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PII: S0301-0511(10)00308-X
DOI: doi:10.1016/j.biopsycho.2010.12.001
Reference: BIOPSY 6329

To appear in:

Received date: 15-9-2010
Revised date: 11-11-2010
Accepted date: 5-12-2010

Please cite this article as: Martin, C.D., Barcelo, F., Hernandez, M., Costa, A., The time course of the asymmetrical “local” switch cost: Evidence from event-related potentials, *Biological Psychology* (2010), doi:10.1016/j.biopsycho.2010.12.001

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Transition type (*switch* versus *repeat*) influences both cue and target processing
Task rule (*color* versus *form*) influences both cue and target processing
Asymmetrical local switch cost originates during target but not cue processing
Asymmetrical local switch cost explained by attentional effects

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The time course of the asymmetrical "local" switch cost: Evidence from event-related potentials

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Shortened title: Asymmetrical switch cost and ERPs

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Abstract

The goal of the study was to explore the time-course of the asymmetrical “local” switch cost observed in task switching. We investigated event-related potentials induced by cue and target processing when participants were engaged in a card-sorting switching task. Participants were instructed to match each card (target) following one of two possible task rules, the color or the form. The correct task rule changed unpredictably after a variable number of trials, and was signaled by cues indicating to switch or repeat the previous task rule. We observed that Transition type (*switch* versus *repeat*) and Task rule (*color* versus *form*) influenced both cue and target processing. Interestingly, the interaction between Transition type and Task rule, indicating an asymmetry in the local switch cost, affected the brain responses during target processing but not during cue processing. These results suggest that the asymmetry in the local switch cost relates to task execution processes.

Keywords

Frontal N1; attentional capture; Task difficulty; Task execution; Task preparation

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Introduction

Despite the intense research on task switching, there is still some debate regarding the underlying control processes (see Altmann 2003; Monsell 2003; Bryck and Mayr 2008; Sakai 2008; Schneider and Anderson 2010, for reviews). The goal of the present study was to explore the time course of the processes involved in task switching by investigating the electrophysiological correlates of what is known as the "asymmetrical local switch cost". We paid special attention to those cognitive processes that can be engaged before the target is presented (at cue onset) and to those which are only present at target onset.

The "local switch cost" or "behavioural switch cost" refers to the longer reaction times for targets involving a task change as compared to targets for which no task change is required (e.g., Meiran 1996; Altmann 2002; Rushworth, Passingham et al. 2002; Altmann 2003; Monsell 2003). For example, when asked to classify target cards according to their colour or their form (cf. Figure 1), participants are slower when they have to switch to the other task rule than when they have to repeat the same task rule that they were using for the previous targets (Milner 1963; Rubinstein, Meyer et al. 2001; Barcelo 2003; Barcelo, Perianez et al. 2007). The instruction to switch or to repeat the task rule is signalled by a cue.

Interestingly, the magnitude of the local switch cost seems to depend on how dominant or easy the task at hand is. That is, the local switch cost is larger when switching to the easier of the two tasks involved in the experiment, than when switching to the more difficult task. The consequence of this so-called task-difficulty effect is an asymmetry in the local switch cost (Allport and Wylie 1999; Meuter and Allport 1999; Goschke 2000; Yeung and Monsell 2003; Costa and Santesteban 2004). Asymmetrical local switch costs have given rise to different theoretical proposals (Allport 1994; Meuter and Allport 1999; Allport and Wylie 2000; Mayr and Kliegl 2000; Gilbert and

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Shallice 2002; Mayr 2002; Mayr and Kliegl 2003; Yeung and Monsell 2003; Schneider and Anderson). However, at present we lack a definite understanding of the causes of this asymmetry and, in particular, whether it originates at an early stage of cue processing or later during target processing.

We aimed at exploring the time-course of the processes involved in the local switch cost asymmetry. In doing so, the excellent temporal resolution of event-related potentials was applied to inspect anticipatory task preparation processes at cue onset, as distinct from task execution processes during the presentation of the target. In order to explore the contribution of processes taking place at cue and target onset separately, we used an "intermittently-cued" task design where targets are presented in runs that are interrupted occasionally by cues signalling either to repeat the same task rule (e.g., F F F Repeat-cue F F F), or to switch to the other task rule (e.g., C C C Switch-cue F F F; Gopher, Armony et al. 2000; Monsell 2003, for a review). This paradigm has been useful in revealing the contribution from both cue and target processing to the local switch cost. In particular, it has been found that if enough time separates the cue and the target, some of the processes required for task switching can be anticipated during cue processing (the so called "preparation effect"; cf., Sudevan and Taylor 1987; Meiran 1996; Monsell 2003). Nevertheless, even with very long cue-target intervals, some task switching operations cannot be anticipated and must take place at target onset (the "residual cost"; cf., Rogers and Monsell 1995; Kimberg, Aguirre et al. 2000; Sohn, Ursu et al. 2000).

Previous ERP studies have shown that both cue and target processing contribute to the local switch cost. The ERPs elicited by the presentation of the cue (cue-locked ERPs) differ for repeat and switch cues (Barcelo, Perianez et al. 2002; Brass, Ullsperger et al. 2005; Miniussi, Marzi et al. 2005; Nicholson, Karayanidis et al. 2005; Barcelo, Escera et al. 2006; Nicholson, Karayanidis et al. 2006; Barcelo, Perianez et al. 2007; Jost, Mayr et al. 2008; Perianez and Barcelo 2009). This result

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suggests that the decision to switch or repeat can be anticipated at cue onset. The ERPs induced by the presentation of the target (target-locked ERPs) are also sensitive to "transition type" (*repeat* versus *switch*; Barcelo, Perianez et al. 2002; Swainson, Cunnington et al. 2003; Jackson, Swainson et al. 2004; Jost, Mayr et al. 2008). This reveals that target processing also contributes to the local switch cost. We also know that both cue and target processing are influenced by "task rule" (*colour* versus *form* rule for instance; Mayr and Kliegl 2000; Kieffaber and Hetrick 2005; Miniussi, Marzi et al. 2005; Nicholson, Karayanidis et al. 2005; Nicholson, Karayanidis et al. 2006; Astle, Jackson et al. 2008).

However, little is known about the relative contribution from cue and target processes to the asymmetry in the local switch cost. In other words, we do not know if the interaction between Task rule and Transition type – leading to the local switch cost asymmetry – depends mostly on task preparation processes (at cue onset), on task execution processes (at target onset), or on some combination of both. In our study, we investigated Transition type (*switch* versus *repeat*; a contrast that indexes the local switch cost), Task rule (*colour* versus *form;* a contrast that indexes task difficulty or dominance), and the interaction between Transition type and Task rule (that indexes the local switch cost asymmetry; cf., Rubinstein, Meyer et al. 2001). The main focus of this study was to examine modulations of the brain responses to cue and target events by these two factors, and/or their interaction.

