TMS of the FEF Interferes with Spatial Conflict

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Abstract

■ In the Simon task, a conflict arises because irrelevant spatial information competes for response selection either facilitating or interfering with performance. Responses are faster when stimulus and response position correspond than when they do not. The FEFs, which have long been characterized for their role in oculomotor control, are also involved in the control of visuospatial attention when eye movements are not required. This study was aimed at investigating whether the FEFs contribute to spatial conflict. Double-pulse TMS was applied to the FEF of either left or right hemisphere during the execution of a Simon task at different time windows after the onset of the visual stimulus. A suppression of the Simon effect was observed after stimulation of the FEF for stimuli appearing in the contralateral hemifield when TMS was applied to the left hemisphere after stimulus onset (0–40 and 40–80 msec). A reduction of the correspondence effect was observed after right FEF TMS for stimuli presented in the left visual hemifield when stimulation was delivered in the 80–120 msec range after stimulus onset. These outcomes indicate that the FEF play a critical role in encoding spatial attribute of a stimulus for response priming, which is the prerequisite for response conflict in the Simon task. Moreover, our finding that the left FEF have a dominant role during spatial conflict extends the idea of the left-hemisphere lateralization of the motor network in action selection by suggesting that the FEF may constitute part of this network. ■

INTRODUCTION

The visual environment continuously presents us with multiple opportunities for action, and a conflict often arises between sensorimotor processes and different possible responses. In many situations, irrelevant information may interfere with response selection, and this effect of interference is particularly robust when the irrelevant information is strongly associated with a dimension of the response.

In the Simon task, a conflict arises because irrelevant spatial information competes with relevant nonspatial information for response selection. Here, participants are required to respond to a nonspatial attribute of lateralized targets (e.g., color or shape) while ignoring their spatial position. For example, participants may be asked to press the left key when a red circle appears and the right key when a green circle appears. Although stimulus location is irrelevant to the task, RTs are faster when stimulus and response positions correspond than when they do not (Lu & Proctor, 1995; Umiltà & Nicoletti, 1990; Simon & Rudell, 1967).

To explain mechanisms underlying conflict, dual-route models (De Jong, Liang, & Lauber, 1994; Kornblum, Hasbroucq, & Osman, 1990) postulate two parallel routes of information processing: spatial information automatically activates its spatially corresponding response via a fast direct route, whereas the task-relevant stimulus code activates the required response via a slow controlled indirect route (Wascher, Schatz, Kuder, & Verleger, 2001; Kornblum et al., 1990). The direct route may be established by long-term associations between perceptual and motor processes, which may depend on the synaptic consolidation of stimulus–response (S-R) associations widely overlearned during lifetime (Tagliabue, Zorzi, Umiltà, & Bassignani, 2000; Cohen, Dunbar, & McClelland, 1990). When the direct route (carrying the response linked to the spatial position of the stimulus) and the indirect one (holding the task demands) generate the same response codes (i.e., in the corresponding condition [C]), RTs are speeded up, whereas when the two routes generate different response codes (i.e., in the noncorresponding condition [NC]), a conflict must be resolved, resulting in slower responses.

The "attention shift" hypothesis maintains that the irrelevant spatial code of the stimulus is generated by the direction of the attention shift implemented before response selection. When the peripheral stimulus is presented, attention covertly shifts toward its position (Rubichi, Nicoletti, Iani, & Umiltà, 1997; Nicoletti & Umiltà, 1994). According to the premotor theory of attention, shifting attention is accomplished by the generation of the motor program for the corresponding saccade regardless of whether the saccade is subsequently executed or not (Umiltà, Riggio, Dascola, & Rizzolatti, 1991; Rizzolatti, Riggio, Dascola, & Umiltà, 1987). The alternative hypothesis, known as the "referential coding" hypothesis (Hommel, 1993; see also Hommel, 2011), states that the irrelevant spatial code

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is generated as a result of the comparison between the location of the target stimulus and the location of an intentionally defined reference stimulus (e.g., the fixation point). Both the attention shifting and the referential coding accounts of the Simon effect have linked the processing of the spatial code to attention, to some extent at least (for a recent discussion of these hypotheses, see also Van der Lubbe & Abrahamse, 2011).

