Repetitive Transcranial Magnetic Stimulation of Broca's Area Affects Verbal Responses to Gesture Observation

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Abstract

■ The aim of the present study was to determine whether Broca's area is involved in translating some aspects of arm gesture representations into mouth articulation gestures. In Experiment 1, we applied low-frequency repetitive transcranial magnetic stimulation over Broca's area and over the symmetrical loci of the right hemisphere of participants responding verbally to communicative spoken words, to gestures, or to the simultaneous presentation of the two signals. We performed also sham stimulation over the left stimulation loci. In Experiment 2, we performed the same stimulations as in Experiment 1 to participants responding with words congruent and incongruent with gestures. After sham stimulation voicing parameters were enhanced when responding to communicative spoken words or to gestures as compared to a control condition of word reading. This effect increased when participants responded to the simultaneous presentation of both communicative signals. In contrast, voicing was interfered when the verbal responses were incongruent with gestures. The left stimulation neither induced enhancement on voicing parameters of words congruent with gestures nor interference on words incongruent with gestures. We interpreted the enhancement of the verbal response to gesturing in terms of intention to interact directly. Consequently, we proposed that Broca's area is involved in the process of translating into speech aspects concerning the social intention coded by the gesture. Moreover, we discussed the results in terms of evolution to support the theory [Corballis, M. C. (2002). *From hand to mouth: The origins of language*. Princeton, NJ: Princeton University Press] proposing spoken language as evolved from an ancient communication system using arm gestures. ■

INTRODUCTION

Gesture is a universal feature of human communication. In every culture, speakers produce gestures, although the extent and typology of the produced gesture vary. For some types of gestures, execution is frequently associated with speech production (Goldin-Meadow, 1999; McNeill, 1992). In particular, speakers frequently pronounce words while they execute symbolic gestures expressing the same meaning as the word. Consider expressing approbation: while pronouncing "ok," one often forms a circle with the forefinger and thumb in contact at their tips, keeping the rest of the fingers extended.

From an evolutionary point of view, various authors (Rizzolatti & Arbib, 1998; Amstrong, Stokoe, & Wilcox, 1995; Hewes, 1973) hypothesized that spoken language derives from an ancient system using arm gestures in order to communicate. Recently, Corballis (2002) proposed that spoken language developed as the repertoire of gestures was gradually transferred from arm to mouth. This may have happened because of the existence of double motor commands simultaneously sent to both arm and mouth (Gentilucci, Santunione, Roy, & Stefanini, 2004; Gentilucci, Stefanini, Roy, & Santunione, 2004; Gentilucci, Benuzzi, Gangitano, & Grimaldi, 2001). In addition, there is a strict relationship between early language development in children and several aspects of manual activity, such as communicative and symbolic gestures (Volterra, Caselli, Capirci, & Pizzuto, 2005; Bates & Dick, 2002). Canonical babbling in 6–8 months aged children is accompanied by rhythmic hand movements (Masataka, 2001). Word comprehension in children between 8 and 10 months and word productions between 11 and 13 months are accompanied by deictic and recognition gestures, respectively (Bates & Snyder, 1987; Volterra, Bates, Benigni, Bretherton, & Camaioni, 1979).

From a behavioral point of view, words and symbolic gestures are communication signals strictly related to each other. Indeed, executing meaningful rather than meaningless gestures enhances voice spectra parameters of the corresponding-in-meaning simultaneously

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pronounced words. Pronouncing words rather than pseudowords tends to inhibit corresponding-in-meaning gesture execution as shown by the slowing down of arm kinematics parameters (Bernardis & Gentilucci, 2006). That is, the simultaneous emission of the two communication signals enhanced voice parameters and inhibited arm kinematics parameters as compared to the emission of the single signal.