The main question addressed in the present study was whether the asymmetry in the local switch cost is present at the stage of cue and target processing separately. Based on the additive factors logic, we expected an interaction between Transition type and Task rule whenever these two factors influence a common processing stage (Sternberg 1969; Adrover-Roig and Barcelo 2010). Different hypotheses could be put forward at this point. For the sake of clarity, we based our hypotheses on two main theoretical proposals accounting for the asymmetrical local switch cost: The Episodic

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Processing framework (Allport and Wylie 2000; Mayr and Kliegl 2000; Mayr and Kliegl 2003; Rothermund, Wentura et al. 2005; Altmann and Gray 2008; Wong and Leboe 2009) and the Activation/Inhibition account (Allport 1994; Meuter and Allport 1999; Mayr 2002; Yeung and Monsell 2003).

According to the Episodic Processing framework (EP framework), performance in task-switching paradigms mainly depends on prior experiences stored in episodic memory: Task performance is facilitated by having performed the same task a moment before. On switch trials, the high accessibility of a memory representation of the previous task slows down performance of the new task, leading to the local switch cost. Moreover, when switching to the easier task, retrieval of previous episodes of the more difficult task may cause participants to engage in processes related to this more difficult task (larger amount and/or more distinctive representations in memory for difficult tasks; Bryck and Mayr 2008). This would impede responses to the easier task, and lead to larger local switch cost when switching to the easier than to the more difficult task (asymmetrical local switch cost; Wong and Leboe 2009). Based on this framework, the local switch cost asymmetry is due to interference between the task to perform and the task performed a moment before. From this perspective, we would expect an interaction between the Transition type and Task rule factors (leading to the asymmetry in local switch cost), and this would take place during the task execution stage at target onset. Nevertheless, if episodic task codes can be activated by a task cue prior to target onset, the interaction between both factors might also take place during the task preparation stage at cue onset (Altmann and Gray 2008).

According to the Activation/Inhibition account (AI account), performing one of two tasks requires active inhibition of the processing necessary for the other task. At any moment during a task-switching experiment, but mostly at task transition points, the irrelevant task needs to be inhibited. When this task has to be performed on the next trial (after a switch cue), performance is impaired as additional time is needed to overcome the previous inhibition (leading to the local switch cost). To explain the

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asymmetry in local switch cost, this account stipulates that a strong inhibition has to be applied on the mental representations of the easier task when processing the more difficult task. When switching from the more difficult to the easier task it is necessary to overcome the strong inhibition previously applied, and hence, this should induce a larger local switch cost than when switching in the opposite direction (asymmetrical local switch cost; Allport 1994). Therefore, within the AI account, the local switch cost asymmetry results from overcoming the inhibition applied to the irrelevant task. Since the task rule is retrieved during cue processing, we expect the overriding of inhibition to the old task rule to take place at cue onset. Thus, from the AI framework we predict that the interaction between Transition type and Task rule factors (leading to the asymmetry in local switch cost) will occur during the task preparation stage at cue onset. Nevertheless, we cannot exclude that the inhibition of the task not in use may affect processes implemented at stimulus onset. If it was indeed the case, the new rule would be activated at cue onset and the overriding of inhibition of the old task would take place later on, mostly likely at target onset, when the new rule has to be implemented on an actual stimulus.

To sum up, we designed an ERP experiment to investigate the time-course of the asymmetrical local switch cost. Our main focus was to examine if brain responses were modulated by the interaction between Transition type and Task rule at cue and/or target onset. Neither the Episodic Processing framework nor the Activation/Inhibition account could clearly predict these factors to interact during the task preparation or the task execution stage. Thus, our main purpose was not to adjudicate the two theories but rather to provide essential temporal information on task-switching processes in order to constrain future experiments and theoretical accounts.

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Materials and Methods

Participants

Nineteen students from the University of Barcelona (18 females; mean age 21.3 ±2.1; range 19–26 years old) took part in this study and received course credits for participation. All participants were right-handed, had normal or corrected-to-normal vision, and no history of neurological or psychiatric disorder. The experiments were performed in accordance with the Declaration of Helsinki, and informed written consent was obtained from all participants.

Apparatus and Stimuli

A task-cueing protocol inspired by the Wisconsin card sorting test (WCST), the Madrid Card Sorting Test (MCST; Miller 2000; Barcelo 2003), was employed to investigate the local switch cost in task-switching. The MCST is a standard tool to study ERPs elicited by attentional set-shifting effects (Barcelo, Sanz et al. 1997; Barcelo, Munoz-Cespedes et al. 2000; Barcelo 2003). The stimulus material consisted of the 24 choice-cards from the original 64 WCST cards that can be unambiguously matched with four key-cards based on just one stimulus dimension (either the color, form, or number of items in the card; see Figure 1a). Unambiguous cards are required for a sensitive scoring of different types of sorting errors (Barcelo 2003). Each trial consisted of the four MCST key-cards on top of one choice-card, all centered on the computer screen (Figure 1a). The stimulus display subtended a visual angle of 4º horizontally and 3.5º vertically and remained visible until a response was given, or for 3 seconds. The colored geometrical figures were outlined in black against a white background to improve visual contrast, and were matched in luminance. The 24 choice-cards were repeatedly used in 1056 pseudo-randomly arranged target trials that were later subdivided into four blocks of 264 target trials (to enable pauses during the

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experiment). Cues consisted of vertical and horizontal black '~' symbols against a white background that denoted a switch or repetition of the previous task rule, respectively, and were presented for 200 ms (Figure 1). Cues were pseudo-randomly interspersed in the whole sequence of target cards, resulting in 70 transitions for each one of the four conditions obtained by the crossing of two factors: transition type (*repeat* versus *switch*) and task rule (*color* versus *form*). Switch and repeat cues occurred with the same overall probability, and they were equally likely to be associated with either task rule. Each of the four blocks thus consisted of 70 trial sequences, a trial sequence being defined as those choice-cards (targets) presented between any two consecutive cues (see Figure 1a). Sequences consisted of a minimum of 3 and a maximum of 6 trials, although the probability of trial sequences with 4, 5, or 6 cards decreased steadily with p values of 20, 14.6 and 9.3, respectively. The cue-target interval (CTI) ranged randomly between 400 and 600 ms after the cue onset, with an average duration of 500 ms (all multiples of 20 from 400 to 600 were used randomly). Short and randomized CTI were used to ensure that participants would process the cue as fast as possible and would not be able to anticipate the presentation of the first target trial after the cue. The paradigm was previously tested behaviorally and revealed a clear and significant asymmetrical switch cost. The response-stimulus and response-cue intervals ranged randomly between 600 and 800 ms after the response time, with an average duration of 700 ms (all multiples of 20 from 600 to 800 were used randomly).

General Procedure

Participants were instructed to match the choice-card (target) with one of the four key-cards following one of two possible task rules, namely, either the color (easier) or the form (more difficult)[1] of the items in the cards. They were instructed to start

[1] From a long tradition of ERP studies on selective attention, it has long been known that sorting visual stimuli by their color is faster and less error prone than sorting stimuli by its form (Shepp and Swartz 1976; Eimer 1997). This is also true for the color vs. form sorting in the classic

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sorting cards by their color, that the correct task rule would change unpredictably after a variable number of trials, and that the correct task rule would be indicated by the meaning of visual cues. They were informed that after any horizontal '~' sign they would have to keep using the same task rule, and that after any vertical '⎪' sign they would have to switch to the other task rule. The next correct task rule and the length of each sequence both varied pseudo-randomly, so that participants could not predict the start of a new sequence.

