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Task-switching preparation across semantic and spatial domains: An event-related potential study

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Abstract

Previous event-related potential (ERP) studies have identified the specific electrophysiological markers of advance preparation in cued task-switching paradigms. However, it is not completely clear yet whether there is a single task-independent preparatory mechanism for task-switching or whether preparation for a switch can be selectively influenced by the domain of the task to be performed. To address this question, we employed a cued-task switching paradigm requiring participants to repeat or to switch between a semantic and a spatial task. The behavioural results showed a significant switch cost for both domains. The ERP findings, however, revealed that switch and repeat trials for semantic and spatial domains differed in the amplitude modulation of an early P2 and a sustained negativity both expressed over fronto-central scalp regions. Further differences between the two domains also emerged over posterior-parietal electrodes. This pattern of data thus shows that advance preparation in task-switching can be selectively modulated by the domain of the task to be performed.

Keywords: ERPs; advance preparation; task-set; semantic processing; spatial processing.

1. Introduction

A hallmark of cognitive control is the ability to flexibly switch between tasks. One of the most used tools to investigate such ability is the task-switching paradigm in which participants have to repeat the same task or to switch between different ones. The general finding for task-switching paradigms is that response time (RT) gets longer and accuracy decreases for switch trials as compared to repeat trials, a phenomenon known as the "switch cost" (see Kiesel et al., 2010; Monsell, 2003, for reviews). The switch cost is reduced but not completely eliminated even by providing participants in advance with an explicit cue that instructs them to change task (i.e., the cued task-switching paradigm; Meiran, 1996). The observation that a residual switch cost still emerges with preparation intervals longer than 1 sec (Rogers & Monsell, 1995) suggests that advance preparation cannot fully compensate for the behavioural cost of alternating between different tasks (see Jamadar et al., 2010a).

Some theories explain the switch cost during the cued task-switching paradigm by assuming that an active task-set reconfiguration process would be implemented for switch trials as compared to repeat trials in order to prioritize the new task-set against the previous one (e.g., Rogers & Monsell, 1995). Such a reconfiguration process is supposed to be time-consuming and highly dependent on executive control. Support for this claim comes from the finding of a reduction of the switch cost when the cue-target interval is increased and more time can thus be devoted to advance preparation.

Alternatively, other researchers attribute the switch cost to priming or other memory interference processes from the previous task-set that would not necessarily entail executive control (e.g., Allport, Styles, & Hsieh, 1994; Wylie & Allport, 2000). This idea is strengthened by the observation that the switch cost is reduced with longer inter-trial intervals, which has been taken as evidence that allowing ample time before the subsequent trial is presented favors the spontaneous decay of the previous task-set interference. More recently, however, it is accepted that both reconfiguration and interference processes would contribute to the switch cost (e.g., Vandierendonck, Liefooghe, & Verbruggen, 2010).

A number of studies using event-related potentials (ERPs) support the role of an active task-set reconfiguration process taking place during the cue-target interval. The excellent high temporal resolution of ERPs indeed allows researchers to track the time course of switch and repeat trials that follow the presentation of the cue and to compare the neural activity associated with each task condition. In such a way, it is possible to determine whether, and to what extent, switch and repeat trials can be differentiated during the preparation interval that precedes task performance.

Two main ERP components have been often associated with task-switching effects during the preparation interval: a sustained posterior positivity, sometimes termed "differential switch positivity" or simply "switch positivity" (e.g., Jamadar et al., 2010a; Karayanidis et al., 2011), emerging around 300-400 ms after cue onset, and a concurrent or later sustained frontal negativity (e.g., Astle, Jackson, & Swainson, 2008; Lavric, Mizon, & Monsell, 2008). Both brain potentials are typically larger for switch as compared to repeat trials (see De Baene & Brass, 2014; Karayanidis et al., 2010, for reviews), although some studies also reported an enhanced frontal negativity for repeat trials before target onset (e.g., Nicholson, Karayanidis, Poboka, Heathcote, & Michie, 2005).

The switch positivity has been replicated across different studies and task manipulations (e.g., Kieffaber & Hetrick, 2005; Kopp, Lange, Howe, & Wessel, 2014; Li, Wang, Zhao, & Fogelson, 2012; Miniussi, Marzi, & Nobre, 2005; Nicholson et al., 2005; Rushworth, Passingham, & Nobre, 2002). A general consensus exists on the fact that this positivity would reflect anticipatory task-set reconfiguration processes that would be especially related to switch trials. In support of this interpretation, Karayanidis and colleagues (2011; see also Lavric, Mizon, & Monsell, 2008) found faster switch responses to be associated with larger amplitude of the switch positivity as compared to slower switch responses, suggesting that such a slow positivity is linked to "a switch-specific reconfiguration process" (p. 567).

Unlike the switch positivity, the functional meaning of the frontal negativity appears more controversial, perhaps due to the fact that this brain potential has been reported in fewer studies as

compared to the switch positivity. Furthermore, most of the studies observing the frontal negativity have used a common average reference, which led to the suggestion that the frontal negativity and the switch positivity could represent the negative and the positive components of a dipolar distribution, respectively (see De Baene & Brass, 2014; Jamadar et al., 2010a; Karayanidis et al., 2010; Lavric et al., 2008).

However, contrary to this claim, Astle, Jackson and Swainson (2008) found that the two brain potentials, which were measured in the same time interval, could be dissociated in task-switching paradigms that manipulated advance preparation of different response-sets. That is, whereas the switch positivity was present for both overt and covert (i.e., mental counting) responses, the frontal negativity was observed only when the task required an overt response. Moreover, in a study using a go/no-go version of the task-switching paradigm (Astle, Jackson, & Swainson, 2006), it was found that only the switch positivity was present following both go and no-go trials. By contrast, there was no difference in the frontal negativity between switch and repeat trials after a no-go trial, which suggested that this potential was sensitive to the fact that the response-set had been inhibited in the previous trial and this effect carried over to the current trial. Taking the above studies into account, a plausible explanation for the frontal negativity would be thus related to advance preparation of overt response-set processes (see Karayanidis et al., 2010).

In addition to these sustained positive- and negative-going potentials, another reliable ERP signature often reported in the task-switching literature is an early cue-locked fronto-central positivity (P2), emerging approximately at 200 ms after cue onset, which is usually larger following a switch cue relative to a repeat cue (e.g., Finke, Escera, & Barceló, 2012; Periáñez & Barceló, 2009; West, Langley, & Bailey, 2011). The enhanced P2 amplitude for switch trials has been generally attributed to the functioning of an early task-set updating process that would rapidly "detect" a relevant change in the task to be performed (see also De Baene & Brass, 2014).