On the other hand, the interpretation of messages expressed by the combination of word and gesture is different from that of the single communication signal. In fact, the listening of the word and the contemporaneous observation of the speaking actor executing the corresponding-in-meaning gesture (Figure 1) affected the voicing of the verbal response to the two communication signals just as the simultaneous emission did (Bernardis & Gentilucci, 2006). We explained this result suggesting that the observer, when verbally responding to the presented gesture, automatically and covertly imitated (i.e., automatically imagined) the same gesture, going into resonance with the sender (Rizzolatti, Fogassi, & Gallese, 2002). Similar relations were found between transitive actions and pronounced syllables. Indeed, the execution of transitive hand actions, such as grasping and bringing the hand to the mouth, affected the voicing of simultaneously pronounced syllables. The effects on voicing were interpreted as consequent to simultaneous commands sent to both arm and mouth (Gentilucci, Santunione, et al., 2004; Gentilucci, Stefanini, et al., 2004; Gentilucci, Benuzzi, et al., 2001). In addition, the effects of action observation on voicing of simultaneously pronounced syllables were the same as when the actions were executed (Gentilucci, Santunione, et al., 2004; Gentilucci, Stefanini, et al., 2004; Gentilucci, 2003). In other words, the observer automatically and covertly imitated (i.e., automatically imagined) the same action, sending a motor command also to the mouth. These data are in accordance with the concept that a link exists between the actor and the observer such as it exists between the sender and the receiver of a message. This link may derive from an evolved "mirror system," which related execution to observation of transitive actions, providing the necessary bridge from "doing" to "communicating" (Rizzolatti & Arbib, 1998).

Previous neuroimaging studies observed activation of Broca's area when representing meaningful arm gestures (Gallagher & Frith, 2004; Buccino, Binkofski et al., 2001; Grèzes, Costes, & Decety, 1998; Decety et al., 1997; Grafton, Arbib, Fadiga, & Rizzolatti, 1996) and of the left ventral premotor area when observing to imitate meaningless gestures (Grèzes, Costes, & Decety, 1999). Motor imagery of hand movements includes activation of both Broca's and left premotor ventral areas

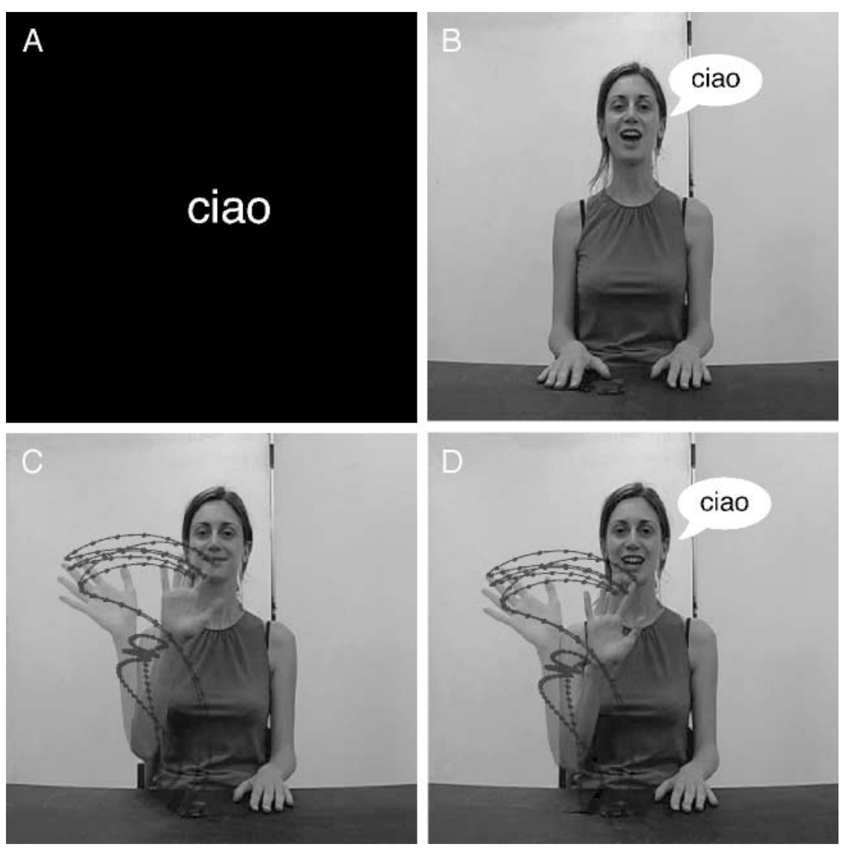

Figure 1. Modalities of stimulus presentation in Experiment 1. (A) Printed word; (B) spoken word; (C) gesture; (D) spoken word and gesture. Only the CIAO communication signal is presented and, in each panel, one frame of the presented videoclip is shown. In C and D two different frames are superimposed. Black lines indicate the index finger and wrist path. Circles show the spatial positions of the markers placed on the index finger and the wrist during gesture execution. Kinematics data were collected in a separate session using the SMART motion capture system.