Target responses were given with the index and middle fingers of both hands, using the numbers 1-4 from a keyboard in correspondence with the positions of the four key-cards. In other words, the "1" key designated the key-card on the far left of the display, while the "4" key designated the key-card on the far right, and so on. All task conditions required a similar number of responses with each of the four buttons. Visual feedback was provided in case of errors: The Spanish words for 'wrong', 'too fast' or 'too slow' were displayed for 200 ms at the center of the screen following any incorrect response, or when a response occurred earlier than 200 ms or later than 3 seconds from target onset, respectively.

Both the speed and accuracy of responses were emphasized for all task conditions. Before the task, subjects performed one practice session of 50 trials to ensure they had understood the instructions. These practice trials did not enter the analyses. All testing was performed using PCs with a 14-inch monitor and controlled with Presentation® software (Neurobehavioral Systems Inc., Albany, CA).

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Please insert Figure 1 here

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WCST (Nagahama, Okada, et al. 2001). Participants were asked to ignore the numerosity dimension of the cards, although this was also present to keep the same stimulus material as in previous studies, and to compare classification performance between 2 and 3 different task rules in a subsequent series of experiments.

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Statistical Design and Behavioral analyses

Mean reaction times (RTs) were obtained from correct trials and error rates from failed trials. Failed trials were defined as those where subjects (a) failed to follow the instruction cue to switch or repeat the previous task rule, or (b) failed to select the correct target response within the currently relevant task rule (Barcelo 2003). Card sorts performed earlier than 200 ms post-card onset ('too soon'), or later than 3000 ms post-card onset ('too late') were also scored as 'miss' and were not considered in the RT analysis.

The local switch cost was computed as the difference in mean RTs between the first switch and first repeat targets following cues (see Monsell 2003; Barcelo, Perianez et al. 2007). Mean RTs and error rates were subjected to repeated measure analyses of variance (ANOVAs) with transition type (*repeat* vs. *switch*) and task rule (*color* vs. *form*) as within-subject factors. Only the first target after a cue was included in the analyses, as first target trials show maximal effects of switch specific local costs (Monsell 2003; Barcelo, Perianez et al. 2007).

Electrophysiological recording and analyses

Electrophysiological data were recorded in reference to an electrode placed on the participant's nose at a rate of 250 Hz from 31 tin electrodes placed according to the 10-20 convention (FPz, FP1, FP2, Fz, F3, F4, F7, F8, FC1, FC2, FC5, FC6, Cz, C3, C4, T3, T4, CP1, CP2, CP5, CP6, Pz, P3, P4, T5, T6, PO1, PO2, Oz, O1, O2). Impedances were kept below 5 kΩ. EEG activity was filtered off-line with a 20Hz low-pass filter and a 0.3Hz high-pass filter (24 dB). Eye blink artifacts were mathematically corrected using the Gratton et al.'s procedure (1983), implemented in Brain Vision Analyzer 1.05 (Brain Products), and any remaining artifacts were manually dismissed. Epochs ranged from −100 to 600 ms after the onset of cue or target presentation. Baseline correction was performed in reference to pre-stimulus activity and individual

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averages were digitally re-referenced to a linked-mastoid reference. For each condition, the grand average was obtained by averaging individual averages. ERP components were defined based on the mean global field power measured across the scalp, which summarizes the contribution of all electrodes in the form of a single vector norm (Picton, Bentin et al., 2000). This procedure was applied on the grand averages obtained for each condition. For each component observed on grand averages, the electrode of maximal amplitude of the peak was defined as the "referent electrode". The latency of each peak corresponded to the latency over the referent electrode. The interval of each component was the time-window centred on the latency value and with a duration based on visual inspection of the mean global field power (intervals ranging from 40 to 150 ms depending on the spreading over of each component). This allowed automatic peak detection in the following intervals (for each individual average): 80-120 ms for the cue-locked P1 (group average peak latency = 100 ms), 120-160 ms for the cue-locked N1 (group average latency = 140 ms), 260-300 ms for the cue-locked N2 (latency = 280 ms), 290-360 ms for the early cue-locked P3 (latency = 325 ms) and 360-450 ms for the late cue-locked P3 (latency = 430 ms). Cue-locked waveforms were not analyzed later than 450 ms after cue onset to avoid overlap in the short CTI condition. For the target-locked ERP components, time-windows were 40-100 ms for C1 (latency = 70 ms), 90-130 ms for P1 (latency = 110 ms), 170-240 ms for P2 (latency = 205 ms), 240-300 ms for N2 (latency = 270 ms), 300-450 ms for P3 (latency = 375 ms) and 120-160 ms for frontal N1 (fN1; latency = 140 ms). Individual mean amplitudes (average of the ERP amplitude in a given interval) were measured for each component and each participant.

Those mean amplitudes were submitted to a repeated measures ANOVA design with Transition type (*repeat* versus *switch*), Task rule (*colour* versus *form*) and Electrode (3 sites) as within-subject factors. For the cue-locked ERP components, P1 and N1 were studied at the 3 electrode sites with maximal mean peak amplitude (O1, O2 and Oz electrodes). Early and late P3 were studied over the parietal scalp (P3, P4

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and Pz electrodes) and N2 was studied over the frontocentral scalp (FC1, FC2 and Fz electrodes). For the target-locked ERP components, C1, P1, P2 and N2 were studied at the 3 electrode sites with maximal mean peak amplitude (O1, O2 and Oz electrodes). The target-locked P3 was studied over parietal regions (P3, P4 and Pz electrodes) and fN1 was studied over the frontocentral scalp (FC1, FC2 and Fz electrodes).

Results

Behavioral results

The ANOVA performed on reaction times revealed a significant main effect of Transition type ($F[1, 18] = 13.52$, $p < .01$), indicating that participants responded faster when classifying cards following a repeat compared to a switch cue (see Figure 2a). A significant main effect of Task rule ($F[1, 18] = 80.02$, $p < .001$) revealed that participants sorted cards faster by color than by form. The interaction between Transition type and Task rule was also significant ($F[1, 18] = 5.60$, $p < .05$), showing that the local switch cost was significant when sorting cards by their color (92 ±20 ms ; $p < .01$) but not when sorting cards by form (14 ±21 ms; $p = .94$; see Figure 2b).

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Error rates, presented in Table 1, were also subjected to a general ANOVA. There was a significant main effect of Task rule ($F[1, 18] = 8.94$, $p < .05$), showing that participants made significantly more errors when classifying by form than by color.

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Cue-locked ERPs

In the occipital region, the general ANOVA revealed a significant main effect of Transition type on the P1 ($F[1, 18] = 7.56$, $p < .05$) and N1 ($F[1, 18] = 16.65$, $p < .001$) cue-locked components (Figure 3a). The P1 peak was significantly larger and the N1 peak was significantly smaller for switch than for repeat cues. There was no main effect of Task rule and no Transition type x Task rule interaction (All Ps >.22).

