

Timing Spatial Conflict within the Parietal Cortex: A TMS Study

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Abstract

■ Orienting and motor attention are known to recruit different regions within right and left parietal lobes. However, the time course and the role played by these modules when visual information competes for different motor response are still unknown. To deal with this issue, single-pulse TMS was applied over the angular (AG) and the supramarginal (SMG) gyri of both hemispheres at several time intervals during the execution of a Simon task. Suppression of the conflict between stimulus and response positions (i.e., the Simon effect) was found when

TMS pulse was applied 130 msec after stimulus onset over the right AG and after 160 msec when applied over the left AG and SMG. Interestingly, only stimulation of the left SMG suppressed the asymmetry in conflict magnitude between left- and right-hand responses, usually observed in the Simon task. The present data show that orienting attention and motor attention processes are temporally, functionally, and spatially separated in the posterior parietal cortex, and both contribute to prime motor response during spatial conflict. ■

INTRODUCTION

Successful behavior depends on mechanisms of attention administering the allocation of neural resources on environmental stimuli potentially relevant for response planning. Multiple opportunities for action are available, and several competing plans for action could be activated; thus, a selection between different competing responses has to be performed before action execution (Cisek, 2007).

Conflict usually arises when simultaneous sensorimotor processes point to different responses, and selection between these responses produces a cost. The Simon task has been shown to be a suitable method for studying conflicts in action selection. Here a conflict arises because irrelevant spatial information competes for response selection with task relevant information (Lu & Proctor, 1995; Umiltà & Nicoletti, 1990; Simon & Rudell, 1967). In the Simon task, participants respond with spatially arranged keys to a nonspatial stimulus attribute (i.e., color or shape) of lateralized targets. Besides the fact that spatial position is irrelevant for the task, RTs are faster when stimulus and response positions correspond spatially than when they do not correspond.

In cognitive psychology, dual route models were proposed to explain the mechanisms underlying conflict in the Simon task (Proctor, Lu, & Dutta, 1995; De Jong, Liang, & Lauber, 1994; Kornblum, Hasbroucq, & Osman, 1990). These models postulate that two parallel pathways, a direct automatic and an indirect controlled one, are involved in

response preparation and selection processes. The irrelevant stimulus information is thought to activate its spatially corresponding response via the fast direct route, whereas the relevant information stimulus activates the required response via the slow controlled indirect route (Wascher, Schatz, Kuder, & Verleger, 2001; Kornblum et al., 1990). The direct route may arise from long-term associations between perceptual and motor processes, which may depend on genetic factors or on the synaptic consolidation of stimulus–response associations widely overlearned during lifetime (Tagliabue, Zorzi, Umiltà, & Bassignani, 2000; Cohen, Dunbar, & McClelland, 1990). The Simon effect was explained in terms of a cost of conflict between the direct route (carrying the response linked to the spatial position of the stimulus) and the indirect one (holding the task demands). When the two routes generate the same response codes (i.e., in the corresponding condition), the RTs are speeded up, whereas when the two routes generate different response codes (i.e., in the noncorresponding condition), a conflict must be resolved, which leads to slower RTs. It was suggested that, in the Simon task, the irrelevant spatial code is covertly generated by the direction of the last attentional shift implemented before response selection (Rubichi, Nicoletti, Iani, & Umiltà, 1997).

Many neuroimaging studies showed that activation and selection of potential response programs involve a large fronto-parietal network. Prefrontal regions, such as the anterior cingulate gyrus and the dorsolateral pFC, receive information from the ventral visual pathway and play a crucial role in the selection of the correct response and in the resolution of conflicts (Kerns, 2006; Egner & Hirsch, 2005; Botvinick, Cohen, & Carter, 2004; Ridderinkhof,

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2002). Moreover, control mechanisms over response conflict in the Simon task have been shown to recruit premotor cortex (Egner, Delano, & Hirsch, 2007; Praamstra, 1999). This network was proposed to be the main neural substrate for the indirect route, which is responsible for elaborate task instructions. The posterior parietal cortex (PPC), as part of the dorsal visual stream (Goodale & Milner, 1992), is thought to be implicated in both visuospatial attention (Chambers, Payne, Stokes, & Mattingley, 2004; Ashbridge, Walsh, & Cowey, 1997) and in transforming sensory information into motor outputs (Mattingley, Husain, Rorden, Kennard, & Driver, 1998; Goodale & Milner, 1992; Umiltà, Riggio, Dascola, & Rizzolatti, 1991; Rizzolatti, Riggio, Dascola, & Umiltà, 1987). Furthermore, the PPC is indicated as being the neural substrate of the direct route when irrelevant competing information are spatial in nature (Rusconi, Turatto, & Umiltà, 2007; Stürmer, Redlich, Irlbacher, & Brandt, 2007).

Recently, lateralized neural mechanisms within the PPC were proposed as being responsible for different, although related, attentional processes (Rushworth & Taylor, 2006; Rushworth, Ellison, & Walsh, 2001): The right PPC was thought to be responsible for orienting attention in space, whereas the left PPC was suggested as being involved in attentional processing directed toward motor selection (i.e., motor attention). Rushworth and colleagues used the TMS technique to dissociate between the roles of the right angular gyrus (AG) and the left supramarginal gyrus (SMG) in covert visuospatial orienting attention and in the selection of overt finger movements. They found that the right AG was critically involved in a task that required orienting attention, whereas the left SMG was involved in a task that entailed motor attention and response selection (Rushworth et al., 2001). This anatomo-functional dichotomy is supported by neuropsychological findings, which showed that lesions in the right PPC are associated with hemispatial neglect (Vallar et al., 1988), whereas left parietal damage is mostly associated with praxis deficits (Goldenberg, 2009).

