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report

Single-Pulse Transcranial Magnetic Stimulation of Parietal and Prefrontal Areas in a Memory Delay Arm Pointing Task

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Smyrnis, Nikolaos, Christos Theleritis, Ioannis Evdokimidis, Rene M. Müri, and Nikos Karandreas. Single-pulse transcranial magnetic stimulation of parietal and prefrontal areas in a memory delay arm pointing task. *J Neurophysiol* 89: 3344–3350, 2003; 10.1152/jn.00810.2002. Fifteen healthy volunteers performed a memory-pointing task using their right arm while single-pulse transcranial magnetic stimulation (TMS) above motor threshold was applied over the posterior parietal or prefrontal cortex of the left or right hemisphere in four blocks of trials. The stimulation was randomly delivered at one of three time intervals during the 3-s delay period (early: 300 ms, intermediate: 1,500 ms, late: 2,700 ms). A separate block with no stimulation was used as control. Only early left parietal stimulation resulted in an increase in the variance of movement amplitude but not direction for all targets in two-dimensional space (both hemifields). The results point to the significance of the contralateral posterior parietal cortex early on during the memorization of the target for an upcoming movement. Taking into consideration the limitations of TMS and those imposed by the particular task, the lack of specific effects of prefrontal stimulation provides evidence that these areas might not be involved in the performance of simple memorized arm movements.

INTRODUCTION

Arm pointing to a visual stimulus is a complex task that involves a transformation of the retinotopic coordinates of the stimulus to arm-centered coordinates related to the action of muscle synergies involved in the movement (Soechting and Flanders 1992). Lesion studies in humans have documented the pivotal role played by the parietal cortex in the visuomotor transformations required for accurate reaching to visual targets (Perenin and Vignetto 1988). More recent functional imaging studies have identified areas in the posterior parietal cortex, as well as the motor, premotor, and prefrontal cortices that are activated when humans perform reaching movements (Grafton et al. 1996; Kertzman et al. 1997; Lacquaniti et al. 1997). A series of studies recording the neuronal activity of primates while they were performing pointing arm movements to a visually presented stimulus, identified neurons related to both the visual stimulus and to the direction of the upcoming movement in the motor cortex (Georgopoulos et al. 1989), the premotor cortex (Johnson et al. 1996), and the posterior parietal cortex (Battaglia-Mayer et al. 2001; Ferraina et al. 1997; Johnson et al. 1996).

An emerging view of the cortical organization for arm reaching is that a combined network of parietal-frontal areas is involved in the process of visuomotor transformations required for accurate reaching movements (Battaglia-Meyer et al. 1998; Burnod et al. 1999). The frontal-parietal network involved in the planning and execution of arm movements could also include a prefrontal-posterior parietal component when the target location in space needs to be retained in working memory for a later execution of a pointing movement to the memorized target. The idea of a prefrontal-parietal network subserving spatial working memory has been suggested in the study of eye movements (Goldman-Rakic 1988). Specifically, neurons in the posterior parietal cortex (Chaffee and Goldman-Rakic 1998; Gnadt and Andersen 1988) and the prefrontal cortex (Chaffee and Goldman-Rakic 1998; Funahashi et al. 1989) discharge in relation to the spatial location of a visually presented target while the animal "holds" this information in memory for a delayed eye movement response [oculomotor delay (OCD)]. Furthermore, task-related neurons in the parietal cortex are activated early during the delay, and their discharge declines during the delay, while prefrontal neurons increase their discharge later during the delay and before the onset of the saccade (Chaffee and Goldman-Rakic 1998).

In a series of studies using single-pulse transcranial magnetic stimulation (TMS) while humans performed memory saccades, posterior parietal cortical stimulation delivered early during the delay affected the accuracy of memorized saccades, whereas stimulation of the prefrontal cortex later on during the retention period also affected saccade accuracy (Müri et al. 1996, 2000; Oyachi and Ohtsuka 1995). These results confirmed the critical involvement of parietal cortex in the early encoding period and the involvement of the prefrontal cortex later during the retention period.