In the parietal region, the early cue-locked P3 component was modulated neither by Transition type nor by Task rule (All Ps >.13; Figure 3a). The late cue-locked P3 component was significantly larger in response to switch than to repeat cues ($F[1, 18] = 8.09$, $p < .05$) with no Task rule effect ($F[1, 18] = 2.16$, $p = .16$) and no interaction ($F[1, 18] = 2.07$, $p = .17$).

In the frontocentral region, the N2 cue-locked component was significantly modulated by Transition type ($F[1, 18] = 4.74$, $p < .05$) and Task rule ($F[1, 18] = 7.75$, $p < .05$), with no interaction ($F[1, 18] = .45$, $p = .51$; Figure 3b): Thus, N2 mean amplitude was larger for repeat than for switch cues, and larger for color than for form task rule.

To summarize, the brain responses to cue processing started to be modulated by Transition type (*switch* versus *repeat*) around 100 ms after cue display (with larger P1 mean amplitudes for switch cues). The earliest task rule effect appeared around 200 ms after cue display (with larger N2 mean amplitudes for the color rule). No Transition type x Task rule interaction was observed for the whole duration of the cue-locked waveform.

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Target-locked ERPs

In the occipital region, the general ANOVA revealed that visual C1 target-locked mean peak amplitude was significantly larger following a repeat than a switch cue ($F[1, 18] = 5.71$, $p < .05$) with no Task rule effect ($F[1, 18] = 2.80$, $p = .11$), and no Transition type x Task rule interaction ($F[1, 18] = .49$, $p = .49$; Figure 4a). The mean peak amplitudes of P1, P2 and N2 target-locked potentials were modulated neither by Transition type nor Task rule (All Ps >.17).

In the parietal region, target-locked P3 amplitude was significantly larger after a repeat than a switch cue ($F[1, 18] = 11.58$, $p < .01$), and significantly larger when classifying by color than by form ($F[1, 18] = 4.47$, $p < .05$) with no Transition type x Task rule interaction ($F[1, 18] = 1.10$, $p = .31$; Figure 4a).

In the frontocentral region, the general ANOVA revealed a significant Transition type x Task rule interaction ($F[1, 18] = 12.07$, $p < .01$) on the target-locked fN1 component (Transition type main effect: $F[1, 18] = 4.12$, $p = .06$; Task rule main effect: $F[1, 18] = 2.95$, $p = .10$; Figure 4b). Post-hoc analyses revealed that the fN1 mean peak amplitude was significantly larger following a switch than a repeat cue when classifying by color ($p < .01$), with no Transition type effect when classifying by form ($p = .99$).

To summarize, the brain responses to the first target following either a repeat or a switch cue started to differ around 50 ms after target display (with larger C1 mean peak amplitudes for repeat trials). The earliest ERP modulations from Task rule on target processing started around 350 ms after target display (with larger P3 peak for color Task rule). Most importantly, a significant interaction between Transition type and

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Task rule was observed in the fN1 [120 – 160 ms] time-window, revealing larger fN1 mean peak amplitudes in response to color switch –rather than repeat– target trials.

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Discussion

The goal of the present study was to explore the time-course of task-switching processes by assessing the electrophysiological counterparts of the local switch cost, and the cost asymmetry associated with it in certain cases. In particular, we were interested in assessing if the local switch cost asymmetry occurs during the anticipatory task-preparation stage (at cue onset) or during the task-execution stage (at target onset). In order to infer the presence of electrophysiological correlates associated with the local switch cost asymmetry, we searched for those ERP components that were specifically modulated by the interaction of two factors: Transition type (*switch* vs. *repeat*) and Task rule (*colour* vs. *form*).

The behavioural results revealed the expected effects of both transition type and task rule. That is, reaction times were larger for switch than for repeat trials. Regarding the task rule, participants were faster and more accurate when sorting by color than by form, showing the difference in dominance between both task rules (cf. Rubinstein, Meyer et al. 2001, for similar task rule effect). Importantly, we also replicated the interaction between Transition type and Task rule, suggesting a larger local switch cost for the easier color rule.

More interesting for our purposes was to determine how these behavioural effects (i.e., the interaction between Transition type and Task rule) affect the

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processing of cues and targets separately. In order to do so, we explored how these factors modulate cue-locked and target-locked ERPs separately.

Cue-locked ERPs

The comparison of the ERPs elicited by switch and repeat cues revealed several differences. The first ERP modulation by Transition type was observed on the P1/N1 ERP complex. However, given that we used different symbols for switch and repeat cues (vertical and horizontal "~" symbols, respectively), it is not possible to conclude whether these early P1/N1 effects were caused by changes in the low-order representations of physical features, or by high-order representations associated with transition type (cf. Garcia-Garcia, Barcelo et al. 2010).

From about 200 ms after cue onset, the Transition type factor modulated various components in the ERP waveform. Firstly, the frontal N2 component was smaller for switch cues as compared to repeat cues. Secondly, we observed larger cue-locked late P3 mean amplitudes over mid-parietal regions in response to switch cues compared to repeat cues. Similar effects of transition type on the frontal N2 and late P3 components have been reported previously (Barcelo, Perianez et al. 2002; Rushworth, Passingham et al. 2002; Brass, Ullsperger et al. 2005; Miniussi, Marzi et al. 2005; Nicholson, Karayanidis et al. 2005; Poulsen, Luu et al. 2005; Barcelo, Escera et al. 2006; Nicholson, Karayanidis et al. 2006; Barcelo, Perianez et al. 2007; Jost, Mayr et al. 2008; Perianez and Barcelo 2009). There is ample agreement that these ERP components could index processes related to the anticipatory reconfiguration of the task to be performed next (Barcelo, Perianez et al. 2002; Karayanidis, Coltheart et al. 2003; Nicholson, Karayanidis et al. 2005; Barcelo, Escera et al. 2006; Barcelo, Perianez et al. 2007; Jost, Mayr et al. 2008; Perianez and Barcelo 2009). Note that several studies revealed the opposite transition type effect for the N2 component - that is, an N2 peak larger for switch than for repeat cues (Brass, Ullsperger et al. 2005; Miniussi, Marzi et al. 2005; Jost, Mayr et al. 2008). Differences between task

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paradigms might account for these inconsistent results. One possible explanation is that the cue-locked N2 component is not only affected by transition type but also by perceptual priming associated with cue switching: It has been shown that cue switches in the absence of task switch elicit smaller cue-locked N2 amplitudes compared to cue repetitions (Perianez and Barcelo 2009). Thus, mean N2 amplitude seems to depend on the combined effects of both cue- and task-switching. As cue and task switching were confounded in our study, we cannot rule out that the present cue-locked N2 effects were caused by cue switches, task switches, or a combination of both. The exact association between various ERP components and specific processes involved in task-switching is still debated. Nevertheless, our results are consistent with the general idea that some preparatory task switching operations can be engaged in anticipation of target display (Lavric, Mizon et al. 2008).