However, the role of the PPC in situations of spatial stimulus–response conflict has not been extensively studied. Only one study investigating the role of the anterior and posterior portions of the PPC in a conflict task failed to clearly dissociate between different and/or asymmetrical contributions of these areas to different attentional mechanisms (Rusconi et al., 2007). Thus, it is still unknown how orienting and motor attention processes are related to the spatial conflict created by the direct route during choice reaction task. On the other hand, the proposed dichotomy between orienting and motor attention was based on results obtained from different tasks (Rushworth et al., 2001) and a direct comparison of the involvement of the different parietal subregions in a single task is still lacking.

Interestingly, behavioral findings on the Simon effect revealed a peculiar result, which may help to reveal the neural substrates of orienting and motor attention processes during conflicting conditions. Usually, the correspondence effect is greater for right-hand responses compared with left-hand responses (Tagliabue et al.,

2007). This phenomenon was supposed to depend on the dominance of the left hemisphere in motor attention and response selection, and it has been argued that visuo-motor processing through the direct (automatic) pathway might be more efficient for the dominant hand in right-handed subjects (Tagliabue et al., 2007; Rubichi & Nicoletti, 2006; Schluter, Krams, Rushworth, & Passingham, 2001; Schluter, Rushworth, Passingham, & Mills, 1998). Recently, a computational model by Spironelli, Tagliabue, and Umiltà (2009) was proposed to explain the asymmetry in the correspondence effect through differently lateralized neural mechanisms in the PPC for orienting attention (involving both the left and right AG) and motor attention (carried out by the left SMG). However, only behavioral data inspired such a model, and validation from a neurofunctional point of view is lacking. Moreover, it is still unknown whether conflict created by the direct route is related to either attention orienting or response selection processes.

The present study examined the different contributions of the AG and SMG of both hemispheres while dealing with a spatial conflict task. In two experiments, participants performed a Simon task with laterally presented stimuli as a single-pulse TMS (spTMS) was delivered. In the first experiment, spTMS was applied over the left or right AG at various time intervals after stimulus onset, whereas in the second experiment, a spTMS was delivered to the left or right SMG. In both experiments, the vertex was stimulated as control site. If stimulation of these areas generated a reduction of the Simon effect, then it can be assumed that a region involved in the direct route had been hit, because the Simon effect is due to the interference of the direct route on the task-driven indirect route.

In our hypothesis, if the right and left PPC are involved in different attentional processes related to the direct route, a different timing of the TMS effect should be revealed by stimulation of the right and left hemispheres. We predicted that if the right AG is involved in the generation of the stimulus spatial code, which is the precondition of the conflict in the Simon task, then a reduction of the Simon effect will be induced by TMS in an early time window at that site. A later effect could instead be associated with the stimulation of the left hemisphere, which is thought to be involved in transforming stimulus spatial information into codes for action (Rushworth, Johansen-Berg, Gobel, & Devlin, 2003; Rushworth et al., 2001).

Furthermore, we hypothesized that the asymmetry in the correspondence effect between right- and left-hand responses would be suppressed only after stimulation of the parietal region involved in motor attention. Following the computational model of Spironelli and colleagues (2009), spatial information is primed to the motor system via the parietal module involved in motor attention. In agreement with this view, the behavioral asymmetry in the magnitude of the Simon effect observed between right- and left-hand responses depends on the left-lateralized location of this system. The temporary TMS interference on the activity of this area should be able to suppress this asymmetry.

EXPERIMENT 1

Methods

Participants

Eleven healthy undergraduate students of the University of Padua (all right-handed, mean age = 24 years, $SD = 3$ years) with normal or corrected-to-normal visual acuity took part in the first experiment. All subjects were checked for TMS exclusion criteria (Wassermann, 1998) and gave their written informed consent before participation. The intensity of stimulation and the duration of the TMS sessions were in accordance with the safety guidelines established by Wassermann (1998), and the procedure was approved by the ethics committee of the Department of General Psychology, University of Padua. The subjects were reimbursed with cash for participating in the two sessions of each experiment. All participants were naive as to the purpose of the study.

Apparatus and Stimuli

The participants were seated in a dimly lit and sound-proof room with their head held by a fixed head-and-chin rest at a distance of 50 cm from a 17-in. monitor controlled by a Pentium 4 PC programmed with E-Prime (Psychology Software Tools, Pittsburgh, PA). The targets were the letters "N" and "H" subtending $1.4^\circ \times 1.8^\circ$ (width \times height) of a visual angle presented for 200 msec in white on a black background, 3.5° laterally with respect to a fixation cross.

Procedure and Experimental Design

Each participant was tested in two experimental sessions lasting approximately 2 hr each. The participants completed a block of 40 practice trials followed by the experimental blocks. A trial started with the presentation of a central fixation cross (subtending $0.5^\circ \times 0.5^\circ$ of visual angle) lasting 400 msec. Then a stimulus was presented for 200 msec at a visual angle of 4.6° , either to the left or to the right of the central fixation point. A contralateral filler "#" was also presented. The maximum response time was 1200 msec. The intertrial interval varied randomly between 1500 and 2500 msec. After an incorrect response, a tone (600 Hz) was delivered to provide feedback on the wrong answer. At the end of each block, feedback concerning mean RT and accuracy was displayed on the screen. A schematic representation of the trial sequence is depicted in Figure 1A. The participants were engaged in a two alternative choice reaction task and were instructed to maintain their gaze on the fixation point during the whole experimental session. Half of the participants were asked to respond, as quickly as possible, by pressing the leftmost key ("Z") on the keyboard with the index finger of the left hand when the target letter was an "N" and the rightmost key ("M") with the right hand when it was an "H." The other half

of the participants received the opposite hand-target assignment.