A neural correlate for encoding spatial coordinates of stimulus and response during conflict may be attributed to cerebral areas devoted to the control of visuospatial attention and visuomotor integration. The posterior parietal cortex (PPC), as part of the dorsal visual stream, is thought to be involved in both visuospatial attention and transformation of sensory information into codes for action (Kravitz, Saleem, Baker, & Mishkin, 2011; Goodale & Milner, 1992; Rizzolatti et al., 1987). Recent studies suggested that PPC plays a critical role in processing irrelevant spatial information for response priming during conflict. TMS of PPC, applied after stimulus onset, causes a suppression of the Simon effect as if no stimulus spatial code interfered with performance (Schiff, Bardi, Basso, & Mapelli, 2011; Rusconi, Turatto, & Umiltà, 2007; Stürmer, Redlich, Irlbacher, & Brandt, 2007). On the basis of these results, PPC has been identified as the main neural substrate of visuomotor transmission within the direct route.

A growing body of anatomical and physiological evidence suggests, however, that space representation and visuomotor transformation involve other brain areas than PPC within a distributed fronto-parietal cortical circuit. A prominent role within this network has recently been assigned to the FEF (Corbetta & Shulman, 2002), which have been shown to contribute to transformation of visual signals into saccade commands. This area has long been characterized for its role in the control of eye movements (e.g., Olk, Chang, Kingstone, & Ro, 2006; Moore & Farah, 2001; Gaymard, Ploner, Rivaud, Vermersch, & Pierrot-Deseilligny, 1998) and has also been shown to play a role in the allocation of attention in space, regardless of whether movements are executed or not (e.g., Gosbras & Paus, 2002; Collin, Cowey, Latto, & Marzi, 1982; Collin & Cowey, 1980).

In recent studies, TMS was applied to interfere temporarily with the activity of the FEF while participants were engaged in a cuing task where a central cue predicted the location of the upcoming target and the gaze was maintained at fixation. The results revealed that FEF TMS affects the covert shift of attention with the control of either bilateral or contralateral visual hemifield (e.g., Smith, Jackson, & Rorden, 2005; Grosbras & Paus, 2002). For instance, Smith et al. (2005) showed that briefly disrupting the left FEF eliminated the slow RTs associated with the invalid strategic cues when the target appeared in the right visual field.

Moreover, there is evidence that TMS over the FEF of the right hemisphere disrupts performance during conjunction visual search tasks that require the covert alloca-

tion of attention to the target. In their study, Muggleton, Juan, Cowey, and Walsh (2003) found that performance was worse when the right FEF was stimulated at the same time as the target display was presented. Interestingly, although many functions of the FEF and PPC seem to overlap, the contribution of these areas to visual search has been dissociated in the time course of their involvement (O'Shea, Muggleton, Cowey, & Walsh, 2006). Kalla, Muggleton, Juan, Cowey, and Walsh (2008) reported that TMS over the right FEF disrupted performance (caused a reduction in d-prime scores) in an earlier period than the right PPC in the same conjunction search task. The FEF TMS effect occurred in a 0–40 msec range after stimulus onset and the same effect was obtained by TMS over PPC at 120 and 160 msec, a timing similar to that obtained in previous studies (Walsh, Ashbridge, & Cowey, 1998; Ashbridge, Walsh, & Cowey, 1997).

The activity of the FEF in tasks in which eye movements are not required has been interpreted in terms of the premotor theory of attention (Rizzolatti et al., 1987). However, this interpretation has also been challenged by more recent findings supporting the idea that stimulus encoding and response preparation can be decoupled in the FEF (Juan et al., 2008; Juan, Shorter-Jacobi, & Schall, 2004; Sato & Schall, 2003; Thompson, Bichot, & Schall, 1997). In the macaque brain, two overlapping neuronal populations have been identified, one population of visual neurons that code visual attention and a second population of motor neurons that code saccadic movements. Sato and Schall (2003) recorded the activity of single neurons in the FEF of macaque monkeys during the execution of a search task with prosaccade or antisaccade responses. Two types of neurons were distinguished responding differently to the position of the target and to the endpoint of saccade. Furthermore, visual analysis and saccade preparation have been dissociated in time in human FEF as indicated by two distinct time points of TMS delivery that resulted in elevated saccade latencies in a visually instructed prosaccade/antisaccade task (Juan et al., 2008).

On the basis of the reported functions of the FEF in both orienting attention and transforming visual signals into motor commands, a question arises concerning a possible role of the FEF in encoding irrelevant spatial information for response priming in situations of conflict. The role of the FEF in spatial S-R conflict has never been investigated, however. Only one study (Rusconi, Bueti, Walsh, & Butterworth, 2011) tested the effect of FEF TMS in the S-R compatibility effect induced in numerical tasks (the Spatial–Numerical Association of Response Codes [SNARC] effect). Results revealed that the right FEF TMS after stimulus onset interferes with contralateral orienting attention in the representational space of numbers (i.e., the mental number line) abolishing the compatibility effect for small numbers (referring to the left portion of the mental number line).