(Hanakawa et al., 2003; Kuhtz-Buschbeck et al., 2003; Gerardin et al., 2000; Grafton et al., 1996; Parsons et al., 1995), probably extending to the motor area (Porro et al., 1996). Finally, new data show that motor imagery of symbolic gestures activates Broca's area (Lui et al., personal communication, 2005). On the other hand, Broca's area has been proposed to be involved in encoding phonological representations in terms of mouth articulation gestures (Paulesu, Frith, & Frackowiak, 1993; Demonet et al., 1992; Zatorre, Evans, Meyer, & Gjedde, 1992). On the basis of these neuroimaging data, we hypothesized that Broca's area is involved in translating aspects of activated representations of arm gestures into mouth articulation gestures. These aspects may concern the goal (Buccino, Lui, et al., 2004; Buccino, Binkofski, et al., 2001) and/or the intention (Iacoboni et al., 2005) of the gesture.

In the present study, we used repetitive transcranial magnetic stimulation (rTMS), a technique that provides the unique opportunity to create temporary inactivation of cortical areas (Walsh & Cowey, 2000). It is well documented that the low-frequency (e.g., 1 Hz) rTMS reduces the excitability of the targeted region (Shapiro, Pascual-Leone, Mottaghy, Gangitano, & Caramazza, 2001; Maeda, Keenan, Tormos, Topka, & Pascual-Leone, 2000; Pascual-Leone, Bartres-Faz, & Keenan, 1999; Chen et al., 1997), in effect creating a virtual lesion that may transiently interfere with the cognitive processing beyond the duration of the train itself (Pascual-Leone, Walsh, & Rothwell, 2000). In Experiment 1, we applied rTMS over Broca's area of participants performing a task of congruent verbal response to presentation of communicative words and/or gestures (Bernardis & Gentilucci, 2006). We expected that rTMS dissipated the effects of gesture observation previously found on the verbal responses. We performed also two control stimulations on the same participants performing the same task. The first was applied over the loci of the right hemisphere symmetrical to those of the left cortex stimulation in order to verify whether possible effects of rTMS on the task were common to both hemispheres. The second was a sham stimulation over the sites of the left stimulation in order to have baseline data, obtained using the same experimental setting and procedure, to compare with the data obtained after the left and right stimulations. In Experiment 2, we performed the same stimulations as in Experiment 1 on participants performing the same task as in Experiment 1. In addition, participants performed a new task of verbal responses incongruent (i.e., noncommunicative words) with the presented gestures. We hypothesized that the factor relating gesture to word was the congruence of the goal and/or the intention of the two communication signals. Consequently, we expected no variation in the voicing parameters after the sham stimulation and the left and right stimulations. As an alternative result supporting our hypothesis, we could observe an interference effect of the gestures on incongruent words after sham and right stimulations and no effect of the gestures after left stimulation.

EXPERIMENT 1

Methods

Participants

Seven Italian naive volunteers (age 23–35 years) participated in the study. Only male participants were included to reduce variability in vowel formants (Pickett, 1999; Ferrero, Magno Caldognetto, & Cosi, 1996). They were classified as right-handed according to the Edinburgh Inventory (Oldfield, 1971) and were screened to rule out any history of neurological, psychiatric, medical problems, and contraindications to TMS (Wassermann, 1998). Before the experiment, all signed consent forms approved by the Ethics Committee of the Medical Faculty of the University of Parma.