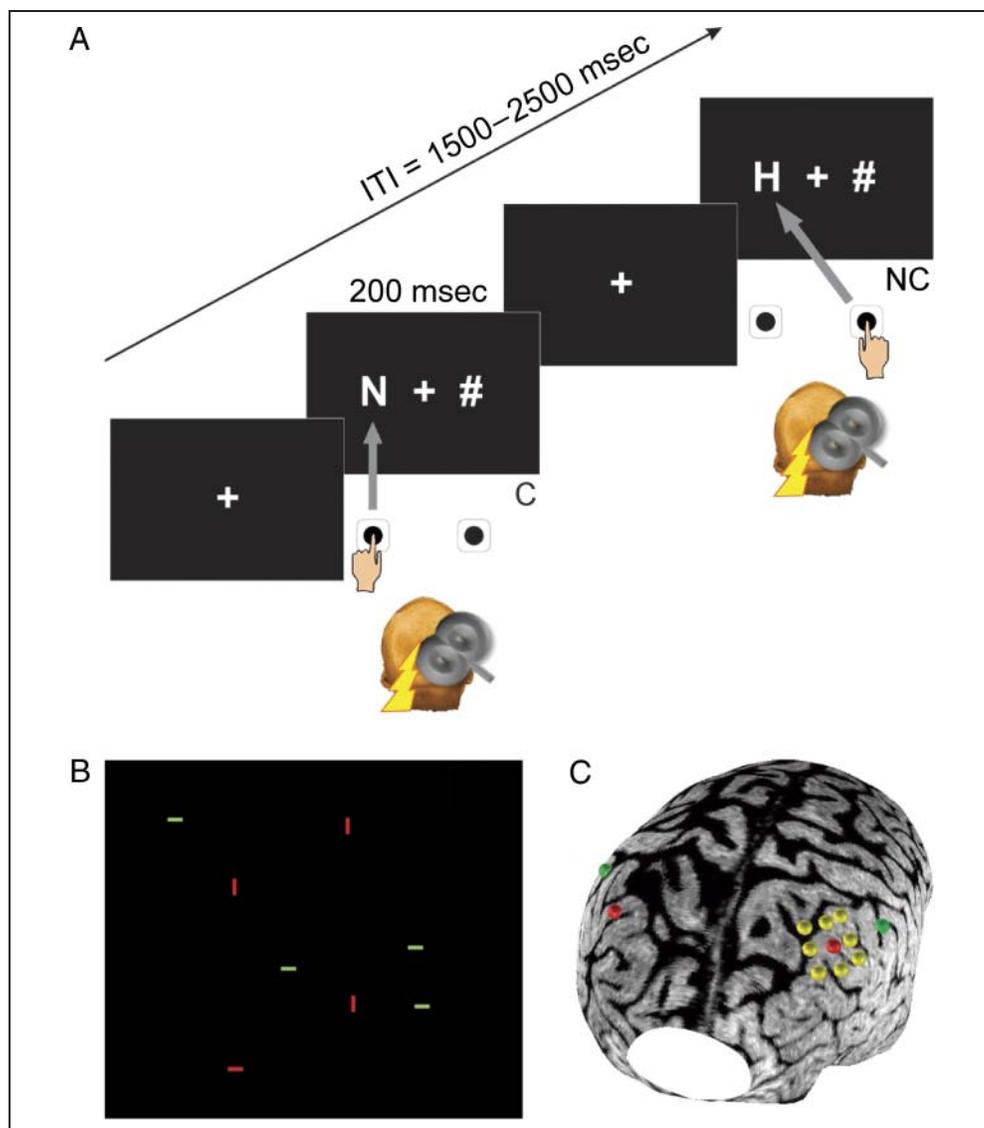
The design of the two TMS experiments involved within-subject manipulation of sites of stimulation, stimulus-response correspondence, and the time intervals between the onset of the target and the application of the TMS pulse (SOA). Each session was divided into three experimental blocks, one for each stimulation site. Each block was composed of 480 trials, in which stimulus position (left or right), response position (left or right), and SOA (70, 100, 130, 160, 190, 220, 250 msec) were fully crossed to produce the same number of trials for each possible combination, presented in a random order. No TMS pulse was delivered in 60 trials of each block (randomly intermixed). A pause was given to the participants every 160 trials. The order of blocks (i.e., site of stimulation) was counterbalanced across participants.

Localization of Brain Targets for TMS Stimulation

The TMS coil was placed on the skull of each subject using MRI images of the participants with theBrainsight stereotaxic neuronavigator (Rogue Research, Inc., Montreal, Canada) coupled with a Polaris Vicra infrared camera system (NDI, Waterloo, Canada). The coil position was monitored on-line during all experiments. An individual T1-weighted MRI scan was obtained from each participant using a Signa 3T system (GE Healthcare, Milwaukee, WI; $1.3 \times 1.3 \times 1.3$ mm, sagittal acquisition).