In this study, we used single-pulse TMS of the posterior parietal cortex and prefrontal cortex of both hemispheres at different times during the memory period of a memorized arm-pointing task. Based on the previous results regarding memorized saccades, we hypothesized that early stimulation of the parietal but not the prefrontal cortex would result in a loss

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of accuracy for memorized pointing movements, while stimulation of the prefrontal but not the parietal cortex later during the delay would result in a similar effect. We used two-dimensional (2-D) pointing movements to memorized visual targets that varied both in amplitude and direction from a central starting position and measured accuracy of both movement amplitude and movement direction. Psychophysical studies of arm pointing demonstrate that amplitude and directional variability in arm pointing are independent of one another (Gordon et al. 1994). Thus we studied the effects of stimulation on both the directional and amplitude accuracy of memorized pointing movements.

METHODS

Subjects

Fifteen right-handed healthy volunteers (10 female, 5 male) participated in the study. Their mean age was 31 ± 3.5 (SD) yr. The participants were recruited from the academic environment of the Aeginition University Hospital and gave informed consent to participate in the study after a detailed explanation of the experimental procedures. The experimental protocol was approved by the Aeginition Hospital Scientific and Ethics Committee and was consistent with the Declaration of Helsinki. Participants were particularly screened to ensure that they had no history of epileptic seizures. As stated, all participants were right-handed. All performed the task using the right hand.

Experimental set-up and stimulation procedure

Subjects sat in a dark room facing a computer monitor (27 × 21 cm) placed 60 cm from the subject's eyes. The subject's head was fixed using a chin rest and head holder. Subjects used the right hand to move an analog joystick device placed on a table in front of them. The *x-y* coordinates of the joystick were sampled at 200 Hz using an A/D computer interface (PC Lab Card 818l, Advantech) and were used on-line to control cursor position on the computer monitor (3 × 3 mm white cross hair).

At the beginning of each trial, the subject moved the cursor into a 6-mm-diam yellow circle displayed at the center of the computer monitor (the origin of the movement). After a variable interval of 1–2 s, a 3-mm-diam white circle appeared at a peripheral position and remained for 0.2 s. The central circle remained on for another 3 s, and during this delay, the subjects were instructed to fixate on the central target. If the subject moved the cursor out of the center target during the delay, the trial was aborted as an error (delay error). The extinction of the central circle ("go" signal) indicated to the subject to move the cursor to the previously displayed peripheral target as quickly and as accurately as possible and to maintain this position until the reappearance of the central circle 3 s later (Fig. 1*A*). In a series of pilot experiments, nine subjects performed the task while we recorded electrooculogram (EOG) from their right eye. The EOG was displayed on an oscilloscope. We observed that all subjects were fixating the central target while waiting for the "go" signal; thus we did not perform an EOG in the experiment presented here. In 10% of the trials, the "catch trials," at a variable interval after the extinction of the peripheral target, the central target changed color from yellow to purple, and the subjects were instructed to release the joystick and press a button next to it within a period of 1 s. If the subject failed to press the button within that time, the trial was aborted as an error (late response error).

The target positions were located along the circumferences of five imaginary circles with a common center at the initial position of the hand (central circle) and radii of 2, 4, 6, 8, and 10° of visual angle. Targets were positioned every 15° beginning from 0° in a standard polar reference frame (increasing counterclockwise). This arrangement resulted in a total of 80 target locations (5 amplitudes × 16 directions). In each block of trials, all target locations were presented once in random order. The block also included nine catch trials in which target position was randomly chosen among the 80 possible locations.