To sum up, from this brief review of the main electrophysiological correlates of advance preparation in cued task-switching paradigms, it seems clear that preparing for a switch as

compared to preparing for a repeat trial can differentially modulate some specific brain potentials developing during the cue-target interval. Most of the previous task-switching studies have focused on investigating which cognitive factors may influence the ERP markers of advance preparation.

Among others, it has been shown that the electrophysiological correlates of task-switching preparation are sensitive to: 1) the amount of information conveyed by the cue (e.g., Karayanidis et al., 2009; Nicholson et al., 2006), 2) the duration of cue-target and inter-trial intervals (e.g., Li et al., 2012; Nicholson et al., 2005), 3) the specific requirements (go vs. no/go) for response selection (e.g., Astle et al., 2006; Gajewski & Falkenstein, 2011; Jamadar et al., 2010b) and 4) the participants' performance (fast vs. slow switch responses) in switching between tasks (e.g., Karayanidis et al., 2011; Lavric et al., 2008).

Much less is known about the role played by the domain of the tasks that are manipulated in cued task-switching paradigms. In other words, it is still unclear whether preparation for a task-switching is accomplished by a single, task-independent, central mechanism or whether it relies on different mechanisms according to the specific domain of the task to perform. Such a gap is mainly due to the fact that previous ERP studies have usually focused on the contrast between switch vs. repeat trials pooling over the tasks among which participants had to switch. This choice has been often motivated by the finding of a null behavioural interaction between the requirements to switch/repeat task and the specific task rules to be implemented, such that the ERP data have been averaged across the different tasks in order to increase the signal-to-noise ratio of switch and repeat trials (e.g., Goffaux et al. 2006; Karayanidis et al., 2009; Nicholson et al., 2006). As a consequence, it is not completely clear to date whether task-switching preparation is domain-independent or rather it is influenced by the domain of the task to be performed (see also Ravizza & Carter, 2008).

Among the few researchers who have investigated task-switching across different tasks, Hsieh and Wu (2011; see also Hsieh, Wu, & Lin, 2014) compared the electrophysiological correlates of advance preparation in task-switching between stimulus-dimensions vs. response-mappings. The authors reported both common and distinct modulations of cue-locked ERPs associated with the

two task-switching types, which suggests the presence of both shared and unique mechanisms underlying preparation to shift across different tasks.

An issue which is still poorly explored, however, is the comparison of task-switching between tasks that are typically processed in distinct brain regions, like for instance semantic and spatial tasks, which are known to be mainly processed on the left and right hemisphere, respectively (e.g., Corbetta & Shulman, 2011; Fairhall & Caramazza, 2013; Thompson-Schill et al., 1997). In the present study, we asked whether there might be different preparatory mechanisms when shifting, on a trial-by-trial basis, between tasks that require participants to make a spatial decision vs. tasks requiring a semantic decision. To our knowledge, only a previous study by Miniussi, Marzi and Nobre (2005) tackled a similar research question using a cued task-switching paradigm. In their experiment a symbolic cue predicted, with 80% validity, the stimulus-dependent task to be performed on any given trial: a lexical-decision task (i.e., to decide whether a letter string was a real word or not) or an angle-decision one (i.e., to decide whether an angle was acute or obtuse). The authors found a similar scalp distribution of the switch positivity for verbal and spatial tasks, which pointed to the conclusion that task-switching preparation would draw at least on some common task-independent processes. Nevertheless, another key finding in Miniussi and colleagues' (2005) study was that frontal and parietal modulations after a cue switch were larger in the verbal task as compared to the spatial one. This result thus suggests that the domain of the task to be performed may also influence general task-switching preparation processes.

To further explore the electrophysiological correlates of task-switching preparation across different domains, in the present context we decided to use a cued task-switching paradigm that, unlike Miniussi and colleagues' (2005) study, implemented the same stimulus materials for both semantic and spatial tasks. This was done to maximally strengthen task-set reconfiguration for the two domains during the preparation interval, as the appearance of the same stimuli for both semantic and spatial tasks reduced the possibility of an additional later task-set reconfiguration process afforded by the identity of the stimuli itself. Moreover, using exactly the same stimuli,

while manipulating the cognitive operations underlying different domains, allowed minimizing the influence that the type of material could also exert on the electrophysiological correlates of task-switching preparation. Accordingly, we designed a semantic task and a spatial task in which the stimuli consisted of several animal pictures belonging to two semantic categories (i.e., "preys" and "predators") and arranged in such a way to form different spatial diagonals. The participants' task was to identify the deviant set of animals (either "preys" or "predators") or the deviant angle as compared to two other sets of animals belonging to the same semantic category or to two other equal spatial configurations, respectively. Each task was predicted with full certainty by two auditory cues that were assigned to the semantic and spatial domains in a counterbalanced order across participants.

While participants performed the task, continuous electroencephalographic (EEG) activity was recorded. To determine whether task-switching preparation differs according to the domain of the tasks being switched, we computed three cue-locked ERP components (P2, frontal negativity and switch positivity) that, as detailed above, have been shown to be sensitive to the requirement to shift task being usually larger for switch than for repeat trials. On the basis of prior cued task-switching studies, we expected to observe a reliable RT switch cost for both semantic and spatial domains. As regards the ERP data, two main predictions could be put forward. If task-switching preparation relies on a common task-independent mechanism, we expected to replicate the finding of larger P2, frontal negativity and switch positivity amplitudes for switch trials as compared to repeat trials in both domains. Conversely, if updating and/or task-set reconfiguration processes would differ between the two domains, thus selectively influencing task-switching preparation, a general prediction would be that semantic and spatial rules should differentially modulate the amplitude and/or time course of the electrophysiological indexes of switch and repeat trials within the cue-target preparation interval.

2. Method

2.1. Participants. Twenty-two volunteers took part in the experiment in exchange for course credits or cash payment of 20 euro. All participants gave informed consent prior to their inclusion in the study. They reported to have normal or corrected-to-normal visual acuity and normal hearing. None of the participants had any history of drug or alcohol abuse, or history of psychiatric, neurological or other medical illness. The study was approved by the Bioethical Committee of the Azienda Ospedaliera di Padova and was conducted according to the guidelines of the Declaration of Helsinki. Data from two participants were discarded because of excessive noise in the EEG recording. We also discarded data from two left-handed participants (average score: -92.5, range: 45-100, in the Edinburgh Handedness Inventory (Oldfield, 1971) as they displayed a different ERP lateralization pattern as compared to the right-handed participants (average score: 90). The data from the remaining eighteen participants (mean age: 26.4 years, range: 20-46 years, 13 females) were used for both behavioural and ERP analyses.