The right AG was identified by means of the hunting procedure described by Ashbridge et al. (1997), which has been employed in several previous studies (Ellison, Schindler, Pattison, & Milner, 2004; Rushworth et al., 2001; Walsh, Ellison, Ashbridge, & Cowey, 1999). A 3×3 cm grid was applied with the central square on the position of the scalp, which corresponded to electrode P4 of the international 10–20 system (oriented 45° away from the midsagittal line). After a practice block of 40 trials, the participants performed nine blocks of a conjunction visual search task consisting of 20 trials each. spTMS were applied 100 msec after stimulus onset to one of the nine marked sites of the grid (the order was randomized between subjects). The right AG site used for the experimental session was defined as the site where spTMS increased the mean RTs of about 50 msec in the visual search task compared with the other eight stimulation sites of the grid. Previous studies showed that this procedure accurately pinpoints the position of the posterior part of the PPC, specifically the part corresponding to the right AG (Rushworth et al., 2001, 2003). See Figure 1B and C for a description of the visual search task and of the hunting procedure. The left AG stimulation site was defined as the point on the left hemisphere corresponding to the one localized in the right hemisphere. The vertex was used as the control site. Correspondence between the anatomical region and the spot obtained from the hunting procedure was confirmed in all the subjects by using their own

Figure 1. (A) A schematic representation of the trial sequence of the Simon task. spTMS were randomly delivered in each trial at different SOAs (70, 100, 130, 160, 190, 220, 250 msec) in respect to stimulus presentation. (B) A representative frame of the conjunction visual search array (i.e., color and orientation) adopted to find the position of the right AG, with psTMS applied 100 msec after stimulus presentation. (C) The 3-D MRI brain reconstruction of a representative subject with the 3×3 cm grid depicted around the P4 site used in functional localization of the right AG. Left AG and right and left SMG were marked on the brain image.



individual MRI. Mean and standard deviations of stimulation sites were reported according to the Montreal Neurological Institute system (standard deviations are in brackets): for the left AG, $X = -40(5)$, $Y = -72(3)$, $Z = 44(6)$, whereas for the right AG, $X = 44(6)$, $Y = -68(6)$, $Z = 40(4)$.

TMS Parameters

TMS was applied with a Magstim Super Rapid2 system (Magstim Company Ltd., Spring Gardens, Wales, UK). The intensity of the magnetic stimulation was set separately for each participant 10% above the individual motor threshold. Motor threshold was defined as the minimum percentage of the stimulator output that can evoke a visually detectable twitch in a tense muscle of the hand of each participant contralateral to the stimulated motor cortex. The procedure started with an estimated suprathreshold intensity, which was modified in steps of 2–3% (following a simple up–down adaptive pro-

cedure) until approximately five movements are observed in 10 consecutive trials on the most responding region. In Experiment 1, the resulting mean intensity was around $63 \pm 2\%$ of the maximum stimulator output.

Results

Before proceeding with the analyses of results, we checked for the presence of any nonspecific effect of the side of stimulation on the magnitude of the Simon effect. In fact, the TMS pulse (over left and right hemispheres) provides an acoustical spatial signal (e.g., the coil click, which is associated with the application of the magnetic pulse), which could theoretically interfere with stimulus–response correspondence. The TMS click could drive the attention and so increases the Simon effect for right- and left-hand responses based on the stimulation side, beside any specific effect of the magnetic pulse. To deal with this issue, an ANOVA was performed on the mean RTs of TMS trials with Side of Stimulation (left and

right), Correspondence (corresponding vs. noncorresponding condition), and Response Position (left vs. right hand) as within-subjects factors.

A main effect of Response Position [$F(1, 10) = 32.921, p < .001, \eta_p^2 = 0.77$] showed that right-hand response were faster than left-hand responses. The main effect of Correspondence [$F(1, 10) = 27.960, p < .001, \eta_p^2 = 0.74$] revealed that corresponding trials were faster than noncorresponding trials. Furthermore, the Response position \times Correspondence interaction showed that the correspondence effect was greater for the right than for the left responses [$F(1, 10) = 33.728, p < .001, \eta_p^2 = 0.77$]. Interestingly, the side of Stimulation \times Response position \times Correspondence interaction was far from significant ($p \geq .6$), allowing us to exclude any nonspecific effect of the TMS side on the size of the Simon effect (see Figures 2D–F).

A repeated measures ANOVA was performed on the mean RTs of TMS trials with the stimulation site (left and right AG and vertex), SOA (70, 100, 130, 160, 190, 220, 250 msec), and Correspondence (corresponding vs. noncorresponding trials) as within-subject factors. Paired sample t tests were then performed to compare the magnitude of the correspondence effect (difference between noncorresponding and corresponding trials) obtained after stimulation of the experimental sites and the vertex at specific SOA.

A main effect of Correspondence was found [$F(1, 10) = 36.375, p < .001, \eta_p^2 = 0.78$] wherein corresponding trials were faster than the noncorresponding ones. Overall, the correspondence effect amounted to 15 msec. The Site \times Correspondence interaction [$F(2, 20) = 4.197, p < .05, \eta_p^2 = 0.30$] revealed that a spTMS produced a significant reduction of the correspondence effect when applied to the right AG (10 msec) with respect to both the left AG (17 msec) and the vertex (18 msec). However, the three-way interaction between Site \times SOA \times Correspondence [$F(12, 120) = 2.117, p < .05, \eta_p^2 = 0.18$] allowed a further description of the TMS effects. Figure 2 shows the mean RTs for the corresponding and the noncorresponding conditions at each SOA, separately for the three stimulated sites. A suppression of the correspondence effect was obtained when TMS was applied to the left and right AG compared with the vertex, but only when pulses were delivered 130 and 160 msec after stimulus onset to the right AG [$t(10) = 2.834, p < .05$] and to the left AG [$t(10) = 3.997, p < .01$], respectively (Figure 4A).