Single-pulse TMS was applied by a MagStim 200 magnetic stimulator with a stimulation coil of 90 mm mean diameter. The rising time of the pulse was 5 μs, and the decay was approximately linear, lasting 160 μs. Four cortical regions were stimulated in separate blocks: the posterior parietal cortex (PPC) of the right and left hemisphere and the dorsolateral prefrontal cortex (DPFC) of the right and left hemisphere. There was also a control block with no stimulation. Blocks were presented in random order for each subject. Within each block, the time of stimulation varied randomly among three time points measured from the onset of the delay period: 300 ms (early), 1,500 ms (intermediate), and 2,700 ms (late) (Fig. 1*A*). The region of the PPC was stimulated according to a previously described procedure (Elkington et al. 1992; Müri et al. 1996). The posterior part of the coil was placed tangentially 3 cm posteriorly and 3 cm laterally to the vertex, while the anterior part was lifted from the scalp, the handle pointing backward. Since the magnetic field decays off very rapidly with increasing distance, this placement prevents an unsuitable spread of the stimulus, which is kept sufficiently large to achieve the desired effect. For the DPFC stimulation, the optimum scalp position for activating small hand muscles was determined, and the coil was placed 5–6 cm forward from this position (Epstein et al. 2002; George et al. 1995; Müri et al. 2000; Pascual-Leone and Hallett 1994; Pascual-Leone et al. 1996). The coil was placed in an analogous tangential position, with the handle pointing backward and the stimulating segment in the anterior-posterior direction. Each region was stimulated at 70% of total stimulator output, which was 10–30% above individual motor threshold, and the coil current flow was set clockwise for right hemisphere and counterclockwise for left hemisphere stimulation.

Data analysis

For each trial, the *x-y* coordinates of the cursor during the movement trajectory were transformed to a velocity curve (see Fig. 1*B*). On this curve, an experimenter marked the *x-y* position at the point where the velocity returned to zero and remained zero for the remaining trial time (the total movement endpoint). An interactive program, created using Testpoint software (Capital Equipment) was used for this analysis. As can be seen in Fig. 1*B*, we allowed for a small noise level at zero velocity. The noise level was defined by the experimenter as the level at the beginning of the response latency after the "go" signal. The *x-y* position data were then transformed using a polar coordinate system to compute the equivalent direction (D) and amplitude (A) movement endpoint. These values were then subtracted from the direction and amplitude of the target to compute the respective errors (see Fig. 1*B*).

The trial data from blocks in which stimulation was applied were arranged in three groups according to the stimulation time (early TMS: 300 ms, intermediate TMS: 1,500 ms, late TMS: 2,700 ms). We then computed four output parameters for each subject, for each TMS group, and each stimulation area: *1*) mean or systematic directional error (*Ds*) and *2*) its variance, or direction variable error (*Dv*); and 3) mean or systematic amplitude error (*As*) and *4*) its variance, or amplitude variable error (*Av*). In the first analysis, the output parameters were computed for the entire 2-D working space, including all target positions (5 amplitudes × 16 directions = 80 target locations). In the second and third analyses, we used targets presented only in the left and only in the right visual hemifield, respectively (5 amplitudes × 7 directions = 35 target locations in each analysis). Thus a total of 3 target presentation groups × 4 parameters per group = 12 parameters measured for each TMS group, each subject, and each