Transcranial Magnetic Stimulation

We performed rTMS over the frontal region of the left cortex, then over the symmetrical sites of the right cortex, and finally, we performed sham stimulation over the same sites as those of the left cortex stimulation. The interval between two successive stimulation sessions was at least 1 week in order to avoid practice effects on task execution (see below).

By using a Magstim Stimulator (The Magstim Company, Whitland, UK, 2.2 T maximum power), powered by two booster modules and connected to a figure-of-eight coil (7 cm diameter), we delivered single biphasic TMS pulses, and moving on a grid of approximately 1 cm by 1 cm, we found the hot spot for eliciting muscle-evoked potentials (MEPs) in the opponens pollicis (OP) muscle contralateral to the stimulated side. The coil handle formed a 45° angle with the midline, pointing laterally and caudally. MEPs were collected using Ag/AgCl electrodes with hand muscles at rest (amplification: ×1000; sampling rate of 4000 Hz; band pass: 5–5000 Hz). The resting motor threshold was defined as the minimal intensity that induced MEPs greater than 50 μV peak-to-peak amplitude in 5 out 10 trials. This value was searched for each participant in order to equate starting intensity in the successive localization of speech arrest (SA) site (see below). The location of the OP muscle was, on average, 6.1 ± 1.5 cm lateral and 0.5 ± 0.7 cm anterior with respect to Cz (Figure 2). The intensity was 60.3 ± 6.2% of the maximum stimulator output. The OP site was used as a reference point for the successive searching for an SA.

Short trains of magnetic pulses over Broca's area can interfere with speech production producing an SA (Epstein, 1998; Pascual-Leone, Gates, & Dhuna, 1991). In particular, it evokes nonmotor SA, as opposed to motor

SA observed stimulating the mouth motor area (Stewart, Walsh, Frith, & Rothwell, 2001). Nonmotor SA differs from motor SA because it is not associated with EMG activity evoked in lower facial muscles (Stewart et al., 2001).

Moving from the OP muscle hot spot, we searched for a nonmotor SA. The coil was moved laterally and rostrally on a grid of approximately 1 cm by 1 cm, stimulating with short trains of 10 magnetic pulses at a frequency of 5 Hz (Epstein et al., 1996). As starting intensity, the OP muscle resting motor threshold was used. Intensity was progressively increased until a maximum of 120% or until an SA was evoked. SA was tested in a task in which the participants were required to count aloud repetitively from 1 to 10. It was described by both the participants and the experimenters as a slowing and blurring of speech or a sensation of inability to "get out the words." We looked for the optimal stimulation intensity choosing the lowest one evoking SA. The optimal intensity was verified before left and sham stimulations and it was found stable. We followed the method of Stewart et al. (2001) to qualify speech disruption observed during the stimulation as nonmotor SA. Specifically, we verified that the same stimulation over the symmetrical sites of the right hemisphere did not produce comparable effect (see below), and verified in 10 trials lack of MEP from the mentalis muscle at rest when stimulating with single biphasic pulses at the same intensity. In all the participants, no MEP was observed. Finally, in a posttest examination, we verified where in the frontal region the most anterior and posterior rTMS sites were located. We performed MRI scans and in a separate session we localized on the scalp the site of the previous left rTMS, verifying that an SA could be evoked with the previously used parameters without evoking MEPs in the mentalis muscle. Then, using the stereotaxic neuronavigator SoftTaxic system (E.M.S., Bologna, Italy), we reconstructed the stimulation sites on MRI scan data. Surface rendering of the MRI series was performed using OSIRIX Medical Imaging Open Source software.

Before applying rTMS on the right sites symmetrical to those of the left stimulation, we excluded SA in all participants. Before sham stimulation, we verified that in the location of the left stimulation, an SA could be evoked with the same parameters used in the previous left stimulation session and no SA could be evoked with sham stimulation. During the sham stimulation, the coil was positioned 2 cm above the scalp by means of a wooden (2 cm high) cylinder rigidly connected to the coil (Nikouline, Ruohonen, & Ilmoniemi, 1999).