2.2. Apparatus and stimuli. Stimulus presentation and response collection were controlled by E-prime 2 software (Schneider, Eschman, & Zuccolotto, 2002) running on a personal computer connected to a 19″ LCD monitor. This computer was interconnected to an Intel Core laptop computer recording continuous EEG. The stimulus materials consisted of two auditory cue stimuli, comprising a high pitch sound with a frequency of 1500 Hz and a low pitch sound with a frequency of 200 Hz, and of eighteen visual target stimuli that depicted land-living mammals subdivided into 9 prey and 9 predator animals. Only four-legged animals were included. All animals unambiguously faced right and were slightly tilted (i.e., at 15° in a clockwise manner). The animals were presented into three white circles that were arranged in a row and displayed in the center of the screen against a grey background. Each circle contained three identical animal pictures that were positioned in such a way to form a diagonal, with one picture positioned in the center of the circle and the other peripheral two displayed at a distance of 2.3 cm from the central image (see Figure 1).

PLEASE INSERT FIGURE 1 ABOUT HERE

The angles of the diagonal resulting from the arrangement of the three animal pictures varied randomly between the values of 22.5°/202.5°, 45°/225°, 67.5°/247.5°, 112.5°/292.5°,135°/315° and 157.5°/337.5° from an imaginary horizontal line across the circle (the slashes mean that the angles denote the same diagonal arrangement). The deviation from this angle could be ± 22.5° away from the other two angles. This means, for instance, that the angle of 45° could be attained by adding 22.5° to 22.5° or by subtracting 22.5° from 67.5. Horizontal and vertical arrangements were not included to avoid any pop-out effect of the deviant angle that could dramatically ease the spatial task.

2.3. Procedure and Task. The task was a cued task-switching paradigm, in which an auditory cue preceded each target presentation indicating the semantic task or the spatial task. For half of the participants, the high pitch sound was associated with the semantic rule and the low pitch sound with the spatial rule. For the other half of the participants, the reverse associations were used. A trial started with the presentation of the auditory cue that was played for 300 ms via two loudspeakers (Yamaha NX-50) located on both sides of the screen. The sound intensity was set at a comfortable level (i.e., ¼ of the maximum volume) that was maintained constant for all the participants. Following a fixed time interval of 1900 ms after the cue offset, the target stimuli were then displayed for 2200 ms. Thus, there were 2200 ms from cue onset to target onset (see Androver-Roig & Barceló, 2010, for a quite similar interval in a modified task-cueing version of the Winsconsin Card Sorting Test). The employment of such a long cue-target interval was aimed at enabling participants to fully develop advance preparation before target onset, thus avoiding overlapping activity with subsequent target-related processing. Along the same line, we also decided not to vary

the duration of cue-target interval either between blocks of trials, since prior work has shown that participants may rely on different preparatory strategies for short vs. long block intervals (Nicholson et al., 2005), or within blocks of trials, not to add a further shift between short and long intervals to our main task-switching manipulation and in order to avoid any variable foreperiod effects (e.g., Vallesi, Lozano & Correa, 2013).

The participants' task was to identify which of the three circles showed a deviant item with respect to the other two according to a semantic or a spatial rule. In the semantic task, participants had to identify the circle containing the deviant animal. For instance, if there were two circles containing prey animals and only one circle with a predator, they had to indicate the circle displaying the predator irrespective of the diagonal arrangement of the animals (see Figure 1 in which the correct response is the circle on the right). By contrast, in the spatial task, participants had to ignore the semantic category of the stimuli and focus on their spatial arrangement by indicating the circle displaying a deviant angle as compared to the other two circles (in Figure 1 the correct response corresponds to the circle on the left). For each task condition there was only one univocally correct response, in the sense that the circle displaying the deviant angle could not also contain the deviant animal or vice versa. Switch/repeat trials were equally probable and administered randomly.

Participants responded by pressing the "j", the "k" or the "l" keys on the computer keyboard with the index, middle or ring finger of their right hand or, in different blocks, by pressing the "s", the "d" or the "f" keys with the ring, middle or index finger of their left hand, respectively. Each key was spatially associated with each circle so that the first key was to be responded to if the deviant circle was the one positioned on the left, the middle key if the deviant circle was the central one, and the third key if the deviant circle was positioned on the right. The deadline for the response was 2500 ms after stimulus onset. Following a variable inter-trial interval ranging from 1000 to 1500 ms, the next trial began.

The experiment consisted of 8 blocks of 50 trials each. Four blocks required a left-hand response and the remaining four a right-hand response. Half of the participants started with the left hand and the other half with the right hand. Before the EEG session, participants were administered with both a tutorial, which carefully explained the task, and a practice phase. At the beginning of the practice phase, all the animal pictures were presented one by one with their name below each figure. Participants were asked to mentally classify them as preys or predators and to let the experimenter know in case of any doubt about the corresponding semantic category. Following this phase, they were to perform each single-task separately before practicing the two tasks together. Half of the participants started with the spatial task and the other half with the semantic task. Moreover, in order to familiarize themselves with the stimulus-response mapping, they also had to change from left to right hand, and vice versa, through the practice blocks. Specifically, half of the participants used the left hand in the two single-task blocks and the right hand in the task-switching block. The remaining participants started with the right hand in the single-task blocks and changed to the left hand in the task-switching block.

Each single-task practice block consisted of 30 trials. At the end of each block, participants were informed about their mean RTs and mean accuracy rates. If accuracy was below 66% after the first block, subsequent mini blocks of 15 trials each were presented until participants managed to perform the task above 66%. If accuracy was between 66% and 80%, participants could decide to receive more training or not. If, instead, accuracy was above 80%, the program automatically passed on the next test block. The same criteria applied to the task-switching practice, which consisted of a first block of 40 trials and of subsequent mini blocks of 20 trials each administered only if participants' performance failed to reach the threshold of 66% of accuracy (or if participants wished to practice more when accuracy was between 66% and 80%).

In the practice phase, participants received a feedback which varied according to their performance after each trial (the Italian word for "Correct" displayed in blue or the Italian words for "Incorrect" and "No response. Try to be faster" displayed in red for 1500 ms). In addition to the

practice phase, both at the beginning of the EEG session and after the first four blocks of experimental trials (i.e., when the hand used to respond had to be changed), participants were briefly presented with a short practice block of 8 trials. Like what stated above, they had to reach the threshold of 66% of accuracy to start the proper experimental session. A short rest between blocks of trials was allowed.

2.4. EEG recording. Participants were seated in front of the computer monitor and were instructed to avoid eye blinks and movements during cue and 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 positioned 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 off-line 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 0.1-100 Hz and digitized at a sampling rate of 500 Hz.

3. Analysis

3.1. Behavioural data analysis. Data from practice trials, the first trial of each block, trials with errors and trials without responses were discarded from the RT analysis. Mean RTs for correct responses and Accuracy (percentage of correct responses) were analyzed separately through repeated-measures ANOVAs with Hand (left, right), Domain (semantic, spatial) and Switching from the previous task (repeat, switch) as within-participants factors.