When comparing the ERPs elicited by cues leading to color or to form task rule we observed only one main difference, namely a modulation of the frontal N2 component. Interestingly, the N2 was larger for the easier task rule (color) than for the more difficult one (form). Note that this effect goes in the same direction as the effect for transition type: the more difficult the condition (being switching or sorting by form), the smaller the amplitude of the N2 component. The important aspect for our purposes here is that the to-be-used task rule is already being computed during cue processing, and hence well before the target is presented (Meiran 1996; Mayr and Kliegl 2000; Barcelo, Perianez et al. 2002; Kieffaber and Hetrick 2005; Miniussi, Marzi et al. 2005; Nicholson, Karayanidis et al. 2005; Nicholson, Karayanidis et al. 2006).

Having established that both the Transition type and Task rule factors separately affect the processing of the cue, we proceeded to examine the main question of the study about the local switch cost asymmetry. Indeed, the finding of a significant interaction between these two factors in the behavioral data revealed the presence of the predicted local switch cost asymmetry. The behavioral results, however, left open the important question of whether the neurocognitive processes that

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originate such an interaction occur at target onset, or are already present after cue onset.

The ERP results were clear in this respect, since the interaction between Transition type and Task rule did not modulate the waveforms in the cue-target interval. Even though it is always problematic to interpret a null effect, it should be noted that both Transition type and Task rule factors each separately produced significant ERP modulations during the same time window (see above). Consequently, the present results suggest that the local switch cost asymmetry does not depend on anticipatory processes initiating at cue onset, at least for the short cue-target intervals (400-600 ms) employed in the present study. Future research has to be done to ensure that there is no interaction between Transition type and Task rule at cue onset even with longer cue-target intervals. Another limitation of the study is that gender was not appropriately balanced among participants, and thus the results cannot be generalized to the male population without further evidence.

Target-locked ERPs

As expected, Transition type (*switch* vs. *repeat*) significantly modulated several time-windows in the target-locked waveforms. First, the C1 ERP component – [40-100 ms] time-window – was significantly modulated by Transition type (with larger C1 peak amplitudes for task-repeat trials). This Transition type effect on the early C1 target-locked component might likely be due to “carry over” effects of cue processing (after-effects of the cue-locked P3 modulation by Transition type). In the frontocentral region, the fN1 component was significantly larger when participants had to switch to a new task rule than when they had to repeat the same task rule to classify the target. Later, the P3 component was larger when participants had to repeat the task rule than to switch to a new one, which is a very consistent ERP finding in the task-switching literature (cf. Barcelo, Sanz et al. 1997; Barcelo, Munoz-Cespedes et al. 2000; Barcelo, Perianez et al. 2002; Swainson, Cunnington et al. 2003; Barcelo, Perianez et al. 2008).

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These effects of transition type on the target-locked fN1 and parietal P3 components have already been reported and attributed to several different processes. The frontal N1 component has been associated with attention capture in order to facilitate sensory and motor responses to the eliciting stimulus (Desimone and Duncan 1995; Clark and Hillyard 1996; Escera, Alho et al. 1998; Hillyard and Anllo-Vento 1998), whereas the target P3 component has been related to the rehearsal and implementation of task rules in working memory (Barcelo, Perianez et al. 2002; Jost, Mayr et al. 2008; Perianez and Barcelo 2009).

When comparing the brain responses elicited by targets classified by color or by form we observed only one significant modulation of the P3 component. Interestingly, the target P3 was larger for the easier color rule than for the more difficult form rule. Note that this effect goes in the same direction as the transition type effect: the more difficult the condition (either switching or form) the smaller the target-locked P3 amplitudes. Likewise, the more difficult the condition (either switching or sorting by form) the smaller the cue-locked N2 amplitudes. This finding is consistent with the idea that higher working memory load at task preparation (i.e., because of a switch cue or the retrieval of the form rule) could impair task execution of the next target with short cue-target intervals (Barcelo, Perianez et al. 2008; Perianez and Barcelo 2009).

What is more relevant for our purposes is the extent to which the interaction between the Transition type and Task rule factors modulates the target-locked brain responses. Such a modulation only affected the frontally-distributed fN1 component: whereas similar frontal fN1 amplitudes were elicited by colour and form classifications in response to task-repeat target trials, significantly larger fN1 amplitudes were elicited by task-switch target trials when participants sorted cards by colour -rather than by form[2]. This finding is, to our knowledge, the first concurrent electrophysiological

[2] Note that the main Transition type effect observed on the fN1 component might be an after-effect of cue processing, as for the C1 component. Nevertheless, the important result for our purpose is based on the Transition type x Task rule interaction observed on this component, an interaction that cannot be explained by cue processing after-effects: cue-locked late P3

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evidence for the local switch cost asymmetry. Thus, the present ERP evidence, obtained from the comparison of both cue-locked and target-locked brain responses, suggests that the asymmetry in the behavioral local switch cost could arise at the stage of task execution, around 120 ms following target onset, in correspondence with the observed modulations in the target-locked frontal N1 waveform. Amplitude enhancements of the frontal N1 subcomponent have been previously associated to increased demands for attentional control (Clark and Hillyard 1996; Hillyard and Anllo-Vento 1998). The functional role of the neural generators of this frontal N1 might consist in triggering a transient arousal burst, thus facilitating sensory and motor responses to a momentary relevant stimulus (Naatanen and Picton 1987; Naatanen 1990; Giard, Perrin et al. 1994; Escera, Alho et al. 1998). Frontal N1 modulation in our experiment means that when participants have to switch to colour – compared to form switches – attentional control circuitry provides "bias signals" to boost attention during the processing of the target stimulus. In the next section, we consider the theoretical implications of this observation.

Theoretical accounts of asymmetrical local switch cost

The main empirical observations of the present study are that both transition type (*switch* or *repeat*) and task rule (*color* or *form*) manipulations already influence brain processes at cue onset (Meiran 1996; Barcelo, Perianez et al. 2002; Monsell 2003; Van Loy, Liefooghe et al. 2010) as well as at a later stage of task execution at target onset. Most importantly for our purposes, the critical interaction between Transition type and Task rule factors only modulates the brain responses during target presentation, which can be taken as evidence that the local switch cost asymmetry does not stem from anticipatory processes during the cue-target interval.

amplitudes were systematically larger for switch cues compared to repeat cues (an otherwise very consistent finding in the literature). In contrast, the above mentioned interaction revealed larger target-locked fN1 for color switches compared to all other conditions.

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Different theoretical proposals have explained the asymmetrical local switch cost without taking into account whether this asymmetry originates at the level of cue or target processing. Based on the present results, theoretical accounts need to consider that the asymmetry in the local switch cost originates at the stage of task-execution (target onset) and not task-preparation (cue onset). In the following, we discuss how the present results can be integrated with two different theories accounting for the asymmetrical local switch cost.

According to the Episodic Processing framework, the local switch cost asymmetry is due to interference between the task to perform and the task performed a moment before. Thus, the Transition type x Task rule interaction (leading to the asymmetry in local switch cost) is supposed to take place at least at target onset (task execution stage). The results of our experiment are consistent with the EP framework, since the interaction between Transition type and Task rule was observed only at target onset. Based on the assumption that the target-locked fN1 component is associated with attention capture, the present results reveal that more attentional resources are allocated to switching to the easier –compared to the more difficult– task. The attempt to counteract the proactive interference from a previous difficult task would require a larger allocation of attentional resources than conversely.