This study aimed at investigating the role of the FEF in spatial conflict. To address this issue, we temporarily

interfered with activity of the left and right FEF by applying double-pulse TMS while participants were performing a standard Simon task with lateralized stimuli. We predicted that if the FEF play a role in automatic encoding of the irrelevant stimulus spatial code, temporary interference with the neural activity in this area should reduce the impact of direct route processing on performance, thus reducing the correspondence effect. FEF TMS during the Simon task was thus expected to interfere with the processing of the irrelevant spatial attribute of the target, at least for stimuli appearing in the contralateral visual hemifield. Moreover, to evaluate the timing of the involvement of the FEF, we applied magnetic stimulation at various time intervals after stimulus onset. On the basis of previous data on visual search tasks (e.g., O'Shea et al., 2006), we predicted that TMS would interfere in the Simon task in an early timing after the onset of the visual stimulus.

METHODS

Participants

Fourteen healthy undergraduate students of University College London (all right-handed; mean age = 23 years, SD = 2 years) with normal or corrected-to-normal visual acuity took part in this experiment. All participants were checked for TMS exclusion criteria (Wassermann, 1998) and gave their written informed consent before participation. The local ethics committee approved the procedure. The participants were reimbursed with cash for participating in the experiment. All participants were naive as to the purpose of the study.

Apparatus and Stimuli

The participants were seated in a dimly lit and soundproof room with their head held by a fixed head-and-chin rest at a distance of 60 cm from a 17-in. monitor. The experiment was programmed with Matlab Psychtoolbox (Brainard, 1997). The target stimulus was either a red or green square subtending 1.5° × 1.5° (width × height) of visual angle presented for 200 msec on a black background.

Procedure and Experimental Design

Each participant was tested in one experimental session (1 day) lasting approximately 1.5 hr. Participants completed a block of 20 practice trials followed by the experimental blocks. A trial started with the presentation of a central fixation point (a circle subtending 0.5° of visual angle) lasting 400 msec. Then a stimulus was presented for 200 msec at a visual angle of 4.5° either to the left or to the right of the central fixation point. The intertrial interval was 3000 msec. After an incorrect response, a tone (600 Hz) was delivered to provide feedback on the wrong answer. Participants were instructed to maintain their gaze on the fixation point during the whole experimental session and were asked to keep their eyes on the central point. Participants were instructed to respond, as quickly and as accurately as possible, by pressing the left key ("F") on the keyboard with the index finger of the left hand when the target square was red and the right key ("J") with the index finger of the right hand when the target square was green (Figure 1). The maximum RT was 1200 msec.

The design involved within-participant manipulation of sites of stimulation, S-R correspondence, and time intervals
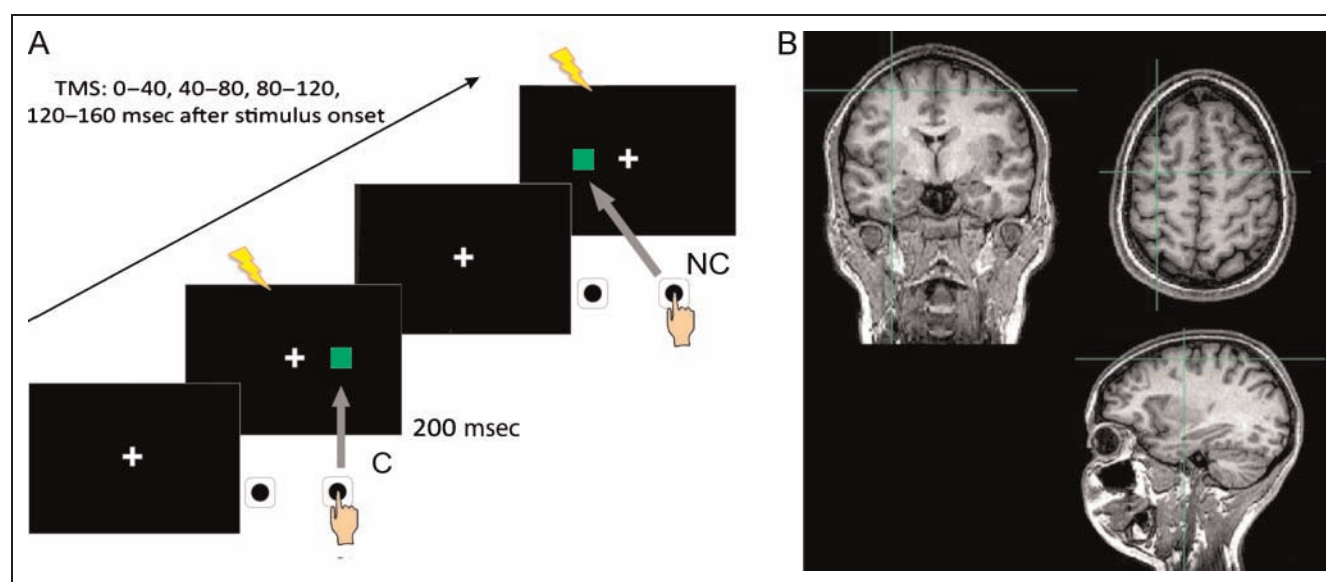
Figure 1. A schematic representation of the trial sequence in the Simon task. (A) Paired-pulse TMS was randomly delivered in each trial at different time intervals after the onset of the visual stimulus. (B) The left FEF stimulation site is shown in coronal, sagittal, and transverse sections of a participant MRI. The targeted location was identified for each participant by applying a normalization procedure. The left FEF site corresponded to the Montreal Neurological Institute standard coordinates −32, −2, 57 and the right FEF to +32, −2, 57.