Effect of AGs Stimulation on the Correspondence Asymmetry

The time windows of the TMS effects discovered in the present study (i.e., 130 and 160 msec after stimulus onset)

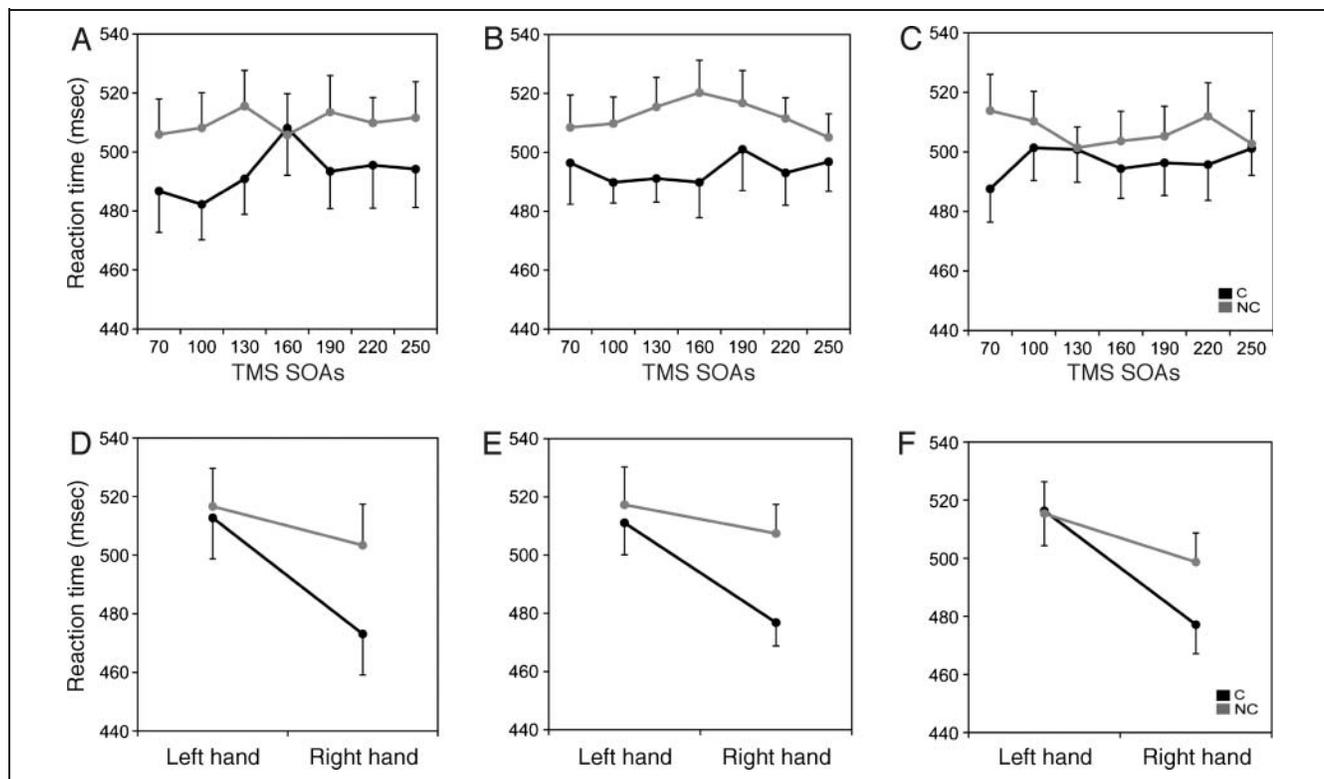


Figure 2. In Experiment 1, the left and right AG and the vertex were stimulated with spTMS at different SOAs (70, 100, 130, 160, 190, 220, 250 msec). Results of ANOVA on the correspondence effect highlighted a suppression of the Simon effect when spTMS was applied to the left AG 160 msec after stimulus onset (A) and to the right AG 130 msec after stimulus onset (C). No suppression of the Simon effect was detected when TMS was applied to the vertex (B). Panels D, E, and F depict the correspondence effect for right and left hand for the left AG, vertex, and right AG, collapsed across the SOAs respectively. ANOVA did not reveal any nonspecific effect of the site of stimulation on the correspondence asymmetry.

are similar to those previously identified during visual search (Walsh, Ashbridge, & Cowey, 1998; Ashbridge et al., 1997) and visual discrimination tasks (Chambers, Stokes, Janko, & Mattingley, 2006). Thus, we hypothesize that, in these time windows, both the right and left AG are performing a spatial analysis of the incoming visual information, which caused attention to be oriented toward the target position. Because behavioral asymmetry between the right- and left-hand correspondence effect was supposed to arise from motor attention and response selection processes attributed to the left SMG (Rushworth et al., 2001), we expected that stimulation over the right and left AG would not affect such asymmetry. Therefore, we analyzed the data by considering response position as an additional factor on the SOAs where the TMS had an effect. Two separate repeated measures ANOVAs were performed for the right and left AG, compared with the vertex, in the SOA where the TMS had an effect (130 and 160 msec). The ANOVAs included Site (experimental vs. control), Correspondence (corresponding vs. noncorresponding condition), and Response Position (left vs. right hand) as factors. The comparison between right AG and vertex stimulation showed a very similar pattern to the comparison between the left AG and the vertex. The main effects of Correspondence [right AG: $F(1, 10) = 5,759, p < .05, \eta_p^2 = 0.36$; left AG: $F(1, 10) = 12,065, p < .01, \eta_p^2 = 0.55$] and Response Position [right AG: $F(1, 10) = 13,740, p < .01, \eta_p^2 = 0.58$; left AG: $F(1, 10) = 41.053, p < .001, \eta_p^2 = 0.80$], showed that the right-hand responses were faster than the left-hand responses. The significant Correspondence \times Response position interaction [right AG: $F(1, 10) = 6,263, p < .05, \eta_p^2 = 0.38$; left AG: $F(1, 10) = 20,680, p < .001, \eta_p^2 = 0.67$] showed that the correspondence effect for right-hand responses was greater than the correspondence effect for left-hand responses. The significant Site \times Correspondence interaction showed a reduction of the correspondence effect with respect to vertex [right AG: $F(1, 10) = 8,519, p < .05, \eta_p^2 = 0.46$; left AG: $F(1, 10) = 17,312, p < .01, \eta_p^2 = 0.63$]. The lack of an interaction between Response Position, Correspondence, and Site revealed that stimulation did not affect the right- or left-hand asymmetry (Figure 4C, left and middle columns).

