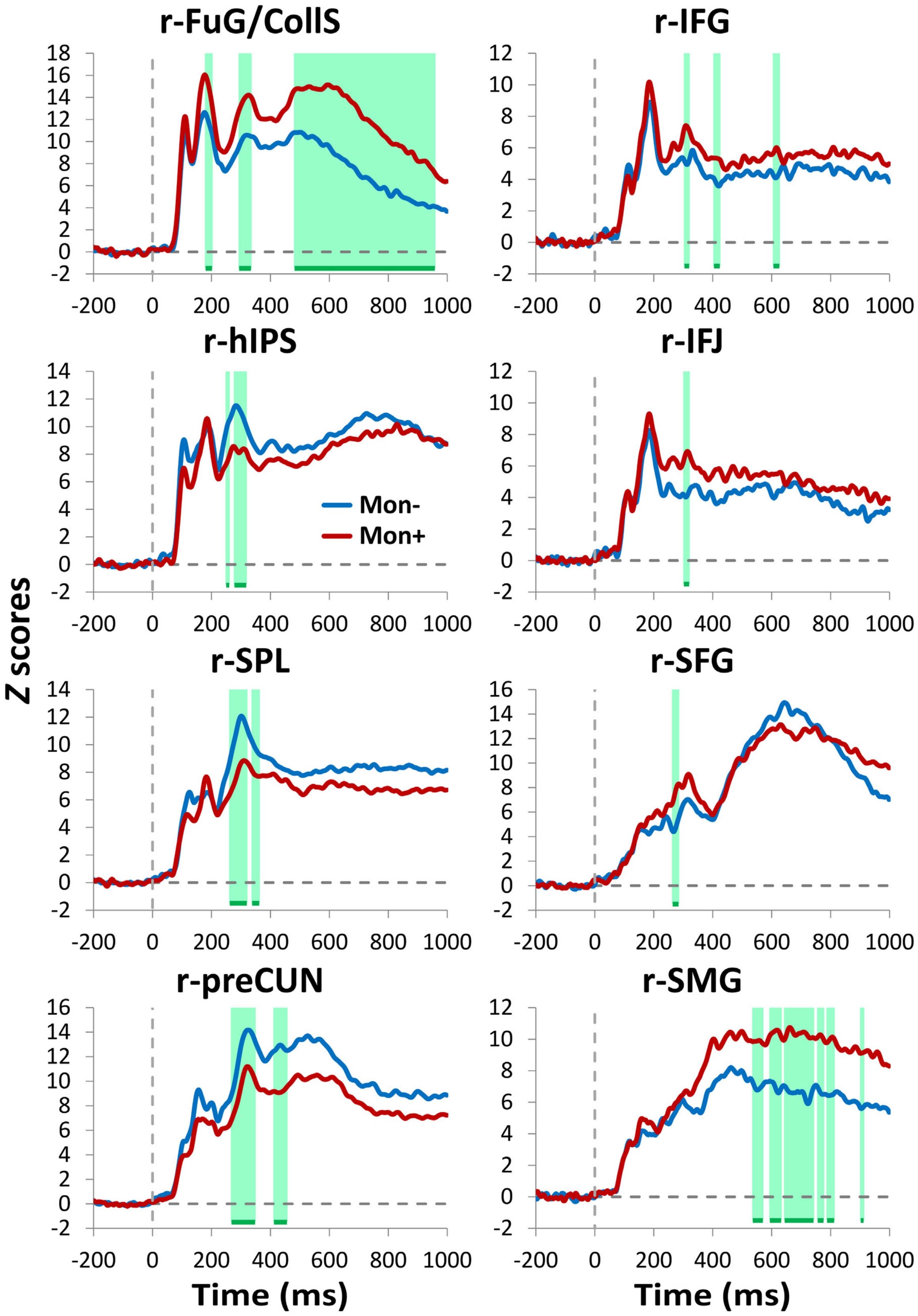

Fig. 6. Estimated cortical sources time courses. The trace plots show the time courses of baseline-normalized activations (*Z* scores) for some relevant clusters of cortical sources showing a significant difference between monitoring (in red) and non-monitoring (in blue) conditions (see Fig. 5). The green shaded region in each plot represents the time window in which these effects were significant. All the clusters shown here were located in the right hemisphere (r-). FuG/CollS: fusiform gyrus and collateral sulcus; hIPS: horizontal part of the intraparietal sulcus; SPL: superior parietal lobule; preCUN, precuneus; IFG: inferior frontal gyrus; IFJ: inferior frontal junction; SFG: superior frontal gyrus; SMG: supramarginal gyrus. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

between the two domains, it is important to consider here that a significant monitoring cost was observed for both the spatial and verbal tasks, which demonstrates that our experimental manipulation had an influence on both cognitive domains. Moreover, the finding of a significant positive correlation between the spatial and verbal monitoring costs lends further support to the idea that the two indices may share common underlying processes.