between the onset of the target and the application of the double-pulse TMS (SOA). Participants performed a baseline condition without TMS of 64 trials followed by 12 experimental blocks, four for each stimulation site (right FEF, left FEF, and control site). Each block was composed of 64 trials in which stimulus position (left or right), response position (left or right), and TMS timing (0–40, 40–80, 80–120, 120–180 msec) were fully crossed to produce the same number of trials for each possible combination presented in a random order. A total of 256 trials were given for each stimulation site. The order of the site of stimulation was counterbalanced across participants.

Localization of Brain Targets for TMS Stimulation

Right and left FEF were localized by using the Brainsight frameless stereotaxy system (Rogue Research, Montreal, Canada). The stimulation sites were identified on each subject's T1-weighted MRI scan and were then coregistered with scalp coordinates over which TMS was delivered (Figure 1). The location of each subject's right and left FEF was determined according to anatomical landmarks. Stimulation was applied over the posterior middle frontal gyrus, just rostral of the junction of the precentral sulcus and the superior frontal sulcus (Blanke et al., 2000). We also checked the site of stimulation by referencing it to each individual motor hand area (Ro, Cheifet, Ingle, Shoup, & Rafal, 1999). With this method, on average, TMS was applied 5 cm lateral of the sagittal midline and 3–4 cm rostral of each subject's motor hand area. This site corresponds well with scalp coordinates used in other TMS studies of the FEF (Kalla et al., 2008; Muggleton et al., 2003; Müri, Hess, & Meienberg, 1991). After normalization of the MRI images to the Montreal Neurological Institute series average (Evans, Collins, & Holmes, 1996), mean coordinates for the sites stimulated were ±32, −2, 57. These coordinates correspond well with mean Talairach coordinates for the FEF derived from a review of PET imaging studies (Paus, 1996). As a control site, the point on the scalp corresponding to CPz in the 10–20 international system for electrode placement was chosen. TMS over a control site was chosen for the nonspecific effects of TMS, such as somatosensory and acoustic artifacts.

TMS Parameters

A Magstim Super Rapid2 machine (Magstim Company, Dyfed, United Kingdom) was used to deliver two magnetic pulses at a frequency of 25 Hz during the task over the right FEF, the left FEF, and CPz. A fixed level of 60% of the maximum machine output was employed. This level was selected as it has previously proved effective in TMS studies of FEF (e.g., Kalla et al., 2008). A series of figure-of-eight TMS coils (70 mm) was used to apply stimulation over the cortical sites of interest. Coils were cooled before use to prevent overheating during a trial block

and were replaced after two blocks. For all the stimulation sites, the experimenter clamped the coil with the handle running in an anterior–posterior direction.