3.2. Electrophysiological data analysis. Signal pre-processing was performed using BrainVision Analyzer 2.0 (Brain Products GmbH). Raw data were first band-pass filtered off-line with cutoffs at 0.1 and 30 Hz (Butterworth zero phase, 12 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 during the entire recording were replaced through spherical spline interpolation (Perrin, Pernier, Bertrand, & Echallier, 1989). Overall, only four electrodes (T8, TP10, CPz and AF8) were interpolated for three participants (one electrode each for two participants and two electrodes for another participant). The data were then re-referenced to the average of all electrodes. They were finally segmented into epochs [-200, 2200 ms] with respect to the cue onset (baseline ±50 ms around the cue-onset; see Jamadar et al., 2010a).

Epochs were discarded if, on any channel, absolute difference between two sampling points exceeded 30 μV/ms, if peak-to-peak deflections in a segment exceeded ±100 μV within intervals of 200 ms, if amplitude exceeded a value of ±80 μV and if activity was lower than 0.1 μV within intervals of 200 ms. Finally, each epoch was visually inspected and trials containing any residual artifact were manually removed. After artifact rejection, the total numbers of artifact-free trials per condition were: 1394 for the semantic-repeat, 1286 for the semantic-switch, 1226 for the spatial-repeat and 1243 for the spatial-switch condition. A minimum criterion of 28 artifact-free trials per condition and participant was required to ensure a sufficient signal-to-noise ratio. Only trials with correct behavioural responses were analysed. In addition, practice trials and the first trial of each block were excluded from further analysis. Four separate grand average waveforms were constructed relative to cue categories: semantic-repeat, semantic-switch, spatial-repeat and spatial-switch, according to whether semantic and spatial trials were signaled either by the same cue (i.e., "semantic-semantic" or "spatial-spatial" trial sequences) or by a different cue with respect to that used in the previous trial (i.e., "spatial-semantic" or "semantic-spatial" sequences).

The ERP analysis focused on the following cue-locked potentials: frontal P2, frontal negativity and switch positivity that were chosen on the basis of visual inspection of the grand average

waveforms and according to prior literature. The P2 amplitude was analyzed over fronto-central electrodes (left: F1, F3, FC1, FC3; midline: Fz, FCz; right: F2, F4, FC2, FC4) in a time window ranging from 200 to 240 ms after cue onset (see Finke, Escera, & Barceló, 2012 and West, Langley, & Bailey, 2011, for very similar analysis windows and electrodes). A repeated-measures ANOVA tested for amplitude differences in the P2 with Domain (semantic, spatial), Switching from the previous task (repeat, switch) and Electrode side (left, midline, right) as within-participant factors.

Regarding the analysis of the frontal negativity and the switch positivity, ERP amplitudes were measured from fronto-central (left: F1, F3, FC1, FC3; midline: Fz, FCz; right: F2, F4, FC2, FC4) and posterior-parietal (left: P1, P3, PO3, PO7; midline: Pz, POz; right: P2, P4, PO4, PO8) electrodes, respectively, where the two brain potentials were maximally expressed (e.g., Karayanidis et al., 2009; West, Langley, & Bailey, 2011). As depicted in Figures 3 and 4, negative and positive waveforms over fronto-central and posterior-parietal scalp regions almost overlapped in time. Therefore, we analyzed the frontal negativity and the switch positivity within the same latency range. Three time bins of 600 ms each were selected in order to explore the time course of switch and repeat trials across the whole cue-target interval: (1) 400-1000 ms, (2) 1000-1600 ms, and (3) 1600-2200 ms. Amplitude differences over fronto-central and posterior-parietal regions were tested using a five-way repeated-measures ANOVA with the within-participant factors of Scalp region (fronto-central, posterior-parietal), Time bin (1, 2, 3), Domain (semantic, spatial), Switching from the previous task (repeat, switch) and Electrode side (left, midline, right). For the scalp region factor, we pooled over all the above-mentioned electrodes that were contained within each region. For all ERP analyses, amplitude was calculated as the mean voltage measured across the pooled electrodes that were included in a particular montage (e.g., left electrodes side) and within the specified temporal window. Significant effects of Electrode side were reported only if they interacted with Domain, Switching or both. The Greenhouse-Geisser correction was applied when sphericity assumption was violated according to the Mauchly's test (Jennings & Wood 1976). Corrected degrees of freedom and corrected probability values are reported.

For both ERP and behavioural analyses, post-hoc comparisons with the Tukey's HSD test were used to analyze both pair-wise comparisons within significant interactions and significant main effects involving more than two levels.

4. Results

4.1. Behavioural results

4.1.1. RTs. The significant main effect of Switching [$F(1,17)=20.55$, $p<.001$, partial $\eta^2=.5$] showed that participants were slower when they had to switch from one task to another rather than when the same task was repeated. The main effect of Domain was also significant [$F(1,17)=34.31$, $p<.0001$, partial $\eta^2=.6$] being RTs longer for the semantic domain than for the spatial domain. The switch cost was not affected by the domain of the task to be performed as revealed by the non-significant Domain x Switching interaction [$F<.1$] (see Figure 2.A).

PLEASE INSERT FIGURE 2 ABOUT HERE

Although there was no asymmetrical switch cost in our data, as indexed by the lack of a significant Domain x Switching interaction (e.g., Martin et al., 2011), we calculated for both domains an index of task-switching by computing the RT difference between switch and repeat trials (62 ms for the semantic domain vs. 58 ms for the spatial domain) in order to directly compare the magnitude of the switch cost across the two domains. A paired two-tailed t-test on these behavioural indexes confirmed no difference in the switch cost between semantic and spatial domains [$t(17)=.21$, $p=.83$]. The main effect of Hand and all the interactions involving Hand as a factor were not significant (all ps>.1). Accordingly, in the EEG analysis the data across the two hands were collapsed in order to increase the signal-to-noise ratio.

4.1.2. Accuracy. The main effect of Switching [$F(1,17)=6.54$, $p=.02$, partial $\eta^2=.2$] mirrored the RTs data by showing that participants were less accurate in the switch condition as compared to the repeat condition. There was also a significant main effect of Domain [$F(1,17)=4.62$, $p=.04$, partial $\eta^2=.2$] indicating that accuracy was higher for the semantic domain than for the spatial one, a result that goes in the opposite direction with respect to the RTs data showing a speed-accuracy trade off. The interaction between Domain and Switching was far from significance [$F(1,17)=2.06$, $p=.1$, partial $\eta^2=.1$] (see Figure 2.B). None of the remaining terms of the ANOVA reached statistical significance (all *p*s>.1).

4.2. Electrophysiological results

Cue-locked ERPs over fronto-central and posterior-parietal electrodes as a function of repeat and switch trials are displayed separately for the semantic and the spatial domain in Figures 3 and 4, respectively.