EXPERIMENT 2

In Experiment 1, a suppression of the Simon effect was found when a TMS pulse was delivered 130 and 160 msec after stimulus onset on the right AG and left AG, respectively. However, a modulation of the correspondence asymmetry between right- and left-hand responses was not observed. Because the left SMG was suggested to be involved in motor attention, a second experiment was performed in which the left and right SMG were stimulated. We predicted a suppression of the correspondence effect asymmetry after stimulation of the left SMG.

Materials and Methods

Participants

Eight (all right-handed, mean age of 23 years \pm 2), with normal or corrected-to-normal visual acuity, took part in the second experiment. None of the participants tested in Experiment 1 took part to the Experiment 2.

Apparatus and Stimuli

Apparatus and stimuli were the same of Experiment 1.

Procedure and Experimental Design

The procedure and experimental design were the same of Experiment 1.

Localization of Brain Targets for TMS Stimulation

spTMS was applied to the experimental sites (right and left SMG, as well as to the vertex) identified on the individual MRI images. Anatomical landmarks were used for SMG, which was defined as the region adjacent to the dorsolateral projection of the lateral sulcus, posterior to the postcentral sulcus and anterior to the STS (Chambers, Stokes, & Mattingley, 2004; Rushworth et al., 2001). Mean coordinates according to the Montreal Neurological Institute system (standard deviations are in brackets): for the left SMG, $x = -53(3), y = -48(2), z = 41(4)$, whereas for the right SMG, $x = 55(5), y = -46(9), z = 39(2)$.

TMS Parameters

TMS parameters were the same as in Experiment 1. The resulting mean stimulation intensity was around $65 \pm 2.1\%$ of the maximum stimulation output. During the experiments, spTMS was delivered in each trial after the target at the onset of one of seven asynchronies.

Results

A repeated measures ANOVA was performed on the mean RTs of TMS trials with the Stimulation Site (left and right SMG and vertex), SOA, and Correspondence as within-subject factors. Paired sample *t* tests were then performed to compare the magnitude of the correspondence effect (difference between noncorresponding and corresponding trials) obtained after stimulation of the experimental sites and the vertex at specific SOA.

The results showed a main effect of Correspondence [$F(1, 7) = 8.518, p < .05, \eta_p^2 = 0.55$] wherein the corresponding trials were faster than the noncorresponding ones. Besides the main effect of SOA [$F(6, 42) = 2.357, p < .05, \eta_p^2 = 0.25$], a three-way interaction between Site \times SOA \times Correspondence was also found [$F(12, 84) = 1.867, p < .05, \eta_p^2 = 0.21$]. When applied 160 msec after

stimulus onset, TMS on the left SMG produced a suppression of the correspondence effect (Figures 3 and 4B). The magnitude of the correspondence effect at this point was significantly different compared with the vertex [$t(10) = 2.993, p < .05$]. When TMS was applied over the right SMG, no difference in the correspondence effect with respect to the vertex was found at any SOA (Figure 4B).

Effect of SMGs Stimulation on the Correspondence Asymmetry

Because the right and left AG were implicated in orienting of attention and, thus, in generation of the spatial stimulus code in the Simon task, the left SMG is thought to be implicated in transforming spatial information into codes for action and, thus, in motor attention. To test this hypothesis, an analysis on asymmetry in the correspondence effect was performed as in the previous experiment.

The comparison between the stimulations of left SMG and the vertex showed a close to significance main effect of Response Position [$F(1, 7) = 4.936, p = .06, \eta_p^2 = 0.41$], wherein right-hand responses were faster than left-hand responses. The significant Site \times Correspondence interaction [$F(1, 7) = 8.129, p < .05, \eta_p^2 = 0.54$] confirmed that the suppression of the correspondence effect only occurred when TMS was applied over the left SMG, 160 msec after stimulus onset. Moreover, the lack of a significant interaction between Response Position and Correspondence [$F(1, 7) = F(1, 7) = 2.064, p = .194, \eta_p^2 = 0.23$] suggested that the right- and left-hand asymmetry, in the magnitude of the correspondence effect, was eliminated. Figure 4C shows that, when stimulating the vertex, the correspondence effect amounted to 17 msec for left-hand responses and 26 msec for right-hand responses, whereas when stimulation was applied over the left SMG, this difference was suppressed (i.e., correspondence effect amounted to -7 msec for left-hand responses and to -6 msec for right-hand responses).