Control Experiment

Twelve healthy undergraduate students of University College London (all right-handed; mean age = 23 years, SD = 1 year) took part in this experiment. Apparatus, stimuli, and procedure were the same as in the main study. Each participant was tested in one experimental session (1 day) lasting approximately 1 hr. Participants completed a practice block followed by the experimental blocks. The design involved the same within-participant manipulation of factors as in the main experiment except for the number of TMS sites. Two sites were stimulated: the interhemispheric control site used in the main experiment (the point on the scalp corresponding to CPz in the 10–20 EEG system) and a left-lateralized sensorimotor (SM) control site. For the SM site, the TMS coil was positioned at 2 cm posterior at the same laterality from each individual motor hot spot. A similar procedure was adopted in previous studies (e.g., Schluter, Rushworth, Passingham, & Mills, 1998). The TMS of this site did not induce a motor twitch in the contralateral hand.

RESULTS

Statistical analyses were performed on the magnitude of the Simon effect (mean RTs for noncorresponding trials minus mean RTs for corresponding trials) calculated as a function of stimulus position (i.e., for left- and right-side stimuli separately). The Simon effect for left-side stimuli was obtained by subtracting left-side responses to left-side stimuli (C) from right-side responses to left-side stimuli (NC). The Simon effect for right-side stimuli was calculated by subtracting right-side responses to right-side stimuli (C) from left-side responses to right-side stimuli (NC). A repeated-measures ANOVA was performed on the magnitude of the Simon effect with TMS Site (left FEF, right FEF, CPz), TMS Timing Condition (0–40, 40–80, 80–120, and 120–160 msec) and Stimulus Position (left, right) as within-participants factors. Pairwise comparisons were then performed to evaluate significant interactions.

Results showed a significant interaction of Site × Stimulus position [$F(2, 26) = 4.74, p < .05, \eta_p^2 = .27$]. Left FEF TMS reduced the Simon effect for right-side stimuli compared with the control site ($p < .05$; Figure 2). The Simon effect for right-side stimuli was 4 msec following TMS over the left FEF (C, 411 msec; NC, 415 msec), whereas it was 27 msec following TMS over the control site (C, 394 msec; NC, 421 msec).