The ANOVA on the frontal P2 amplitude showed only a marginal significant Domain x Switching interaction [$F(1,17)=3.83$, $p=.06$, partial $\eta^2=.1$]. Post-hoc comparisons for this interaction revealed that repeat spatial trials tended to elicit a larger P2 amplitude as compared to switch trials ($p=.06$), whereas there was no difference between repeat and switch trials in the semantic domain ($p=.9$).

The ANOVA carried out on fronto-central and posterior-parietal regions showed both a significant main effect of Scalp region [$F(1,17)=7.82$, $p=.01$, partial $\eta^2=.3$], indexing a more positive voltage over posterior-parietal electrodes than over fronto-central ones, and a significant main effect of Time bin [$F(2,34)=7.31$, $p=.002$, partial $\eta^2=.3$] with a more negative voltage in the first time bin as compared to the second one ($p=.001$). There was no difference between the second and third time bins as well as between the first and third time bins (*p*s>.1). Scalp region interacted with Time bin [$F(1.36, 23.12)=37.49$, $p<.001$, partial $\eta^2=.6$], with Time bin and Switching [$F(1.29, 21.96)=11.05$, $p=.002$, partial $\eta^2=.3$] and with Domain and Switching [$F(1,17)=28.59$, $p<.001$, partial $\eta^2=.6$]. Time bin also interacted with Switching [$F(2,34)=5.81$, $p=.006$, partial $\eta^2=.2$] and

with Domain and Switching [$F(2,34)=3.39$, $p=.04$, partial $\eta^2=.1$]. These two-way and three-way interactions were better qualified by a significant four-way interaction between Scalp, Time bin, Domain and Switching [$F(2,34)=6.06$, $p=.005$, partial $\eta^2=.2$]. Post-hoc comparisons for this four-way interaction showed the following results.

In the first time bin (400-1000 ms), there was no difference for the semantic domain between repeat and switch trials in either the fronto-central or the posterior-parietal scalp region (ps>.6). Conversely, for the spatial domain switch trials in the first time bin were associated with a larger positivity over posterior-parietal electrodes ($p=.0002$) and with a concomitant larger negativity over fronto-central ones ($p=.001$).

In the second time bin (1000-1600 ms), post-hoc comparisons showed that whereas for the spatial domain the frontal negativity was larger for switch trials as compared to repeat trials ($p=.006$), an opposite pattern was found for the semantic domain with a larger frontal negativity for repeat trials as compared to switch trials ($p=.003$). There was no difference between switch and repeat trials over the posterior-parietal region for both semantic and spatial domains (all ps>.1)

In the third time bin (1600-2200 ms), post-hoc comparisons for the spatial domain confirmed a larger frontal negativity for switch trials as compared to repeat trials ($p=.02$) and no difference between the two trial types over the posterior-parietal region ($p=.8$). For the semantic domain, a larger frontal negativity was instead associated with repeat trials as compared to switch trials ($p=.0001$), whereas the opposite was observed for the posterior-parietal region with more negative amplitude for switch trials as compared to repeat trials ($p=.003$).

There were no other significant main effects or interactions except for the Time bin x Switching x Electrode side interaction [$F(2.04, 34.76)=4.14$, $p=.02$, partial $\eta^2=.1$]. Post-hoc comparisons for this interaction showed that in the first time bin switch trials were associated with a larger positive amplitude as compared to repeat trials over the left electrode side ($p=.001$), whereas there was no difference between switch and repeat trials in either the midline and the right side (ps>.1). In both

the second and the third time bin, switch trials did not differ from repeat trials in either of the three electrode sides (all *p*s>.1).

PLEASE INSERT FIGURES 3 AND 4 ABOUT HERE

As already mentioned in the Behavioural results section, although the magnitude of the switch cost did not differ between the two domains, the semantic task was associated with longer RTs as compared to the spatial one. Accordingly, one might wonder whether the differences observed between the two domains in the modulation of the P2, frontal negativity and switch positivity truly reflected the involvement of different task-switching preparation processes or whether instead they could be partly accounted for by the different task demands exerted by semantic and spatial domains. In order to explore this possibility, we re-analysed the ERP data after having equated RTs between the two domains. To do so, we excluded from the analysis of each domain a subset of the fastest and slowest responses for both switch and repeat task conditions with the constraint, however, that no more than 15 trials for each participant and condition should be rejected in order to maintain an acceptable number of trials for the subsequent ERP analysis.

Behaviourally, this re-analysis confirmed a significant main effect of Switching [$F(1,17)=14.89$, $p=.001$, partial $\eta^2=.4$], with longer RTs when participants had to switch from one task to another as compared to when they had to repeat the same task. The lack of a significant Domain x Switching interaction [$F(1,17)=0.43$, $p=.5$, partial $\eta^2=.02$] showed that there was no evidence for the switch cost to be affected by the domain of the task to perform. As expected, after having equated RTs for the two domains, the main effect of Domain was no longer significant [$F(1,17)=1.3$, $p=.2$, partial $\eta^2=.07$]. Crucially for our goal, the ERP statistical analysis of the trials equated for the two domains replicated all the main results reported above.

5. Discussion

The main aim of the current study was to investigate whether advance task-switching preparation could be differentially modulated according to the domain of the task to be performed, that is, semantic or spatial. In order to strengthen task-set reconfiguration processes for the two domains and minimize the influence that the type of material could have on the electrophysiological correlates of advance preparation, we designed a novel paradigm that allowed us to administer the same set of stimuli for both semantic and spatial domains.

The behavioural results replicated previous task-switching studies, being RTs longer and accuracy lower for switch trials as compared to repeat trials. The data also showed participants to be slower in the semantic task than in the spatial task in line with former work (e.g., Miniussi et al., 2005). Importantly, however, the magnitude of the switch cost did not differ between semantic and spatial domains and accuracy was higher for the semantic one. These results thus show that the main effect under investigation in the present work, namely, the switch cost was similar for the two domains despite the differences observed between semantic and spatial tasks in both RTs and accuracy data.

To summarize the ERP results, waveforms elicited by semantic and spatial domains showed several differences that emerged as early as 200 ms after cue onset in the latency range of the frontal P2. Whereas for the spatial domain the P2 amplitude tended to be larger for repeat trials as compared to switch trials, for the semantic domain the P2 amplitude was not modulated by the requirement to repeat or to switch task. Later on, the two domains differed reliably in the modulation of both frontal and posterior brain potentials.