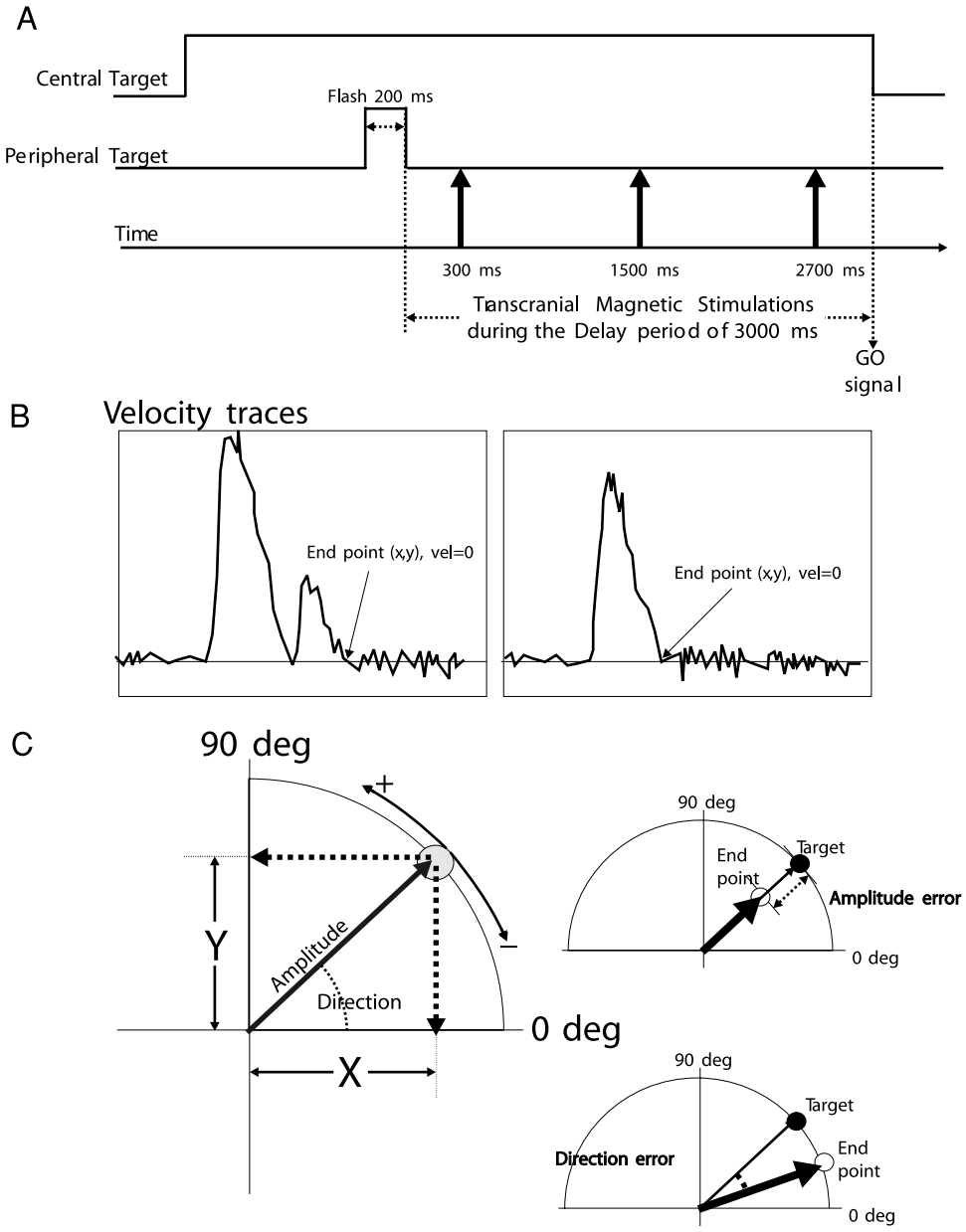

FIG. 1. *A*: experimental paradigm. *B*: instantaneous velocity traces for 2 characteristic types of movements observed in this study. In the *left trace*, movement ended after an initial velocity peak (this type of movement was observed in 50–60% of movements of each subject). In the *right trace*, a 2nd, smaller peak was also observed (this type of movement with a final adjustment was observed in 40–50% of movements of each subject). *C*: how direction and amplitude were defined and the corresponding directional and amplitude errors (D, directional error; A, amplitude error).

stimulation area. We also computed for each subject the three sets of four parameters for the block in which no stimulation was applied (control). We then subtracted the control group value of each parameter from each one of the corresponding group values for each subject and stimulation area and divided by the same control value; e.g., for each subject

$$\mathrm{Ds(right\ prefrontal,\ early\ TMS)} = (\mathrm{Ds(right\ prefrontal,\ early\ TMS)} - \mathrm{Ds(control)})/\mathrm{Ds(control)}$$

These normalized differences from control for each subject and stimulation area formed the final data set for the analyses that we report.