GENERAL DISCUSSION

In the present study, we investigate the role of the AG and SMG of both hemispheres in visual and motor attention while participants are engaged in the execution of a visual Simon task. It is well known that in the Simon task, conflict arises when spatial information, associated with stimulus and response positions do not correspond. In two experiments, spTMS was adopted to modulate the activity of these areas in different time windows (ranging between 70 and 250 msec) during task execution.

The results of the two experiments showed a suppression of the conflict when spTMS was applied on the right AG 130 msec after stimulus onset and when applied on the left AG and the left SMG 160 msec after stimulus onset. No effect of stimulation was found after the right SMG stimulation.

The left AG gets involved right after the homologue area (i.e., 160 vs. 130 msec) probably receives information from the right AG via callosal connection. The callosal connection from the right to the left AG is a fundamental component in the above-described computational model of Spironelli and colleagues (2009) for simulating the Simon effect and its right- and left-hand asymmetry. This connection was thought to convey information from the right orienting attention system to the orienting and motor attention systems in the left hemisphere. The dominant role of the right AG in orienting attention has been widely supported by studies that showed that, in right-handed subjects, the right parietal orienting mechanism spans both the right and left hemispaces whereas the left parietal system contributes mainly to attentional processes in the contralateral hemispaces (Corbetta & Shulman, 2002; Nobre et al., 1997; Mesulam, 1981). Our data further support the dominant role of the right AG in orienting attention; in fact, the correspondence effect showed a reduction also when TMS was applied to the right AG 250 msec after stimulus onset, but this value was not significant when compared with vertex stimulation (Figure 2). This later effect

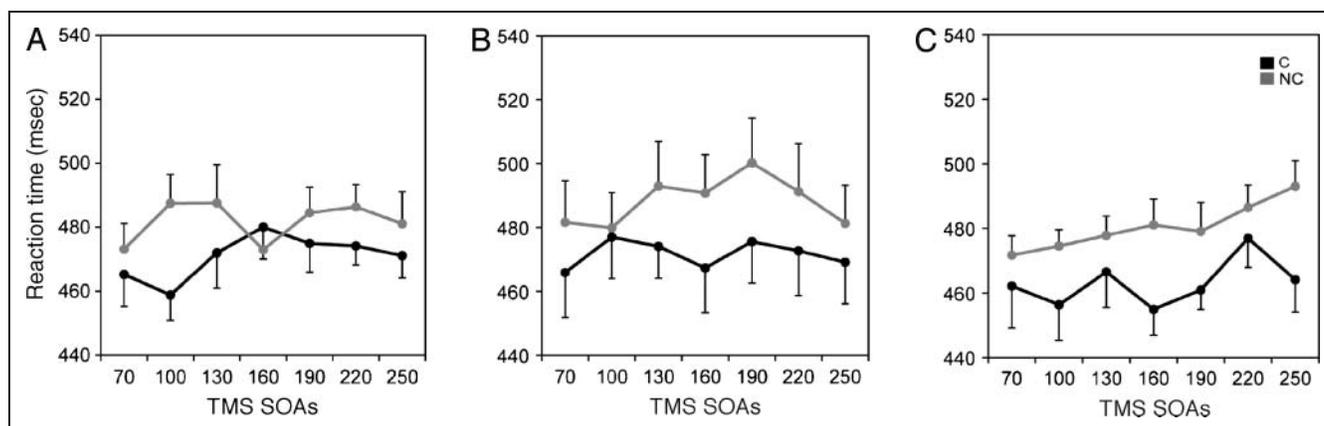


Figure 3. In Experiment 2, RTs for the left and right SMG and the vertex were represented as a function of different SOAs (70, 100, 130, 160, 190, 220, 250 msec, abscissa). A significant suppression of the Simon effect was found when stimulating the left SMG 160 msec after stimulus onset (A). No suppression of the Simon effect was detected when TMS was applied to either the vertex (B) or the right SMG (C).