Furthermore, the effect of double-pulse TMS over the left FEF was better understood by the Site × TMS Timing × Stimulus Position interaction [$F(6, 78) = 2.538, p < .05, \eta_p^2 = .16$]. This outcome revealed that the TMS interference had different effects across time windows. TMS
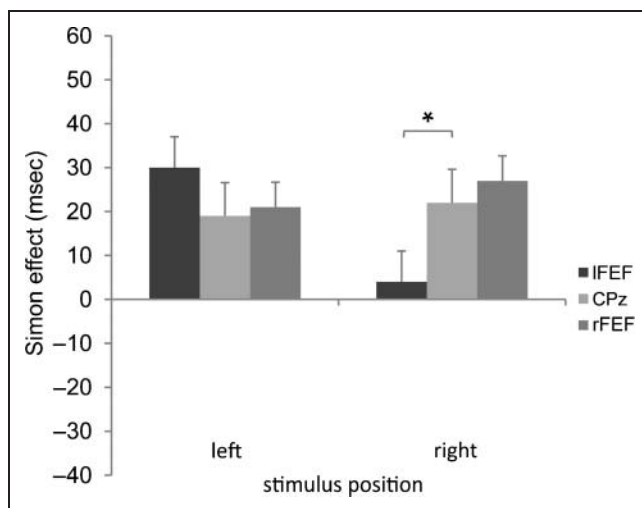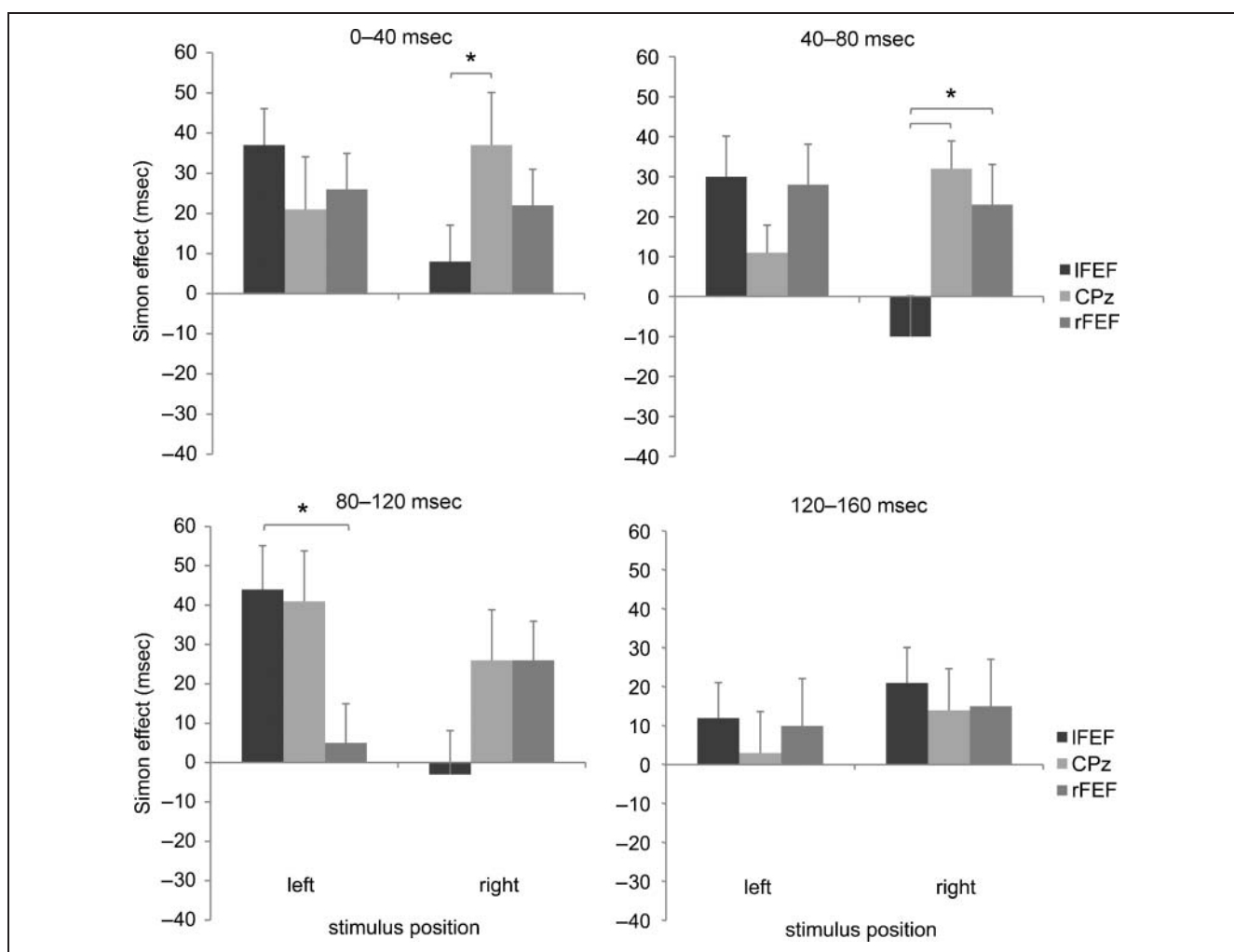
Figure 2. The magnitude of the Simon effect (noncorresponding *minus* corresponding trials) is shown separately for stimuli presented in the left and right hemifield. Left FEF TMS resulted in a suppression of the Simon effect for right-side stimuli.

reduced the Simon effect for right-side stimuli, compared with the control site, when applied over the left FEF in the 0–40 and 40–80 msec range after stimulus onset. In the first time window, the Simon effect was reduced by TMS over the left FEF (8 msec; C, 402 msec; NC, 410 msec) compared with the control site (37 msec, $p < .05$; C, 379 msec; NC, 416 msec). When TMS was applied at 40–80 msec, the Simon effect was inverted (−10 msec; C, 416; NC, 406) as compared with the control site (32 msec; C, 383; NC, 415). In the 80–120 msec time window, there was a significant difference in the magnitude of the Simon effect for left-side stimuli between the left and right FEF TMS ($p < .05$). This effect was primarily driven by a reduction of the Simon effect after right FEF TMS. The Simon effect for left-side stimuli amounted to 5 msec after right FEF TMS (C, 414 msec; NC, 419 msec) and to 44 msec after the left FEF TMS (C, 402 msec; NC, 446 msec). No difference was detected between the Simon effect for left-side stimuli and the Simon effect for the control site (41 msec; C, 400 msec; NC, 441 msec; Figure 3).

Figure 3. The magnitude of the Simon effect (noncorresponding–corresponding trials) is depicted separately for stimuli presented in the left and right visual hemifields. Double-pulse TMS caused a suppression of the Simon effect for right-side stimuli when applied in the 0–40 time windows after stimulus onset as compared with the control site. A reduction of the Simon effect has been observed for left-side stimuli when TMS was applied in the 80–120 msec timing over the right FEF.