A separate analysis was performed for each group of stimulation data (early, intermediate, and late TMS). The reason for performing three separate analyses for each stimulation time and not a two-factor ANOVA with stimulation time and stimulation area as factors was that, by design, the stimulation time was a nested factor within each stimulation area, whereas a two-factor model would require that stimulation area and stimulation time would be randomly intermixed in a randomized design. Within each group, we performed three analyses, one for each set of parameters (total, left, right space). We used the general linear model ANOVA/MANOVA multivariate analysis to estimate the effects of stimulation area on each set of output parameters. The assumption of homogeneity of variance was tested in all cases where a significant effect was observed for a particular parameter in the set using Levene's test for equality of variances. In all cases of a significant effect, we applied Fischer's least square difference for post hoc comparisons of the different means for each area of stimulation. For all statistical analyses we used the STATISTICA software (STATSOFT).

RESULTS

Table 1 presents the percentage of delay errors and the late response errors per subject during task performance. Only subject 6 had an abnormally high percentage of errors in catch up trials. This subject reported, at the end of the experiment, of having difficulty remembering the catch-up trial instruction, but he also reported that during the delay period, he was

TABLE 1. *Errors in task performance*

Subject	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Delay Er.	1	3.5	1	1	2.5	6.7	2.7	5.5	5.2	2.5	6.2	8.2	5	1.7	4.2
L Res. Er.	6.6	8.8	0	0	2.2	55.5	6.6	6.6	2.2	0	13.3	15.5	6.6	8.8	2.2

The performance data for each subject are presented in this table. The second row presents the percentage of delay errors that is trials where the subject moved the cursor out of the center target during the delay period. The third row presents the percentage of late responses in catch up trials (response latency > 1 s).

fixating at the central target as instructed. The ensuing analysis was performed with and without the inclusion of subject 6, and the results were almost identical, so we present the analysis for all 15 subjects included.

Effects of early stimulation (300 ms)

The multivariate ANOVA analysis for the total space target group showed a significant effect on the amplitude variable error difference from control (Table 2). Levene's test for equality of variances for this effect was nonsignificant ($F_3 = 0.23$, $P = 0.8$). Post hoc comparisons showed that the stimulation of the left PPC resulted in a significantly different change in the normalized variable amplitude error difference from control compared with the values observed for the stimulation at the other areas (Table 3). In Fig. 2, we plotted the amplitude variable error difference means and 95% confidence intervals for each mean for the four stimulation areas. It can be seen that only for the left PPC stimulation did the normalized difference of amplitude variable error from control not include zero, thus indicating a significant increase of amplitude variable error from the control value. The analysis of the right and left hemifield target groups did not show significant differences among different stimulation areas.

We further investigated the specificity of this increase in the variable error in amplitude for the left parietal cortex by directly comparing the variance of the amplitude error for all targets among the four stimulation sites in the raw data. The F value for the Levene's test for equality of variances was 2.55 ($P = 0.05$). The variance of the amplitude error was larger for the stimulation over the left parietal cortex (left PPC = 0.52 squared degrees) compared with the variance for the other stimulation sites (right PPC = 0.4, right DLPC = 0.43, left DLPC = 0.43 squared degrees). The same test for the variance of directional error was not significant ($F = 0.63$, $P = 0.59$). Similarly, the Levene tests for equality of variance for directional and amplitude error for the targets of the left and right visual field were also not significant.

TABLE 2. *Multivariate ANOVA for total space and early stimulation*

Indices	Model R	Model R^2	Model F	P
Ds	0.19	0.04	0.72	0.54
Dv	0.18	0.03	0.66	0.58
As	0.20	0.04	0.81	0.49
Av	0.42	0.18	4.07	**0.01**

This table shows the results of the multivariate analysis for the stimulation at 300 ms for all targets (total space). Each one of the indices of performance was measured for each subject and each stimulation area (15 values for all subjects). All indices are differences from control, normalized to control: directional systematic and variable error (*Ds*, *Dv*), and amplitude systematic and variable amplitude error (*As*, *Av*). Only the amplitude variable error was significantly modulated by stimulation at different sites (bold indicates $P < 0.05$).