These observations and interpretation are compatible with another recent hypothesis about the nature of the local switch cost asymmetry: The “sequential difficulty effects” account (Schneider and Anderson 2010). The main idea of this account is that the asymmetric switch cost is not a pure task-switching effect but rather the combination of sequential difficulty effects and what could be a symmetric switch cost. Schneider & Anderson (2010) argue that an impairment following difficult trials might explain the asymmetrical local switch cost, being caused by a depletion of working memory or executive control resources. Assuming that the more difficult of two tasks requires more resources than the easy task, resource depletion would be greater

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following the difficult than the easy task, producing a sequential difficulty effect (asymmetrical cost). In the case of our experiment, this would mean that after using the more difficult form task the brain suffers from depletion in working memory or executive control resources. When switching to the colour task, the brain has to compensate for these depleted resources by allocating a larger amount of attentional resources, to implement the appropriate colour task set at target onset. This sequential difficulty effect may not be so strong when switching from colour to form because the interference from colour sorting is comparatively weaker (i.e., the previously used colour task is easy and does not deplete working memory or executive control resources as much; cf. Schneider and Anderson 2010). This sequential difficulty effect explains well the asymmetrical local switch cost observed in our experiment (Schneider and Anderson 2010; see also Barcelo, Perianez et al. 2008, for a similar model of task switching based on trial-by-trial allocation of working memory resources).

Within the Activation/Inhibition account, the asymmetry in the local switch cost results from overcoming the inhibition applied to the irrelevant task. The present results can be consistent with the AI account if we consider that the inhibition applied to the irrelevant task affects target processing. Overcoming the inhibition would then occur at target onset, which corresponds with the time-window when the Transition type x Task rule interaction was observed in the experiment.

The main conclusion of the present study is that the asymmetry in local switch cost (interaction between Transition type and Task rule factors) originates at target onset rather than at cue onset. Therefore, theoretical accounts of task-switching need to consider that the asymmetrical local switch cost relates to task-execution rather than task-preparation processes, and might be explained by the differential availability of attentional resources at target onset.

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Funding

This work was supported by grants from the Spanish Government (grant numbers PSI2010-17419/PSIC, PSI2008-01191/PSIC with EC Fondos FEDER, Consolider Ingenio 2010 CE-CSD2007-00121). CM was supported by a Post-doctoral fellowship from the Catalan Government (Beatriu de Pinós).

Acknowledgements

We would like to thank Iva Ivanova for her advice about the manuscript and Joke Durnez and Jan Decock for their help in data acquisition. Correspondence should be addressed to Clara D. Martin (claramartin3@gmail.com).

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Figure captions

Figure 1: Experimental design. **a.** Schematic description of the experimental design. Cards were originally presented in four different colours (red, green, yellow, blue) which are schematically represented by different types of lines in the figure. Note that each choice-card can be unambiguously matched with each key-card based on just one stimulus dimension. **b.** Schematic example of two MCST series (repeat and switch). Note that the local switch cost was measured as the difference in reaction times between the first target after a switch and a repeat cue.

Figure 2: Behavioural results. **a.** Reaction times (ms) as a function of the position of the target in a series in the four main conditions “switch to classify by form”, “repeat classifying by form”, “switch to classify by colour”, “repeat classifying by colour”. Error bars represent standard errors. **b.** Critical reaction times used to measure the local switch cost: Reaction times on the first target classified by colour or by form, after a switch or a repeat cue. Error bars represent standard errors. Note that the local switch cost (difference in reaction time between the first target after a switch and a repeat cue) has a magnitude of 92 ms when classifying by colour and of 14 ms when classifying by form.

Figure 3: Cue-locked Event-Related Potentials (ERPs). **a.** ERPs elicited by the presentation of a cue at 3 midline electrode sites (Occipital = O1, O2 and Oz electrodes; Parietal = P3, P4 and Pz electrodes; Central = C3, C4 and Cz electrodes). **b.** ERPs elicited by the presentation of a cue over frontocentral region (FC1, FC2 and Fz electrodes). ERP waves are broken by transition type (switch *versus* repeat) and task rule (colour *versus* form).

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Figure 4: Target-locked Event-Related Potentials (ERPs). **a.** ERPs elicited by the presentation of the first target after a cue, at 3 midline electrode sites (Occipital = O1, O2 and Oz electrodes; Parietal = P3, P4 and Pz electrodes; Central = C3, C4 and Cz electrodes). **b.** ERPs elicited by the presentation of the first target after a cue, over frontocentral region (FC1, FC2 and Fz electrodes). ERP waves are broken by transition type (switch *versus* repeat) and task rule (colour *versus* form).

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Table 1

Position	1	2	3	4	5	6
Switch Form	7.0 (4.4)	4.2 (3.4)	3.7 (2.7)	3.1 (2.8)	5.6 (6.2)	2.6 (7.9)
Repeat Form	7.2 (5.0)	4.3 (2.5)	4.3 (2.8)	2.9 (4.6)	2.0 (3.6)	3.2 (5.8)
Switch Color	5.1 (3.1)	5.2 (3.5)	4.1 (2.6)	3.8 (3.7)	3.8 (4.9)	3.0 (6.0)
Repeat Color	3.7 (2.9)	3.2 (2.8)	1.7 (1.8)	2.2 (3.1)	1.6 (2.7)	1.1 (4.6)

Error rates (%) as a function of the position of the target in a series in the four main conditions “switch to classify by form”, “repeat classifying by form”, “switch to classify by colour”, “repeat classifying by colour”. Standard deviations are presented in parenthesis.