Control Study

Results revealed that temporary interfering with activity of the FEF modulates the magnitude of spatial conflict (i.e., the Simon effect). The left FEF TMS caused a suppression of the Simon effect for stimuli appearing in the contralateral visual hemifield. This effect emerged when TMS was applied early after stimulus onset (0–40, 40–80 msec). Because the position of the TMS coil could provide an additional spatial cue, one might argue that this might have interfered with S–R correspondence. To address this issue, we conducted a control experiment in which an additional left-lateralized site was stimulated to test possible nonspecific effects from left-lateralized position of the TMS coil.

As in the main experiment, a repeated-measures ANOVA was performed on the magnitude of the Simon effect with TMS Site (left SM, CPz), TMS Timing Condition (0–40, 40–80, 80–120, and 120–160 msec) and Stimulus Position (left, right) as within-participants factors. Results revealed no sources of variance. For CPz TMS, the Simon effect amounted to 26 msec for left and right FEF TMS (C, 401 msec; NC, 427 msec) and to 50 msec for right side stimuli (C, 388 msec; NC, 438 msec). For SM TMS, the Simon effect amounted to 35 for the left-side stimuli (C, 392 msec; NC, 427 msec) and to 42 for right-side stimuli (C, 389 msec; NC, 431 msec). This outcome revealed that the TMS of the left SM did not affect the magnitude of the Simon effect. This result allows us to rule out a possible confound of spatial cue introduced by the position of the coil over one hemisphere.

Eye Monitoring

In this study, participants were instructed to maintain fixation at the center of the screen throughout each trial. To verify that TMS delivery over the FEF did not induce involuntary gaze shifts during the task, eye position was monitored in five additional participants in the same experimental conditions as in the main experiment. Participants' gaze behavior was recorded using a Tobii T120 eye-tracking screen run via the Tobii Studio package. The eyes were monitored from the onset of the fixation cross until the end of the stimulus presentation. A gaze movement was determined as a shift of at least 1.5° of visual angle from the central point. Each participant underwent two blocks of task (120 trials per block), in which paired-pulse TMS was applied over the left FEF and CPz (0–40, 40–80, 80–120 msec SOA), respectively. The rate for eye movements in valid trials (after excluding eye blinks) was 0.6% for left FEF stimulation and 0.7% for CPz stimulation. This outcome is in line with data from previous studies that failed to trigger eye movements by TMS of the frontal cortex even when high stimulation intensities were used (Müri et al., 1991; Wessel, Kcempf, Klostermann, & Moser, 1991).

DISCUSSION

Previous studies suggested that the FEF play an important role in encoding stimulus position which may be independent of the execution of eye movements. No studies had investigated the contribution of the FEF in a spatial conflict task, however. In the Simon task, a conflict arises because irrelevant spatial information competes for response selection. In the corresponding condition, responses are speeded up because stimulus spatial code automatically activates a response code that overlaps with the correct response code. In the noncorresponding condition, spatial information competes with manual response preparation generated on the basis of task instructions. The results of this study support the hypothesis that the FEF contribute to the encoding of irrelevant spatial information, which is the precondition of response conflict in the Simon task. In line with our predictions, paired-pulse TMS applied over the FEF caused a suppression of the Simon effect for visual stimuli presented in the hemifield contralateral to the site of stimulation. This effect was evident when TMS was applied to the left FEF in the first three time windows (0–40, 40–80, 80–120 msec), but this value was significant only in the earlier timings (0–40, 40–80 msec) when compared with the vertex stimulation. In contrast, a reduction of the Simon effect was observed for right FEF TMS in the late 80–120 msec time window.

Previous studied reported similar involvement of PPC in the Simon task (Schiff et al., 2011; Rusconi et al., 2007). Schiff et al. (2011) applied single-pulse TMS over the left and right PPC and found a suppression of the Simon effect when the stimulation was delivered in a 130–160 msec range after stimulus onset. The present outcome suggests that both FEF and PPC may be seen as components of visuomotor processing through the direct route during spatial conflict (De Jong et al., 1994). Interestingly, the contribution of these areas to spatial conflict may be dissociated in the time course of their involvement revealing an early role of the FEF and a late role of PPC. A similar dissociation was previously found in visual search tasks (O'Shea et al., 2006; O'Shea, Muggleton, Cowey, & Walsh, 2004).