Effects of intermediate and late stimulation (1,500 and 2,700 ms)

There were no significant differences among areas when stimulation was applied at intermediate and late times for all groups of targets (total space, left hemifield, right hemifield).

DISCUSSION

We investigated the effects of a single-pulse TMS on the performance of memorized pointing movements in 2-D space. TMS was delivered at different delay intervals over the PPC or DLPC of the right or left hemisphere. The only significant effect that differentiated among different areas was an increase in the amplitude variable error observed when the stimulation was delivered early at the left PPC. This effect was present for all targets, independent of visual hemifield.

Methodological considerations

Maintaining central fixation during the task was verified in a preliminary experiment where we used EOG to monitor eye movements during the delay period. In the experiment reported here, we did not monitor eye movements because subjects never actually used the strategy of maintaining their eyes on the remembered target location for two reasons. One was that they had to keep the joystick-controlled cursor within the small central target (3 mm radius) during the delay, and this was a difficult task per se. The other was that they had to respond with a button press to the change of color of the central target (catch up trials). These trials of a secondary task served as a better indicator for us of the fact that our subjects maintained their attention at the central target during the delay period,

TABLE 3. *Post hoc comparisons for Av (total space, early stimulation)*

Stimulation Area	Right Parietal (mean: −0.15)	Right Prefrontal (mean: −0.12)	Left Parietal (mean: 0.21)	Left Prefrontal (mean: −0.09)
Right parietal		0.77	**0.003**	0.60
Right prefrontal	0.77		**0.007**	0.81
Left parietal	**0.003**	**0.007**		**0.013**

This table presents the post hoc comparisons of the means for each stimulation area of the normalized difference from control of the amplitude variable error for all targets (total space). Only the stimulation at the left parietal area had a significantly different effect, which was an increase in variable error from control.

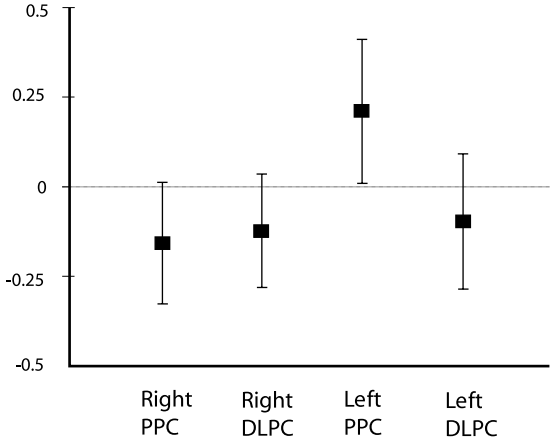

FIG. 2. Mean normalized differences from control (boxes) plus 95% confidence intervals (whiskers) of the amplitude variable error measured for the total movement for all targets (total space) when stimulation was applied at 300 ms (early stimulation). *x* axis, different stimulation areas; *y* axis, normalized difference from control. Horizontal line that crosses 0 indicates whether the 95% confidence intervals include 0. It can be seen that, except for left parietal stimulation, all other intervals include 0. Thus only left posterior parietal cortex (PPC) stimulation resulted in a significant increase of variable amplitude error from control.

because one could argue that although subjects did not fixate the peripheral target during that time they could still maintain their covert attention at this location.