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Figure1
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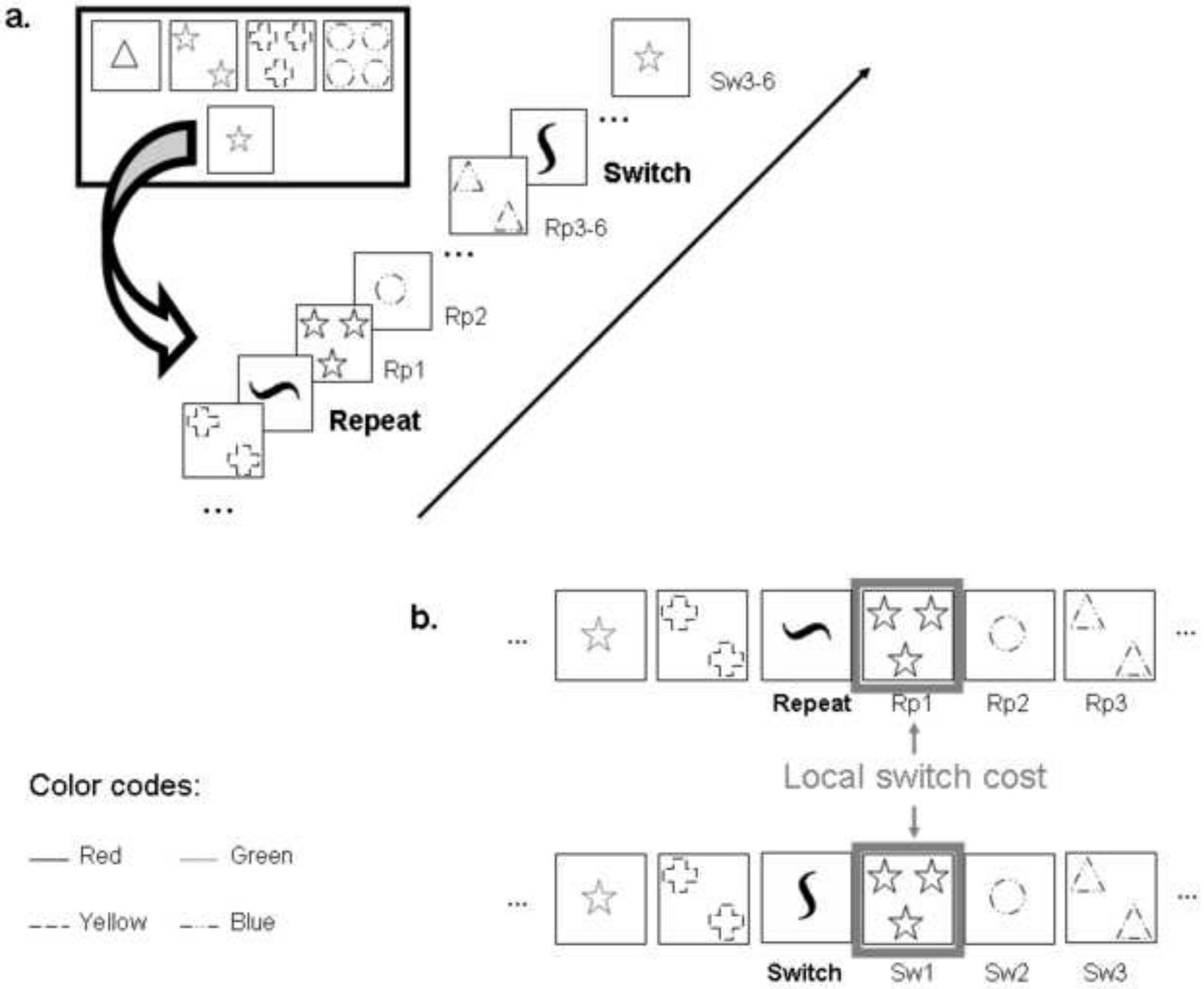

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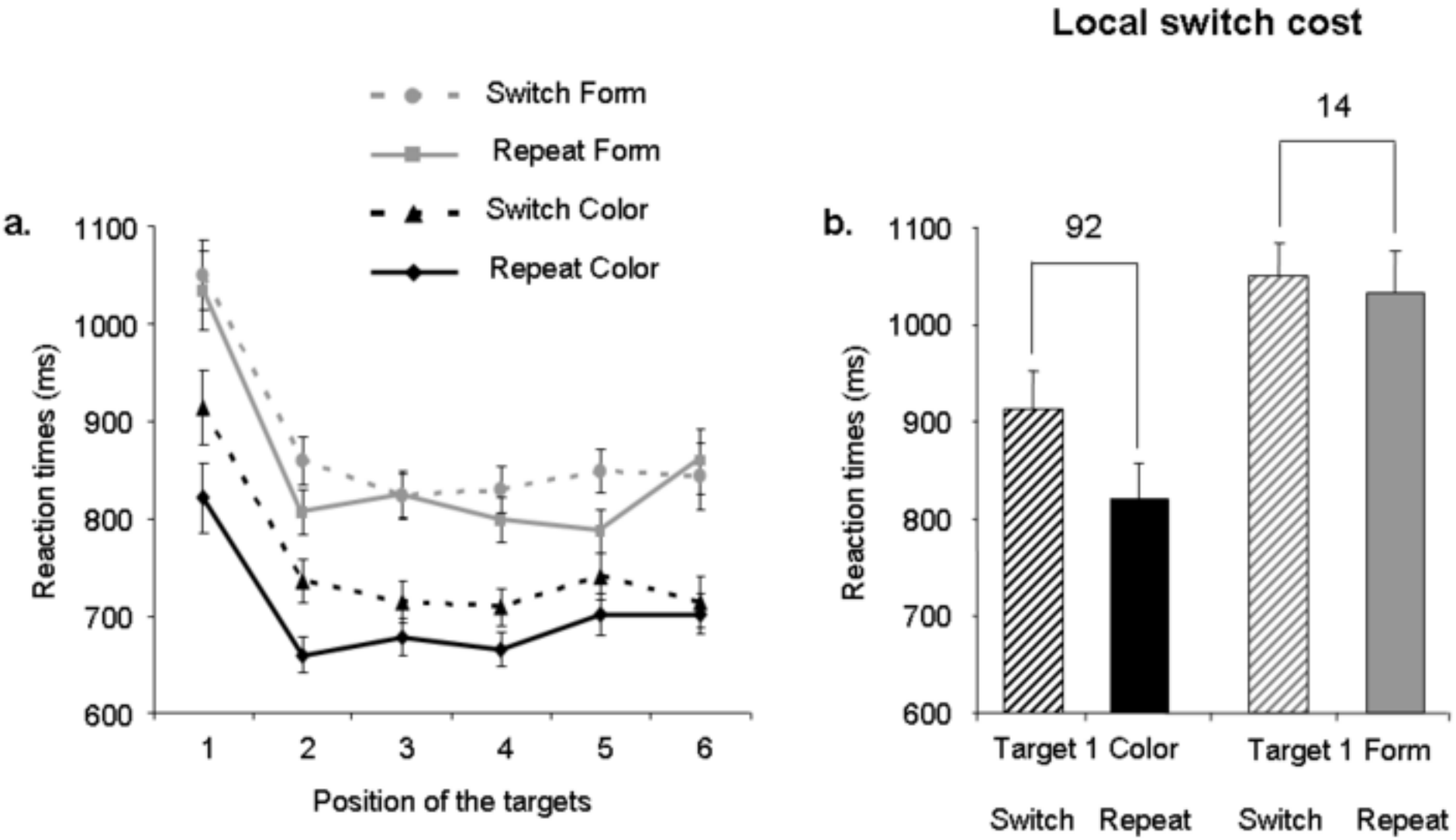