After localization of the stimulation sites in the left and right hemispheres, we applied rTMS, which consisted of 300 pulses at 1 Hz with the intensity eliciting SA. The coil position was horizontal, with the handle pointing anteriorly. This was the position minimizing discomforts during stimulation in most participants. Each (left, right, and sham) stimulation session consisted of four rTMSs. The interval between two successive stimulations was at least 7 min. After each stimulation, one block of trials was run (see below). Duration of each block was always less than 3 min, according to the data on duration of the stimulation effects after 1 Hz rTMS reported in previous studies (Romero, Anschel, Sparing, Gangitano, & Pascual-Leone, 2002; Muellbacher, Ziemann, Boroojerdi, & Hallett, 2000).

Apparatus and Stimuli

Apparatus, stimuli, and procedure have been described in our previous study (Bernardis & Gentilucci, 2006). In brief, participants sat on a chair in front of a table. The stimuli (words, symbolic gestures, or both) were the three communication signals: CIAO [tʃao], NO [nɔ], and STOP [stɔp]. The modality of the communication signal presentation varied in each of four successive blocks of trials. In the first modality (Figure 1A), a printed word was presented on a PC display (printed word modality). In the other modalities, short video clips showed the half body of an actress (face: $3^\circ \times 4.5^\circ$ of visual angle) pronouncing the word (spoken word modality; Figure 1B), or executing the symbolic gesture (gesture modality; Figure 1C), or simultaneously pronouncing the word and executing the gesture (spoken word and gesture modality; Figure 1D). The stimuli were presented on a 19-in. SONY LCD monitor controlled by a PC. The monitor was set at a spatial resolution of 800×600 pixels and at a temporal resolution of 75 Hz. The distance of the monitor from the participant was 57 cm. The trial started with a BEEP followed by a black screen (300 msec), after which the stimulus was presented. The stimulus duration was 3000 msec.

Procedure

The participants were required to pronounce the word corresponding to the communication signal presented with different modalities once recognized. In the modality of simultaneous presentation of word and gesture, the participants were required to pronounce the word once both signals were recognized. In the printed word modality, in order to ensure understanding of word meaning before pronunciation, the participants were required to read silently the word and then repeat it aloud. In sum, each experimental session consisted of four conditions in which the same response was required to stimuli presented, in four successive blocks of trials. The blocks of trials were quasi-counterbalanced across participants. Each stimulus was quasi-randomly presented five times, yielding a total of 15 trials per block. Participants were left free to use as much time as needed to complete each trial. Each block of trials was preceded by rTMS (see above).

Data Recording

The participants wore a lightweight dynamic headset microphone (Shure, model WH20). The frequency response of the microphone ranged from 50 to 15,000 Hz. The microphone was connected to a second PC by a sound card (16 PCI Sound Blaster; CREATIVE Technology, Singapore). Voice data were acquired during word pronunciation using the Avisoft SASLab professional software (Avisoft Bioacoustics, Germany), whereas the participants' voice parameters were calculated using the PRAAT software (www.praat.org). In particular, we analyzed the time course of formant (F) 1 and 2 of the word vowels. It is well known that F1 and F2 exactly define vowels from an acoustical point of view. Both formant transition and pure vowel pronunciation were included in the analysis. Mean F1, F2, pitch, intensity, and vowel duration were calculated.

Movements of the participant's lips were recorded using the 3-D optoelectronic SMART system (BTS, Milan, Italy). The SMART system consists of six video cameras detecting infrared reflecting markers (spheres of 5 mm diameter) at a sampling rate of 60 Hz. Spatial resolution of the system is 0.2 mm. Recorded data were filtered using a moving average filter, that is, a low-pass filter where each value was the average computed over five samples (window duration 66.7 msec). We used two markers placed on the center of the superior and inferior lips. We analyzed the time course of the distance between the two markers in 3-D space. We measured peak velocity of lip opening during the initial mouth aperture and maximal lip aperture (i.e., maximal distance between the two markers). The PC presenting the stimuli was also used to synchronize recording of lip movements with voice recording. The SMART system was used to analyze qualitatively the arm trajectory of the actress executing the gesture. Two markers were placed on the index finger and on the wrist.