In our control condition, the subjects knew that no stimulation would be applied; also, the sensations and the noise from TMS application were absent. It could be argued then that our control condition allowed for both specific and nonspecific effects of TMS stimulation to be detected. The mean and variance of amplitude and directional error for each subject, each stimulation time, and each stimulation area were subtracted from the control values and normalized to the control. Our data then were sensitive to detect all TMS effects, both specific and nonspecific, irrespective of inter-subject differences in these measures that were normalized to the control values for each subject. For this reason, we focused our analysis on detecting significant differences among different stimulation areas, thus looking for specific effects of stimulation on particular areas compared with other areas. This analysis assumes that nonspecific effects of TMS stimulation would be equivalent when different areas would be stimulated. The significant effect that was observed for the amplitude variable error was an increase in the percent of variable error from the control that was significantly greater for the left PPC than for all other areas only when stimulation was delivered at 300 ms during the delay. This effect could not be due to a general effect of TMS stimulation. The effect was also tested with respect to the control by computing the 95% confidence intervals of the mean difference from control. This interval did not include zero, thus confirming a true increase of variable amplitude error from the control. The 95% confidence intervals of the mean values for all other areas did include zero; therefore irrespective of the possibility of general effects of TMS stimulation, the mean amplitude variable error when these areas were stimulated was not different from control. Finally, we used the raw data to compare the variances of the amplitude error (thus the variable error) among the four stimulation areas with no normalization for control. This method, although not sensitive for detecting specific TMS effects, still showed a significant increase of variance for amplitude error when left PPC was stimulated compared with the stimulation of the other areas.

We used both systematic and variable error for both amplitude and direction and observed an effect of TMS specific to the variable error and not the systematic error, indicating that the stimulation of the cortex on each trial might result in an increase in the noise of the amplitude specification, resulting in an overall decrease in the system's efficiency.

Finally, we will mention the TMS technique limitations. We are not certain of the depth of stimulation in the brain or its spatial resolution. Furthermore, it has not been determined which neural elements are the most sensitive to stimulation in a particular area of the brain and whether all the effects of stimulation are attributable to activity at the site of the stimulus or whether activity spreads through neural pathways to other more distant sites (Pascual-Leone et al. 2000). Nevertheless, in our experiment, we found a clear dissociation of prefrontal versus parietal stimulation for a specific behavioral parameter at a specific time during performance of the task. Thus we could argue that TMS did have a very specific effect in disrupting the behavior in a specific measure (amplitude) at a specific time in one area and not in others that are clearly separated in the brain (between the parietal and prefrontal areas lies the motor cortex; this did not show effects of stimulation in all conditions).

Effects of early parietal stimulation

We observed that stimulation of the PPC but not the DLPC early during the memory period had an effect on the subsequent movement accuracy, thus confirming our initial hypothesis on early stimulation. The crucial role of the PPC in visual reaching has been documented in patients suffering from "optic ataxia," a syndrome in which reaching is impaired without an impairment in primary somatosensory, vision, or motor function (Pause et al. 1989; Perenin and Vighetto 1988; Tzavaras and Masure 1976). Lesion studies (Rushworth et al. 1997a,b) and neuronal recording studies in primates (Johnson et al. 1996; Kalaska et al. 1983; Mountcastle et al. 1975) also provided evidence for the involvement of the PPC in the planning and execution of arm movements. Finally, functional imaging studies in humans have identified a network of areas involving the PPC, premotor, and motor cortex that are activated in the planning and execution of reaching and grasping arm movements (Grafton et al. 1992; Kertzman et al. 1997; Laquaniti et al. 1997). Thus our major finding of an increase in the variability of amplitude or equivalently a loss in the efficiency of amplitude specification with PPC stimulation is in accordance with previous findings on the role of this region for arm pointing. A previous study using the same stimulation parameters showed that early PPC stimulation (270 ms after the delay onset) also affected the amplitude accuracy of subsequent memorized eye movements (Müri et al. 1996). Because the round coil was used to stimulate a large cortical area in both studies, we could hypothesize that a large portion of PPC was stimulated, including the major functionally distinct areas superior and inferior to the intraparietal sulcus. The superior parietal lobule has been implicated in primate studies in the control of arm movements arm movements (Kalaska et al.