On the one hand, when participants switched from the semantic to the spatial domain, during the 400-1000 ms time bin switch spatial trials elicited both a larger positivity over posterior-parietal electrodes and a concomitant larger negativity over fronto-central ones. From 1000 ms until the end of the cue-target interval, spatial ERPs were only characterized by a more sustained negativity for switch trials as compared to repeat trials over the fronto-central scalp region. On the other hand, when participants switched from the spatial to the semantic domain, there was no difference

between switch and repeat trials during the first time bin (400-1000 ms) over either the fronto-central or the posterior-parietal region. A later modulation within the semantic domain was found over the fronto-central scalp region, with repeat trials being associated with larger negative amplitude as compared to switch trials, in both the second and the third time bin. Such frontal modulations were accompanied, in the third time bin (1600-2200 ms), by a more sustained negativity for switch trials than for repeat trials over the posterior-parietal region.

The first difference between switch and repeat trials as a function of domain was already observed in the time range of the frontal P2, which tended to be larger for repeat trials than for switch trials in the spatial domain only. Therefore, the modulation of the P2 in the spatial domain differed from previous results of enhanced P2 amplitude following a switch cue as compared to a repeat cue (e.g., Finke, Escera, & Barceló, 2012; Periáñez & Barceló, 2009; West, Langley, & Bailey, 2011). One might interpret this pattern of data as reflecting an encoding benefit due to repetition of the same cue. In the task-switching literature, there has been indeed a great deal of controversy regarding the fact that employing a 1:1 mapping between cues and tasks may confound task-switch costs with cue-switch costs (e.g., Logan & Bundesen, 2003). To overcome this problem, some studies have used a 2:1 mapping between cues and tasks in such a way that a cue change could be also associated with a task repetition (e.g., Hsieh and Wu, 2011). Although we acknowledge that in our design a task change was always preceded by a cue change, this cannot account for our frontal P2 results in the spatial domain. First, the association between cues and tasks was counterbalanced across participants and the cues differed minimally at the physical level. Second, and more importantly, if the modulation of the P2 observed in the spatial domain was related to cue repetition, we should have expected to find the same pattern also for the semantic domain, which was not the case. Such results thus challenge the idea that the cue-locked frontal P2 would merely detect a change in the task to be performed since, as shown here, it was sensitive both to the requirement to repeat the same task and to the domain of the task that needed to be repeated.

Another ERP deflection that was influenced by our task requirements was the switch positivity, which was maximally expressed over the posterior-parietal scalp region in a time window ranging from 400 to 1000 ms (see Figures 3 and 4, middle panel). Several studies have already highlighted the importance of this brain potential in anticipatory preparation for a change in task (e.g., Karayanidis et al., 2010). Within the framework of the task-set reconfiguration theory, the presence of a larger posterior positivity for switch trials vs. repeat trials would index the active reconfiguration of the new task-set against the previous irrelevant one (e.g., Nicholson et al., 2005). Hence, our finding of an enhanced positivity for switch spatial trials as compared to repeat ones fits well with this account. However, it has been proposed that advance reconfiguration could also take place on repeat trials, although to a lesser extent than what required in reconfiguring the new task-set on switch trials. This would be further encouraged when switch and repeat trials have the same probability of being presented within a block (e.g., Brass & von Cramon, 2004; Nicholson et al., 2005). Supporting this proposal, repeat trials that are intermixed with switch trials have been found to elicit a larger positivity as compared to all-repeat trials presented on single-task baseline blocks, which suggests that some task-set reconfiguration processes could also occur on mixed repeat trials (e.g., Wylie et al., 2009).

On the basis of the above-mentioned evidence, it might be reasonable to assume that in the current study participants may have adopted different visual-attention strategies to accomplish the semantic task with respect to the spatial one and that this could have enhanced reconfiguration processes on both switch and repeat semantic trials (albeit note that this was not sufficient to eradicate the behavioural switch cost in the semantic task). Namely, whereas on semantic trials it is likely that participants adopted a speed-wise strategy more based on local processing in order to identify the specific deviant animals among those included in the three circles, on spatial trials they had to scan the animal pictures in a more global manner to pick up the deviant angle. This difference in strategy formation would explain the finding of a more similar positive waveform for both switch and repeat trials in the semantic domain vs. the spatial domain.

Alternatively, it could be possible to hypothesize that switch and repeat semantic trials both elicited the same sustained positivity because of the greater difficulty of the semantic task, which was indeed associated with longer RTs. However, this explanation does not hold to the extent that the same ERP pattern was replicated even after having equated RTs for the two domains. Moreover, the magnitude of the switch cost did not differ between the semantic and the spatial domain, which rules out the possibility that the similar positivity observed for switch and repeat semantic trials could be attributed to general task difficulty or to asymmetrical switch costs.

The employment of different strategies and the likely presence of different reconfiguration processes for the two domains could have played a more critical role in the differential expression of the switch positivity associated with semantic and spatial domains. Such cognitive factors may also help explaining the different negative modulations and time courses that characterized the two domains over the fronto-central scalp region. In all the three time bins considered for the ERP analysis, switch spatial trials were more negative than repeat trials over fronto-central electrodes. Conversely, in the semantic domain, within the first time bin there was no difference between switch and repeat trials over the same fronto-central region. Afterwards, repeating the semantic task gave rise to an increased negativity with respect to switching from the spatial to the semantic one, a pattern that was significantly present during both the second and the third time bin (from 1000 to 2200 ms).

It is difficult to pinpoint the functional meaning of the differential modulation of the frontal negativity by semantic and spatial domains shown here because, as outlined in the Introduction section, no agreement has been reached yet on the role of this brain potential. Recently, it has been suggested that the frontal negativity might reflect a general task preparation mechanism that would not be specific for switch trials (e.g., Karayanidis et al., 2011). However, if we assume that in the present context the frontal negativity was due exclusively to generic anticipation, then it would make sense to predict a larger negativity for repeat trials than for switch trials in both domains, which was not what we observed. In addition to the findings from the switch positivity, these results

thus point to the conclusion that the frontal negativity may also be affected in a different way by the specific participants' strategies activated during the preparation interval.

Our results for both the frontal negativity and the switch positivity differ from the study by Miniussi and collaborators (2005) who found larger negative frontal and parietal modulations after a cue switch to be associated with the more difficult verbal task. Several factors such as different task requirements and timing parameters might have played a role in the differential outcome between the two studies. Nevertheless, it should be emphasized here that asking participants to shift across tasks that implemented exactly the same stimuli for both semantic and spatial domains differentially influenced the specific ERP markers of task-switching preparation. Whilst this finding points to the conclusion that task-switching preparation would draw on distinct task-dependent mechanisms, it should be finally considered whether these results could be partially attributed to the specific task domain transition employed in the current study. In other words, because our participants had always to switch between two different domains (from semantic to spatial and vice versa), one might argue that some carry-over interference effects would have come into play when disengaging attention from one domain to the other, and that this eventually influenced task-switching preparation processes. The same concern applies to Miniussi and colleagues' (2005) study, which also used a between-domain shift design, even if in their case this factor did not result in dramatic differences between spatial and verbal domains in the expression of the ERP markers of task-switching preparation. This finding thus suggests that our results cannot be explained solely by the employment of a between-domain shift paradigm since, unlike our study, Miniussi and colleagues (2005) showed common task-switching preparation mechanisms in the context of a similar between-domain shift manipulation.