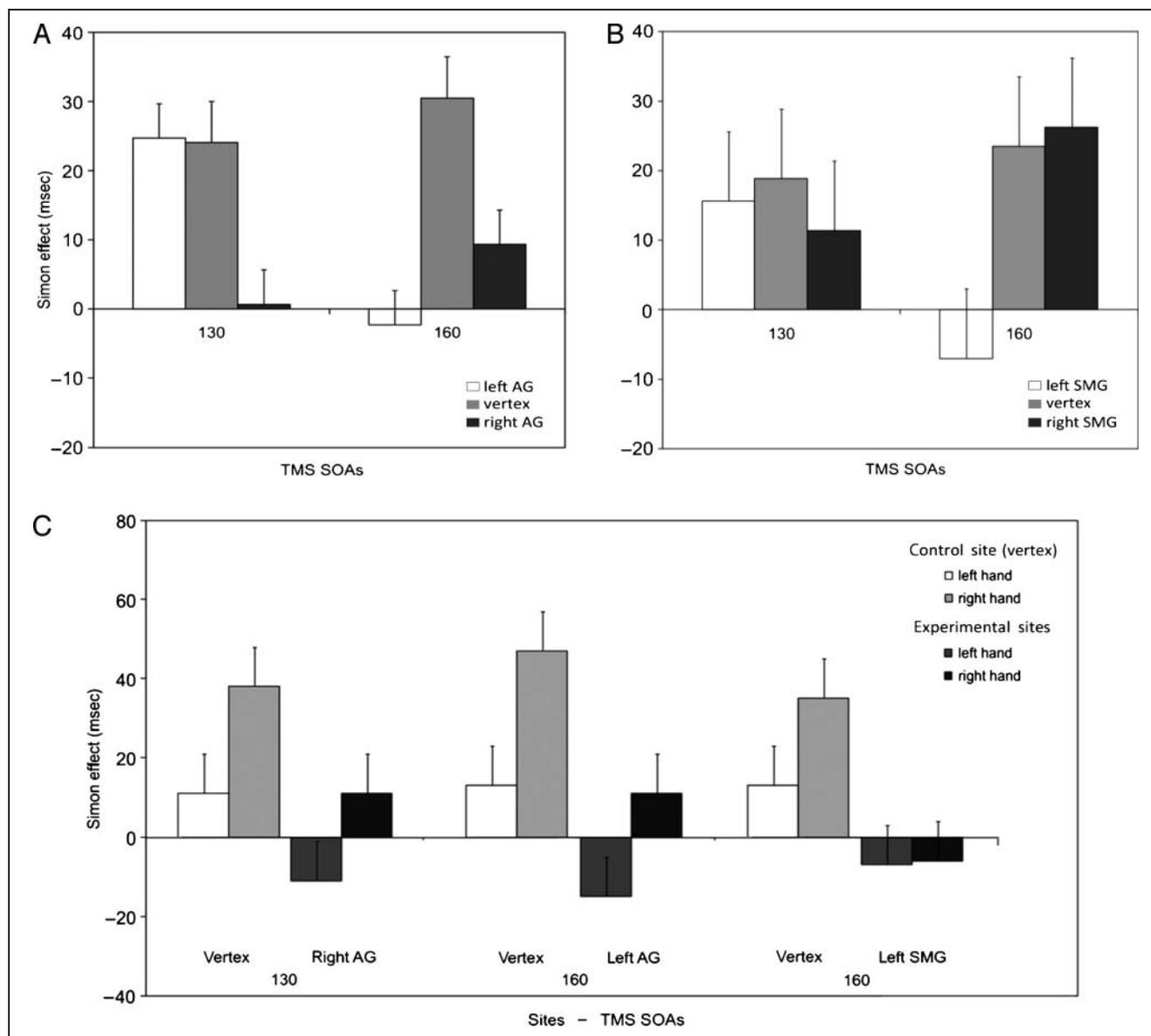


Figure 4. The magnitude of the correspondence effect for the SOAs and sites where a modulation of conflict was found in Experiment 1 (A) and Experiment 2 (B). A suppression of the correspondence effect was obtained when spTMS was applied to the right AG 130 msec after stimulus onset and to the left AG 160 msec after stimulus onset compared with the vertex (spTMS on the vertex). A paradoxical inversion of the correspondence effect was obtained only when spTMS was applied to the left SMG 160 msec after stimulus onset. (C) The left- and right-hand correspondence effects are depicted separately for each site and for the SOAs wherein TMS modulated the overall correspondence effect. In the left-most column, the right- and left-hand correspondence effects for the stimulation of the right AG and the vertex at 130 msec. In the central column, the left AG compared with vertex at 160 msec. In the right-most column, the left SMG compared with vertex at 160 msec. The graph shows that, even when the correspondence effect was suppressed for the stimulation of the left AG and SMG and of the right AG, the asymmetry in the correspondence effect between the right- and left-hand responses was only eliminated after the left SMG stimulation.

is in line with previous data reported by Chambers, Payne, et al. (2004). In their study, TMS was applied over the right AG in a task that required reorienting of spatial attention. The right AG was crucial at two distinct time points during spatial attention shifts, namely between 90 and 120 msec and again between 210 and 240 msec after the cue onset. One interpretation of these findings is that the first temporal window was associated with the fast retinotectal visual pathway whereas the second window was related to the slower geniculostriate visual pathway. Both path-

ways are assumed to convey attentional information to the inferior parietal lobe (Chambers, Payne, et al., 2004). Our data further suggest that, in the early phase, orienting attention is related to the fast activation of the retinotectal pathway, because this is the basis of automatic processing through the direct route. In contrast, in the later phase, attention should be voluntarily oriented toward the relevant information via the slower geniculostriate pathway.

The suppression of the correspondence asymmetry between right- and left-hand responses after stimulation of

the left SMG suggests a selective involvement of this region in priming irrelevant spatial information to the motor system of the dominant hand. These results are the first important verification of the hypothesized role of the left SMG in producing spatial code at the basis of asymmetry between right and left hands in correspondence magnitude. In support to this view, recently, Rushworth, Behrens, and Johansen-Berg (2006) investigated, with diffusion-weighted imaging, the connection pattern of the different parietal subregions. In their study, the SMG was found to have a high probability of connection with the ventral premotor cortex, whereas the AG was found to be connected with higher probability with visual areas within the ventral stream (i.e., the parahippocampal gyrus).

In conclusion, the present data allowed us to dissociate between the functional roles of right or left AGs and that of the left SMG during spatial conflict. Although the AGs are involved in orienting attention, the left SMG is a critical region for transforming spatial information into code for action (i.e., motor attention; Rushworth et al., 2001, 2003). These results provide a new step toward a description of the roles played by different PPC subregions in spatial conflict; furthermore, these data bridge the gap between dual route models of information processing and the attention orienting and motor attention dichotomy (Cisek, 2008). Nevertheless, further experiments are necessary to study the neural substrate of the indirect route, which was not directly investigated in the present study. Evaluation of the prefrontal system during visuomotor transmission in conflict tasks seems particularly important to describe how conflict resolution of competing visual information is implemented. The analysis of the time course of cerebral modulation produced by TMS was convincingly shown to be an important method in cognitive neuroscience for the chronometric study of brain circuit activation (Walsh & Cowey, 2000).

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