Our results can well accommodate both with a premotor theory of attention and with the view that visual analysis and saccade preparation are dissociated in human FEF (Juan et al., 2008). In the Simon task, the target may automatically activate a saccade preparation that competes with endogenously generated manual responses. When the TMS is applied over the FEF, the saccade preparation is disrupted, so that the spatially corresponding response receives neither facilitation nor interference from the competing action. Our data support the idea that TMS specifically interfered with the stimulus spatial code, which probably represents saccade parameters and interacts with the selection of the manual response. Nevertheless, because the effect of FEF TMS in our task is evident along

different timings after stimulus onset, we cannot exclude that TMS had interfered with both visual and motor neurons in the FEF being both related to the automatic activation of the corresponding response in the Simon task. In fact, a reduction of the Simon effect in specific conditions may be obtained by preventing the shift of spatial attention toward the position of the peripheral target (Nicoletti & Umiltà, 1994) or inducing changes in the locus of attention in paradigms with peripheral and central spatial precues (see Van der Lubbe & Abrahamse, 2011).

The predominant role of the left hemisphere in the Simon task, compared with the right-hemisphere dominance found in SNARC task (Rusconi et al., 2011) provides new insight into differences in neural circuits that may underlie the Simon and SNARC effects (Rusconi, Umiltà, & Galfano, 2006; Mapelli, Rusconi, & Umiltà, 2003). These effects of compatibility share some important characteristics: The fact that RTs are affected by task-irrelevant information (stimulus position or magnitude) and the fact that the information influencing response selection is spatial in nature (perceptual or representational). However, some important differences must be considered as the processing of a stimulus appearing in the peripheral field and the processing of central symbolic cues bearing a spatial meaning (the number) could follow different paths before converging and gaining access to the primary motor cortex for response execution (Rusconi et al., 2007). In the Simon task, the spatial irrelevant information provided by stimulus position can be directly extracted and has direct access to motor selection, whereas position on the mental number line is not as directly accessible to the viewers as the physical position of a stimulus. Differences between the Simon effect and the SNARC effect also manifest themselves in their behavioral patterns. For instance, several studies reported that the size of the Simon effect, with standard horizontal S-R mapping, decreases with longer RTs (Vallesi, Mapelli, Schiff, Amodio, & Umiltà, 2005; Rubichi et al., 1997; Hommel, 1993), whereas the size of SNARC effect is stable across different RT ranges (e.g., Mapelli, Rusconi, & Umiltà, 2003). According to Wascher and colleagues (2001), the time course of the Simon and the SNARC effects (decreasing vs. stable/increasing) reflects the presence or absence of the automatic activation of the response. According to these authors, only with spatial–anatomical S-R mapping and visual stimuli, spatial parameters are processed within privileged visuomotor pathways, automatically activating the correspondent response. Spatial–anatomical S-R mapping refers to the overlap between stimulus and natural hand position.

Our results, along with data from Rusconi et al. (2007), support the view that cognitive mechanisms subtending the Simon and the SNARC effects may be instantiated in different neural circuits even if they may still converge to a common area where the conflict is resolved. The access to a representational space and the activation of the response code in the SNARC effect seems to follow a different temporal dynamics, which may be reflected in the activation of different neural circuits.

Beside the need of further investigation, we speculate that the automatic activation of the corresponding response and the resulting time course of the Simon effect with horizontal S-R mapping may be due in part to an early activation of the left FEF, which may exert their influence by a direct connection with the left-lateralized system for action selection in right-handed participants (Rushworth, Johansen-Berg, Gobel, & Devlin, 2003; Schluter, Krams, Rushworth, & Passingham, 2001).

The early involvement of the FEF of the left hemisphere compared with the right hemisphere during spatial conflict may be attributed to the dominance of the left hemisphere in motor attention and action selection processes in right-handed participants (Rushworth et al., 2003; Schluter et al., 2001). In the Simon task, spatial information affects performance at the response selection stage, and visuomotor processing through the direct (automatic) pathway has been proposed to be more efficient for the dominant hand in right-handed participants (Spironelli, Tagliabue, & Umiltà, 2009; Rubichi & Nicoletti, 2006).

In summary, this study provides the first evidence of the involvement of the FEF in a conflict task. Our findings also provide insight into the hemispheric asymmetries of the FEF, which have been explored very little compared with the parietal lobes. Regions in the left hemisphere such as the SMA and the premotor cortex are important for attention to action and action selection (Rushworth et al., 2003; Schluter et al., 2001). Our findings extend the idea of the left-hemisphere lateralization of the motor network in action selection by suggesting that the left FEF may constitute part of the action selection network in the left hemisphere.

Acknowledgments

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