From a cognitive point of view, the RT monitoring cost obtained in our spatial and verbal tasks could be attributed to the cognitive load imposed by the additional monitoring instructions on the non-monitoring tasks. That is, for each monitoring trial participants had to evaluate whether the word was a target or not (i.e., monitor for target occurrence) and to act differently on the basis of the positive or negative answer to their monitoring check (i.e., refrain from implementing the standard categorization rules vs. apply the ongoing rules, respectively). By contrast, for the non-monitoring trials, they had to perform the spatial and verbal ongoing tasks only. Hence, the lengthening of RTs in the monitoring condition might be due to the processes checking for the presence of the target that would operate (totally or partially) in parallel to those needed to accomplish the ongoing task. This logic bears some similarity with dual-task paradigms in which performance on a primary task is hampered by the addition of a secondary task that competes for common processing resources with the primary task (Pashler, 1994). Strictly speaking, however, it is also worth noting that our paradigm differed from classic dual-task designs because target trials were very infrequent, thus not making the “secondary task” as continuous as the “primary task.” In this regard, also note that it is unlikely that the RT increase observed here for the monitoring trials was entirely due to general task difficulty since target trials, the only ones calling for a shift in the stimulus-response mapping, were discarded from all the analyses and the key comparison considered trials in which the overall task structure was completely matched (i.e., monitoring target-absent trials vs. non-monitoring trials).

The ERP data allowed us to further elucidate the nature of the monitoring cost observed in the present study by shedding light on the specific sub-process stages at which monitoring occurred. As it will be shown below, each of these sub-processes was characterized by distinct time courses, polarities and brain localizations that, collectively, support the idea that monitoring is mediated by both low-level perceptual processes and higher-level cognitive processes. Unlike the behavioral data, the ERP analysis showed that the monitoring effect (i.e., monitoring – non-monitoring difference waves) was not modulated by the specific cognitive domain of the task to be performed. Accordingly, all the ERP analyses reported here focused on the Process main effect (monitoring vs. non-monitoring) averaged across the spatial and verbal domains (but see the Supplementary materials for the analyses conducted separately on the two domains).

From a temporal point of view, monitoring-related modulations occurred early in the processing stream, as evidenced by the modulation of a negative voltage deflection developing within the N1 range and distributed over posterior electrodes. Such a modulation took the form of an enhanced N1 wave for monitoring trials as compared to non-monitoring trials. A large amount of studies have demonstrated that the visual N1 component is sensitive to selective attention (e.g., Luck et al., 1990) and, in particular, to discriminative processes (e.g., Hopf et al., 2002; Ritter et al., 1983; Vogel and Luck, 2000). Our results showing a larger N1 wave for monitoring trials could thus be interpreted within this theoretical framework by assuming an increased need to monitor trials to visually discriminate the words in order to successfully detect the target. Alternative explanations related to differences in the physical attributes of the stimuli or to different levels of arousal between monitoring and non-monitoring trials are quite unlikely given that the stimuli were the same in both conditions and that increased arousal has been shown to modulate the P1 but not the N1 wave (Vogel and Luck, 2000). The neural generator sources for the N1 monitoring effect, which included brain areas localized to the right ventral occipito-temporal cortex, are also in line with prior N1 source localization studies (e.g., Gomez Gonzalez et al., 1994; Herrmann and Knight, 2001), thus confirming an early modulation of sensory processing by monitoring.

In support of the idea that monitoring demands boosted visual processing, the ERP data further showed that monitoring elicited more negative ERP amplitudes over parieto-occipital and occipito-temporal electrodes that propagated across the entire epoch. Once again, the cortical source reconstruction of this sustained ERP monitoring effect identified an increased cortical activity for the monitoring as compared to the non-monitoring condition in bilateral ventromedial occipito-temporal cortices. These brain areas encompass a number of extrastriate regions that have been reported in the visual processing of several stimuli including words and letter strings (e.g., Allison et al., 1994; Nobre et al., 1994). Yet, activation of visual processing areas during monitoring goal progress in both numerical and visuo-spatial modalities has been shown in a recent fMRI study (Benn et al., 2014).

As a final indication that monitoring acted on visual processing stages, correlational analyses yielded significant negative correlations between the behavioral monitoring cost and the ERP monitoring effect found over bilateral occipital electrodes (O1–2, Oz, PO7–8). Specifically, around 500 ms after stimulus onset (542–608 ms) those participants who had more negative ERP amplitudes in the monitoring as compared to the non-monitoring condition also exhibited a smaller RT monitoring cost. This finding therefore suggests that a more in-depth visual processing of the word stimuli before the response was delivered was associated with better monitoring performance.

Taking all of the above evidence into account, it is reasonable to suggest that in the present context visual areas were set to differentially process stimuli that had to be monitored. A plausible explanation for this pattern of data is that top-down attentional control, usually sub-served by fronto-parietal regions, modulated activity in visual areas in order to deal with the monitoring demands of the task to be performed. In this vein, it should be considered here that a contribution of fronto-parietal areas to the completion of the monitoring tasks was supported, indirectly, by the electrophysiological data and, more directly, by the source reconstruction analysis of the EEG data.