Data Analysis

The voice and kinematics parameters were analyzed by analyses of variance (ANOVAs) in which the within-subjects factors were stimulation (left vs. right vs. sham), presentation modality (printed word vs. spoken word vs. gesture vs. gesture and spoken word), and communication signal (CIAO vs. NO vs. STOP). In all analyses, paired comparisons were performed using the Newman–Keuls procedure. The significance level was fixed at $p < .05$.

Results

Figure 2A (white circles) shows the left hemisphere stimulation sites, in relation to the international 10–20 system, where nonmotor SA was evoked (Stewart et al., 2001). Mean intensity of stimulation was 64.4 ± 3.2% of maximum stimulator output. Location was, on average, 11.2 ± 2.4 cm lateral and 4.5 ± 1.5 cm anterior with respect to Cz. MRI scan data obtained in two participants showed that the most anterior and posterior stimulation sites were located in BA 45 and BA 44 (near the precentralis sulcus), respectively (Figure 2B).

After evoking SA, we applied rTMS over the same sites and, in other two successive sessions, we stimulated the symmetrical loci of the right cortex and performed sham stimulation over the loci of the left stimulation. After the left stimulation, the participants were able to respond verbally to the stimuli presented with the different modalities. However, changes were observed in the voice spectra as compared to the effects of the other two stimulations. Figure 3 shows the effects of the rTMS on the formant 2 (F2) of the voice spectra. Whereas the factor stimulation was not significant, the interaction between stimulation and presentation modality was [$F(6,36) = 2.8, p < .05$]. The results of the post hoc analyses are as follows. After sham stimulation, F2 increased in the modalities of spoken word and gesture as compared to the printed word modality. In the modality of simultaneous presentation of the two communication signals, F2 further increased in the comparison with presentation of the sole pronounced word and executed gesture. After the right stimulation, the same effects as after sham stimulation were observed. Note that the increase in F2 in the gesture modality as compared to the spoken word modality (Figure 3) did not reach significance. The left stimulation induced a different pattern of response that was constant for all the participants. F2 of the words pronounced in response to gestures was lower than F2 in the modalities of presentation of spoken word and spoken word plus gesture and did not differ from F2 in the printed word modality. F2 in the two modalities of spoken word (i.e., word and word plus gesture) did not differ from each other and was higher than F2 in the printed word modality. Summing up, the left rTMS dissipated the effect of gesture presentation on F2 observed after sham and right rTMS.

The statistical analysis of the pitch parameter revealed a significant interaction between stimulation and presentation modality [$F(6,36) = 3.5, p < .01$], but no effect of the factor stimulation. Figure 4 shows the effects of the three rTMSs on the pitch of the verbal responses to the stimuli presented according to the four modalities. After sham and right stimulations, no differential effect of presentation modality was found on pitch. In contrast, after the left stimulation, pitch in the modality of printed word increased as compared to the other modalities.

Figure 5 shows the effects of the three rTMSs on peak velocity of lip opening during word pronunciation. Peak velocity of lip opening slightly decreased after the left and right stimulations as compared to the sham stimulation (82.7 and 77.0 mm/sec vs. 98.9 mm/sec). This effect did not reach significance [$F(2,12)=3.1, p = .08$].