Along the same line, it should also be noted that the majority of previous ERP task-switching studies have usually employed a switch "between" different tasks (i.e., letter task vs. digit task; e.g., Nicholson et al., 2005). Yet, since these studies typically collapsed the task factor, it is not possible

to get a complete picture of how the combination of task domain manipulation and between-domain shift transition might affect task-switching preparation processes.

Nevertheless, another way of testing whether different types of task-switching would rely on shared or distinct mechanisms is to manipulate task domain in a block-wise manner by keeping the task domains among which participants have to switch separate across different blocks of trials (e.g., Vallesi et al., 2015) or across different groups of participants (e.g., Hsieh & Wu, 2011). A value of a within-domain shift design with respect to a between-domain shift one is that it allows investigating task-switching preparation processes as a function of task domain by controlling for possible carry-over interference effects. However, in the case of a between-participants study, a drawback of using different groups of participants to compare distinct task-switching types is that it is not possible to control for inter-subjects variability, which could also be a confounding variable.

Taking into account the above issues, perhaps a better manipulation to improve our understanding of task-switching preparation as a function of task domain would be to orthogonally manipulate task domain transition (within-domain shift and between-domain shift) in a full experimental design and within the same individuals. Future studies should thus employ, within the same blocks, two different tasks for each task domain (see Kieffaber and Hetrick, 2005, for a partial attempt in this direction, with a design employing both within- and between-modality switches).

Finally, it should be acknowledged that some researchers recently begun to combine into the same experiment single-shifts (i.e., a switch between stimulus dimensions: color or shape, or between response effectors: hand or foot) and dual-shifts (i.e., a concurrent switch of both stimulus dimensions and response effectors) in order to understand whether a dual-shift condition would be associated with similar or distinct anticipatory processes as compared to a single-shift condition (see Hsieh, Wu & Lin, 2014; Tieges et al., 2007; West, Bailey, & Langley, 2009, for ERP studies, and Hübner et al., 2001; Philipp & Koch, 2010, for behavioural evidence). The main advantage of using this kind of design is that it allows researchers to parametrically manipulate the "task shift load" (i.e., single vs. dual-shift conditions; cf. Tieges et al., 2007) in order to explore how the ERP

markers of task-switching preparation would be modulated by the complexity of the switch operation required on dual-shift vs. single-shift trials. However, when implementing this dual-shift design in the context of a task domain manipulation, like the one used here, it is also important to keep in mind that other factors such as higher memory load and concurrent reconfiguration of multiple elements could indeed influence the genuine effects of task domain on task-switching preparation processes.

To sum up, this brief review of the literature on different task-switching designs highlights the importance of carefully selecting, according to the specific task goal of the study, the experimental design that is more suitable to investigate task-switching ability. Here, we showed that a between-domain shift transition across semantic and spatial tasks selectively influenced the specific ERP signatures of task-switching preparation. Our results thus suggest that when participants have to shift on a trial-by-trial basis between two tasks belonging to two separate cognitive domains, task-switching preparation would rely on distinct mechanisms. Future studies will clarify whether it is possible to generalize these conclusions to experimental settings in which task domain is manipulated, for instance, in a block-wise manner.

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Figure captions

Figure 1. Example of stimulus material. When the task required a semantic decision, participants had to choose the circle containing the deviant animal (i.e., prey or predator) as compared to the other two circles. In the figure, the circle on the right was the target since it contained a predator (i.e., tiger), whereas the other two displayed prey animals (i.e., deer and zebra). By contrast, in case of a spatial decision, the correct response would have been the circle on the left since the arrangement of the animal pictures created a deviant angle as compared to the other two circles.

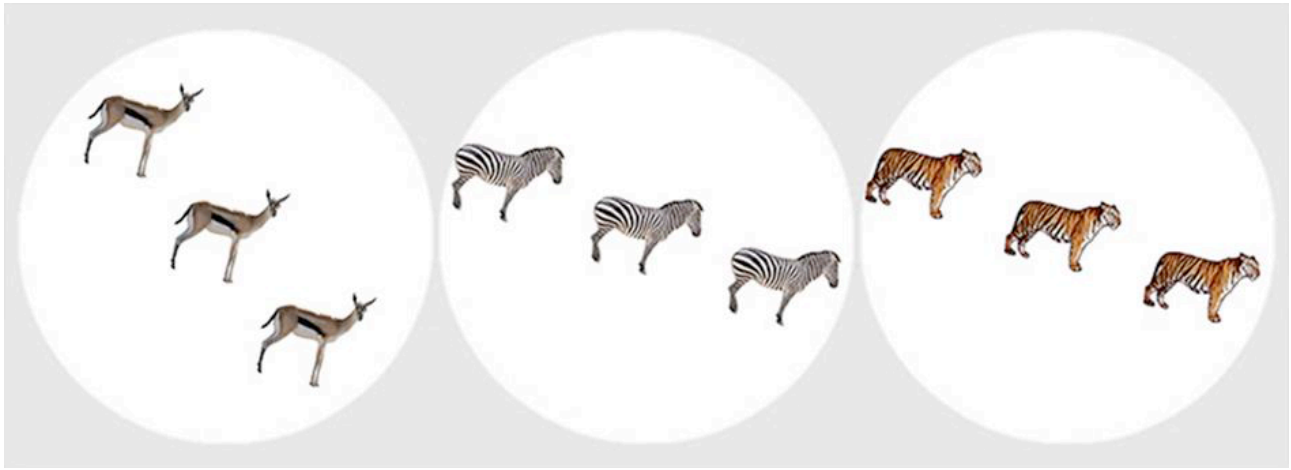

Figure 2. (A). Mean response times (RTs) and (B) percentage of correct responses as a function of Domain (semantic, spatial) and Switching from the previous task (repeat, switch). Vertical bars represent standard errors of the mean.