Regarding the former point, the EEG results showed that relative to the non-monitoring condition, the monitoring one engendered more positive modulations over frontal and centro-parietal scalp regions (see Fig. 4). In particular, the $t_{\max}$ permutation tests revealed two main voltage deflections that overlapped the above-mentioned posterior activity and developed during different time frames. The first modulation occurred within the 242–462 ms time window over frontal and central electrodes. As portrayed in Fig. 4B, during this latency, the waveforms elicited by monitoring trials were characterized by more positive ERP amplitudes as compared to the waveforms associated with non-monitoring trials. The second positive-going modulation, which started at 616 ms and lasted until the end of the epoch, was indexed by larger ERP amplitudes for monitoring as compared to non-monitoring trials (see Fig. 4C). This sustained component was widely distributed over right fronto-centro-parietal electrodes (see Fig. 4F).

We assume that the observed fronto-parietal modulations associated with monitoring probably reflect the operation of specific monitoring sub-processes. In particular, the presence of a more positive scalp frontal activity on monitoring trials could index the recruitment of the greater attentional resources needed to maintain the focus of attention on the monitoring requirements and to deal with the two tasks simultaneously, whereas the later modulation, which propagated over more centro-parietal electrodes, could be related to a last target checking before the response was released. This proposal is in line with prospective memory studies (e.g., Cona et al., 2012, 2014), which also usually report an increased positivity for the prospective memory condition as compared to the ongoing task that is mainly expressed over both frontal and parietal regions. Such modulations have been interpreted as targeting the operation of "strategic monitoring", a similar construct to the one tapped in the present context. This explanation, however, should be tested in future studies that directly manipulate these two putative monitoring sub-processes.

The claim that the first ERP positive component (242–462 ms) observed here could index the recruitment of attentional resources to fulfill the monitoring task is also supported by the source reconstruction analysis. Notwithstanding the risk of inverse inference and the imprecision of ERP source analysis, increased activity for the monitoring condition was found in areas that have been shown to be involved in top-down attentional processes and in maintaining attention over time such as the right PPC (e.g., Blankenburg et al., 2010; Moos et al., 2012; see also Corbetta and Shulman (2002), Ruff (2013), Langner and Eickhoff (2013)). Moreover, a recent meta-analysis of fMRI prospective memory studies (Cona et al., 2015) found the superior parietal lobule and the precuneus to be activated in maintaining intentions during the prospective task. Finally, we observed that relative to the non-monitoring condition, the monitoring one was associated with stronger activation in the right SFG and in ventrolateral prefrontal cortex, including the IFG. These findings replicate previous fMRI monitoring studies showing that the right lateral prefrontal cortex is maximally activated when participants have to monitor for the occurrence of a critical event through the passage of time (e.g., Coull et al., 2000; Vallesi et al., 2007). Thus, our data extend such studies in revealing the involvement of these right frontal areas in tasks that require monitoring in the context of spatial and verbal ongoing tasks.

Regarding the second positive modulation associated with monitoring (from 616 ms to the end of the epoch), which could be related to target checking, the source reconstruction analysis revealed again the involvement of the right IFG and the right SMG. Interestingly, these areas have been shown to have a high probability of connection (e.g., Rushworth et al., 2006) and recent evidence points to the relation between diffusion metrics of the white matter underlying the right SMG and executive control abilities (Yin et al., 2012). More importantly, both SMG and IFG in the right hemisphere were also found to be activated in monitoring regular spatial trajectories (Vallesi and Crescentini, 2011).

A critical aspect of our source reconstruction results is that the participation of fronto-parietal areas appears to be more intermittent as compared to the sustained activity found over posterior regions. This might be due to the nature of our monitoring tasks that, as outlined in the Introduction, required a more transient event-related activity compared to other types of sustained monitoring tasks. It is then likely that in the present context fronto-parietal areas intervened only in a phasic fashion to elaborate the evidence continuously accumulated by the posterior regions to detect the target. Alternatively, it should be considered here that the lack of long-lasting fronto-parietal activations in the source reconstruction analysis could in principle be entirely accounted for by the low signal-to-noise ratio that characterizes the estimated source activity signals. Despite this point, however, it is important to highlight that our study confirmed, even if indirectly through source analysis, a predominantly right hemispheric lateralization for monitoring functions. Moreover, it showed the involvement of visual posterior areas in event-based monitoring processes.

To sum up, coupled with previous reports that have investigated the hemispheric organization of executive functions in the brain (e.g., Ambrosini and Vallesi, 2016; Babcock and Vallesi, 2015; Capizzi et al., 2016; Kim et al., 2012; Stuss and Alexander, 2007; Vallesi et al., 2015), the present data support the idea that the ability to monitor the environment is mostly right-lateralized. Such a conclusion was drawn by using a novel paradigm that orthogonally manipulated process requirements and cognitive domains within the same individuals. Importantly, our findings confirmed the domain-general nature of monitoring with regard to the spatial and verbal cognitive domains used here.

Acknowledgments

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.neuropsychologia.2016.05.032.

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