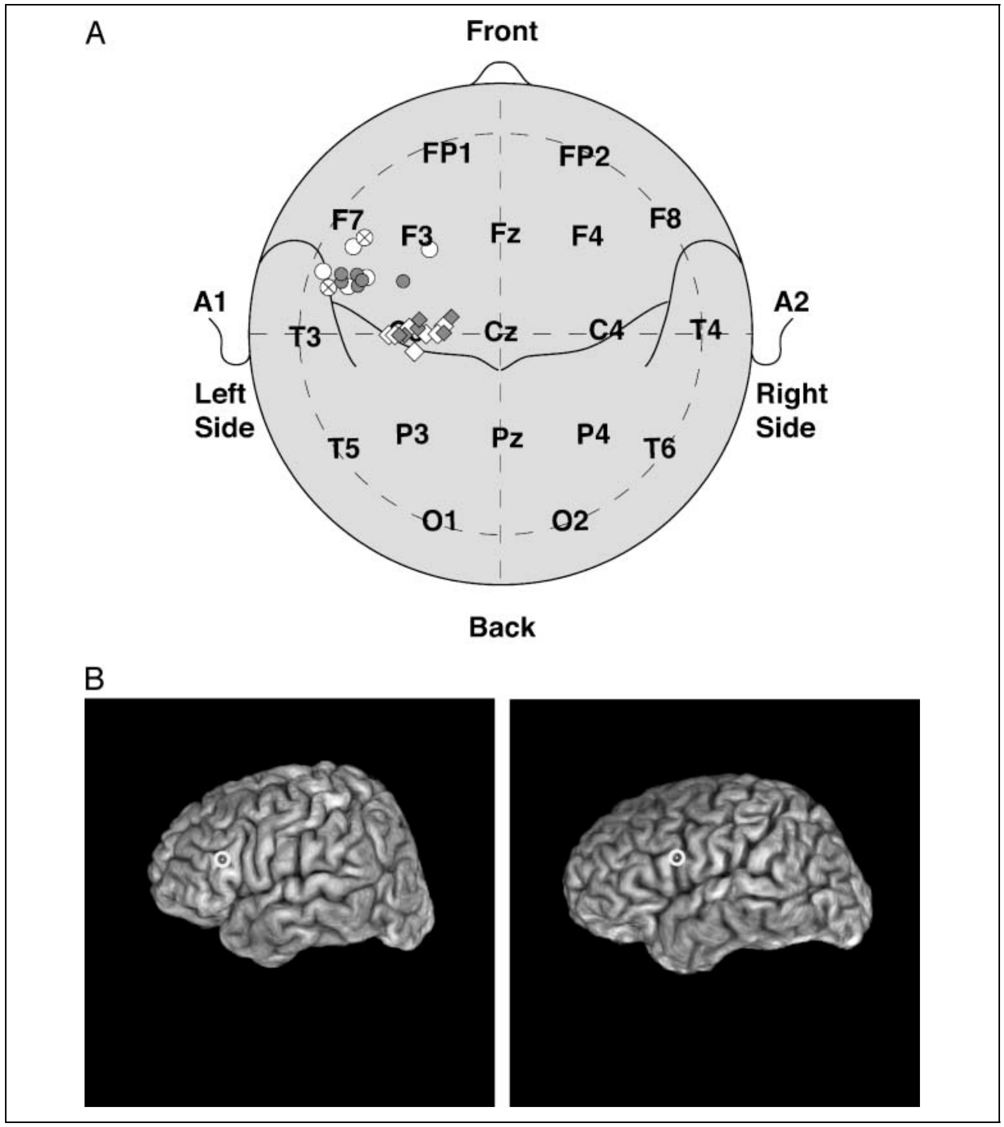

Figure 2. (A) Representation of the left hemisphere rTMS sites (circles) in relation to the international 10–20 system. Diamonds indicate the hot spots for eliciting MEPs in the OP muscle. Crosses indicate the rTMS sites for which reconstruction was performed on MRI scan data using the stereotaxic neuronavigator SoftTaxic system (B). White and gray symbols refer to Experiments 1 and 2, respectively. (B) Surface rendering of the MRI series with circle superimposed to indicate the rTMS target sites of the two participants in Experiment 1 for whom stimulation site reconstruction was performed on MRI scan data.

In contrast, the interaction between stimulation and presentation modality reached significance [$F(6,36) = 2.9$, $p < .05$]. After the sham and left stimulations, peak velocity was higher when responding to printed words as compared to the modalities of spoken word and/or gesture. After the right stimulation, a different pattern of responses was observed. In addition to the printed word modality, lip opening was quicker after presentation of gestures.