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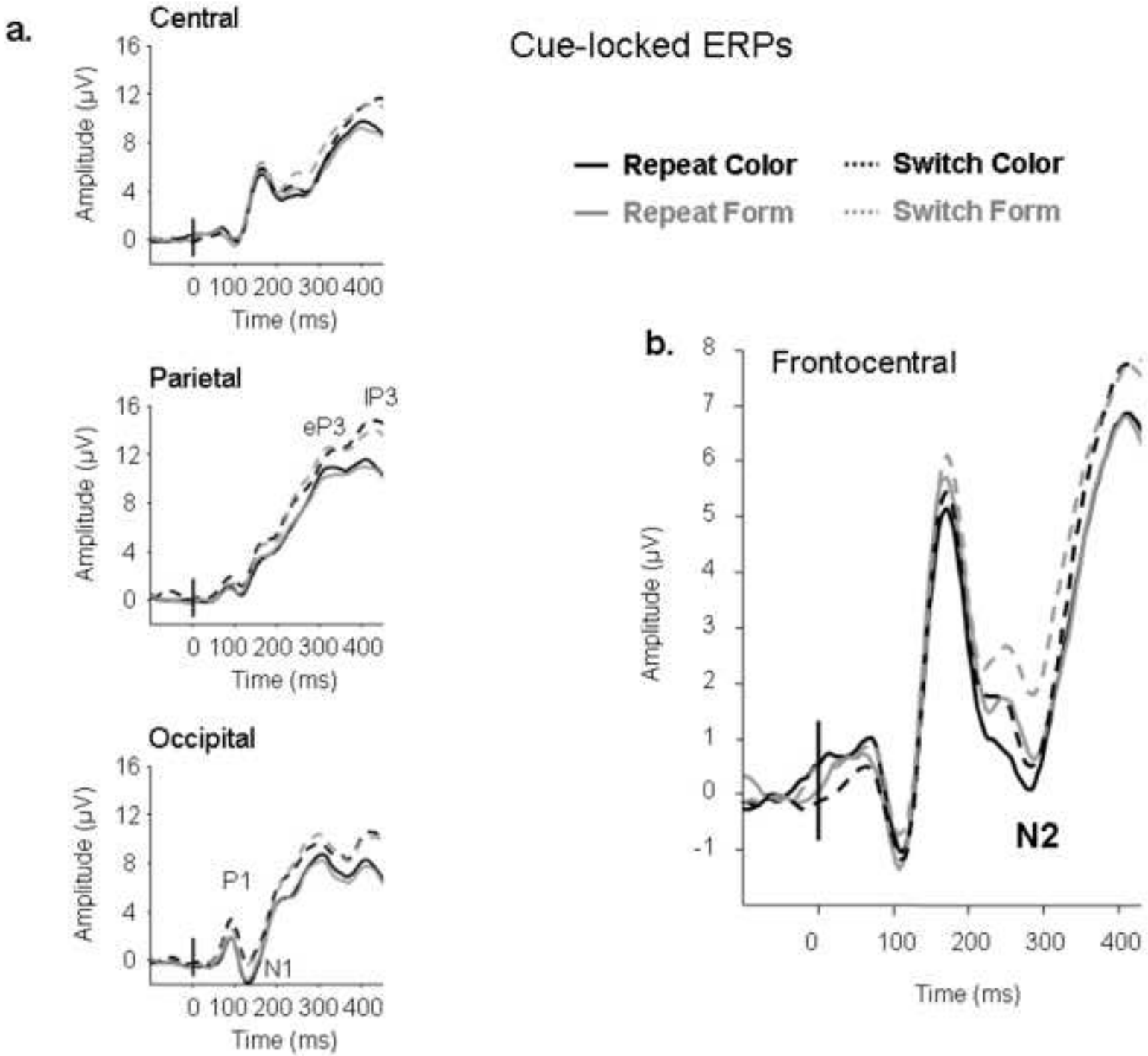
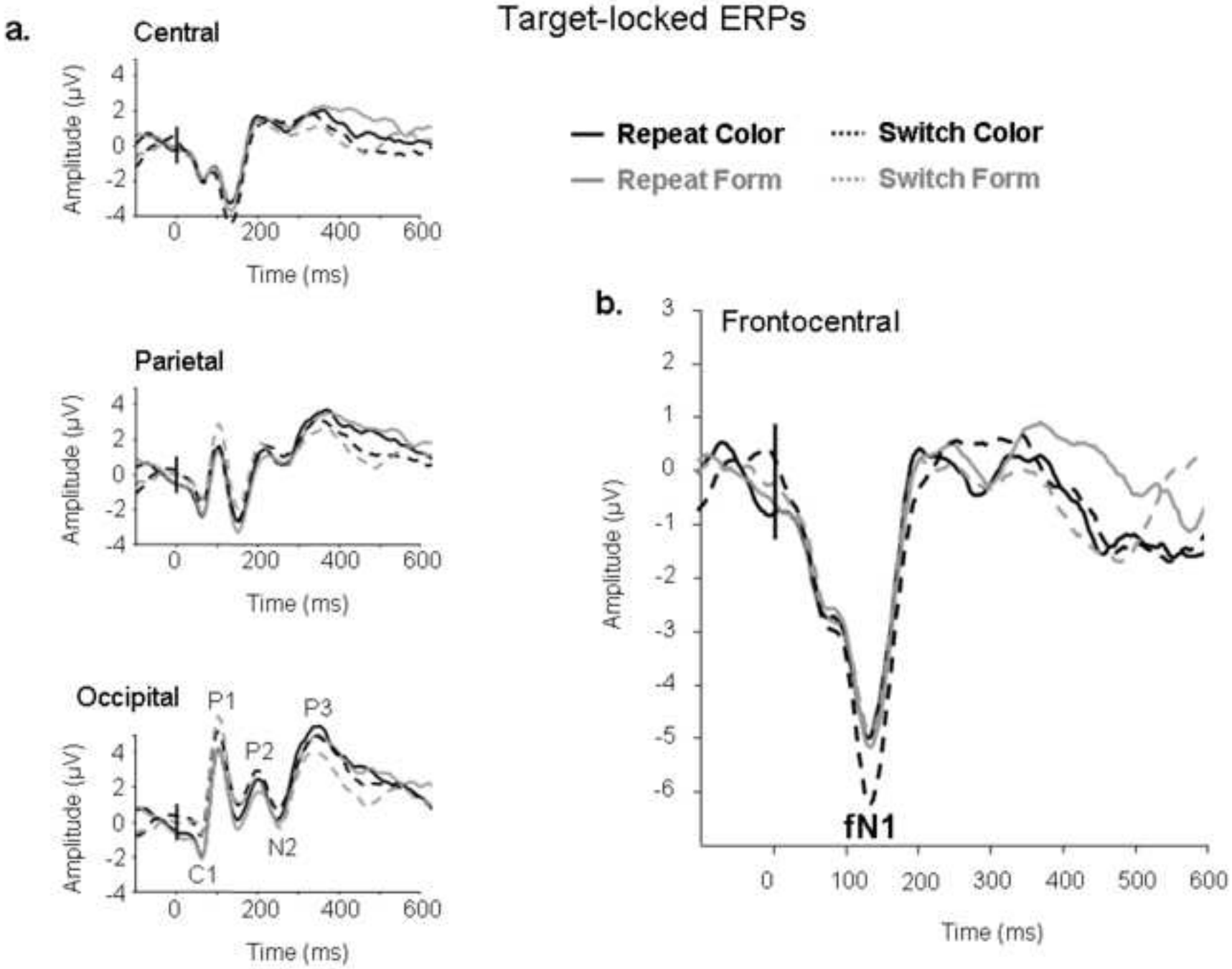
Figure4
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