1983; Mountcastle et al. 1975; Rausworth et al. 1997a,b), while the inferior parietal lobule has bee implicated in the control of eye movements (Andersen et al. 1997; Snyder et al. 1997).

Late stimulation of prefrontal areas

The second part of our original hypothesis, that late stimulation of the DLPC but not the PPC would result in a loss of pointing accuracy as was observed in previous experiments on memory saccades (Müri et al. 1996, 2000), was not confirmed. The reason for this discrepancy between eye movements and arm movements might be that the functional anatomy of the two systems is different at the level of the frontal cortex. Thus in a study of spatial working memory function in humans, the authors compared performance in a task where subjects had to remember a series of spatial locations and later either report a match with a newly presented series (matching task) or reproduce the series with arm-pointing movements (reproduction task) (Pochon et al. 2001). They found specific activation of DLPC only for the reproduction task and argued that prefrontal recruitment is necessary for the manipulation of stored spatial information and not for simple storage of that information. In the study by Owen et al. (1996), patients with prefrontal cortical lesions produced more errors than controls in a self-ordered, spatial working memory task. In this task, subjects have to keep in working memory an increasing number of previously visited spatial locations. The errors of frontal patients were particularly related to the use of an inefficient task strategy. In contrast, patients with temporal or amygdalo-hippocampal lesions produced more errors only at the most difficult task conditions. The authors, based on these findings, claimed that the prefrontal cortex is important in "executive" function, meaning manipulation of stored information and not simply in the storage of spatial information. The only study of neuronal activity in a memory-pointing task was confined to the motor cortex (Smyrnis et al. 1992). In that study, it was observed that motor cortical activity during the delay period predicted the direction of the upcoming movement. Also, a small percentage of neurons were specifically activated during the memory delay but not during the stimulus presentation or movement execution. It could be argued then that the prefrontal cortex might not be related to the simple storage of spatial information for reaching and that this function could be confined in the premotor and motor cortices. The prefrontal activation could become important when the memory demands also include manipulation of the stored information. We are currently investigating this hypothesis using a more demanding memory pointing task to study the effects of single-pulse TMS at the DLPC.

Visual hemifield effects on arm and eye movement accuracy

Müri et al. (1996) observed that stimulation of the right PPC resulted in the decrease of amplitude accuracy of remembered saccades for targets presented at the left visual hemifield. In contrast, the stimulation of the left PPC in the same time window did not result in a decrease of accuracy of remembered saccades, revealing a hemispheric asymmetry for memory-guided saccades (Müri et al. 2000). A similar right-left asymmetry has also been observed in patients with lesions of the left PPC, where the accuracy of memory guided saccades is much less affected than after a right lesion (Pierrot-Desseilligny et al. 1991). We did not observe such visual field effects of TMS in the accuracy of arm pointing movements. On the contrary, the effect of left PPC TMS on amplitude was observed for all targets in 2-D space. A similar observation was made for patients with PPC lesions. These patients were impaired in reaching to all targets (both hemifields) using their right arm, contralateral to the lesion (arm-related effect) (Perenin and Vighetto 1988). In addition to these arm-related effects, these authors also reported that reaching with the ipsilateral to the lesion arm resulted in visual hemifield related deficits. Thus patients with right PPC lesions had difficulty in reaching with both arms for targets presented in the right hemifield, indicating that the lesion of the right PPC had both an arm-related and visual field–related effects. We did not observe visual field–related effects in our study, and this might be related to the difference between a complete loss of PPC function and the transient effect of the TMS on this area.

CONCLUSION

This study provided evidence for the involvement of posterior parietal cortex in the early stages of encoding a spatial location for the purpose of making a pointing movement from memory. This finding is in agreement with previous anatomical, neurophysiological, and imaging data. On the other hand, the stimulation of prefrontal cortex did not result in a significant effect on movement accuracy adding to previous evidence of a lack of involvement of these areas in arm motor control.

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