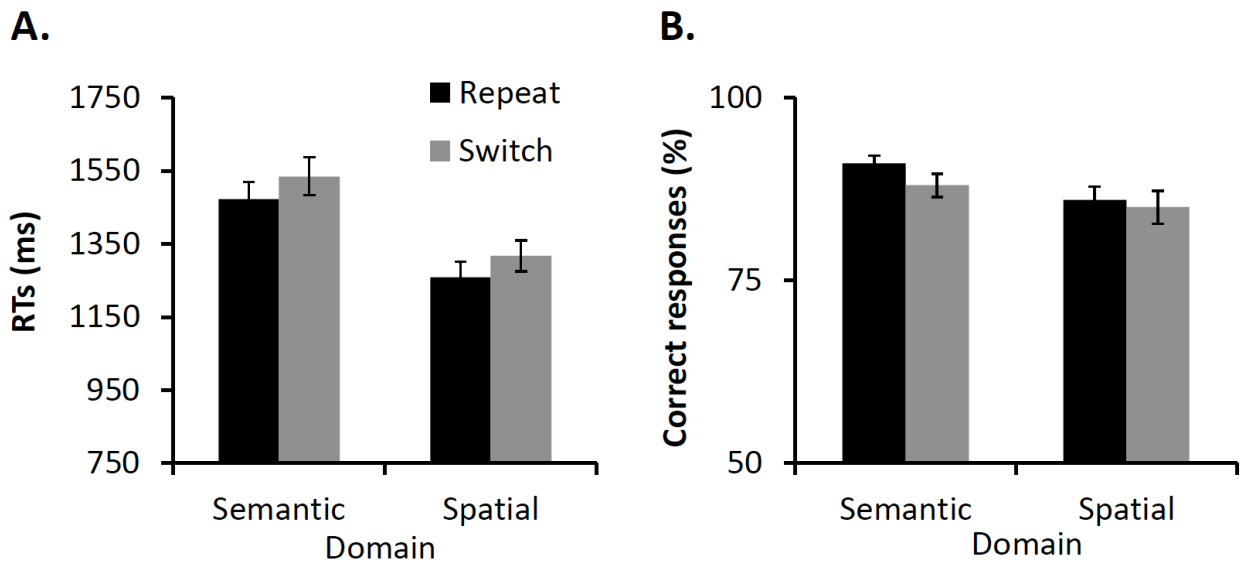

Figure 3. (A) Cue-locked grand averages of the semantic ERP waveforms recorded at pooled fronto-central electrodes (top panel) and posterior-parietal electrodes (middle panel) as a function of Switching from the previous task (repeat, switch) and Electrode side (left, midline, right). ERPs of interest (P2, frontal negativity and switch positivity) are marked on midline electrodes only for general visualization. (B) Differences in the ERP topography between switch and repeat trials for the semantic domain. The difference maps (switch minus repeat) are shown for the time bins used for the ERP analysis of the P2, frontal negativity and switch positivity.

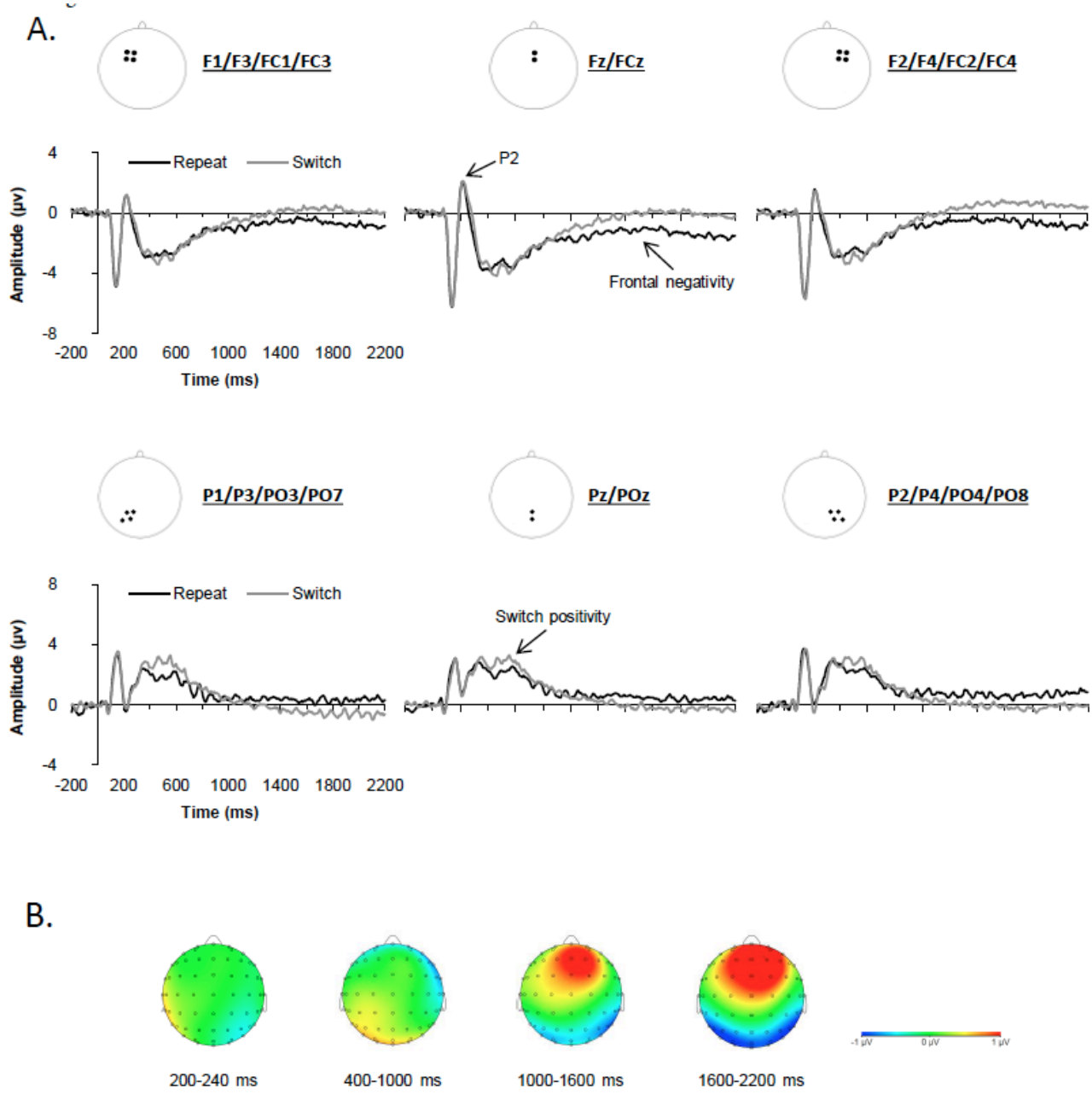

Figure 4. Cue-locked grand averages of the spatial ERP waveforms recorded at pooled fronto-central electrodes (top panel) and posterior-parietal electrodes (middle panel) as a function of Switching from the previous task (repeat, switch) and Electrode side (left, midline, right). ERPs of interest (P2, frontal negativity and switch positivity) are marked on midline electrodes only for general visualization. (B) Differences in the ERP topography between switch and repeat trials for the spatial domain. The difference maps (switch minus repeat) are shown for the time bins used for the ERP analysis of the P2, frontal negativity and switch positivity.