EXPERIMENT 2

As expected (Bernardis & Gentilucci, 2006), after sham stimulation F2 increased in the condition of verbal response to gesture presentation as compared to repetition of silently read words. We previously (Bernardis & Gentilucci, 2006) reasoned that when presented with a gesture the observer covertly imitated the gesture and simultaneously pronounced the corresponding word. Simultaneous emission of congruent gestures and words induced enhancement in F2 (Bernardis & Gentilucci, 2006). This enhancement effect could depend on the gesture acting on the word because both word and gesture share the same goal and/or intention. The left rTMS dissipated this effect. There is experimental evidence that when observing arm actions Broca's area is activated in a goal/intention-dependent manner (Iacoboni et al., 2005; Buccino, Lui, et al., 2004; Buccino, Binkofski, et al., 2001). Consequently, the transient deficit produced by the left rTMS could be related to understanding the goal/intention of the observed gesture. As a result, the gesture could not act on the corresponding-in-meaning word. If this hypothesis is correct, a different effect on a word incongruent (unrelated) with the gesture should be observed after sham, right, and left stimulations. In Experiment 2, we compared congruent with incongruent verbal responses. Because the meaning of the word was incongruent with the gesture, we expected no effect of the gesture on the word after sham, left, and right stimulations. Alternatively, the same hypothesis

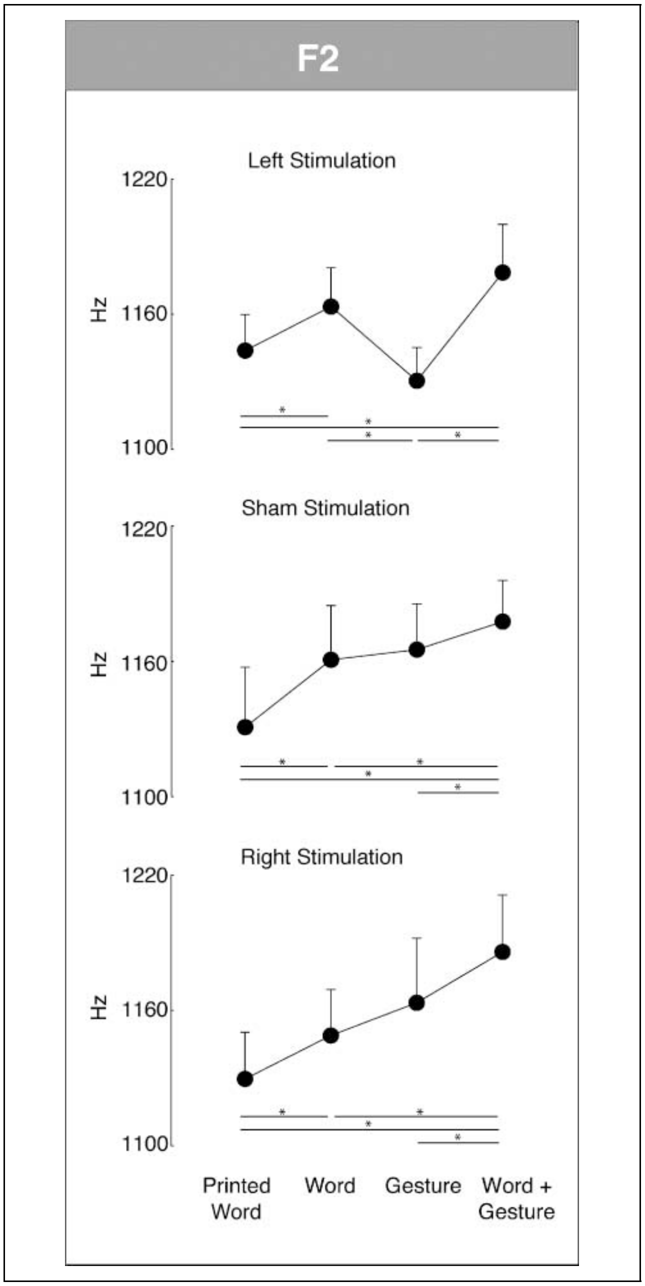

Figure 3. Effects of the modalities of stimulus presentation on vowel formant 2 (F2) of the verbal responses after left hemisphere, right hemisphere, and sham rTMS in Experiment 1. Vertical bars: *SE*. Horizontal bars: significant comparisons between modalities of stimulus presentation. $^*p < .05$.

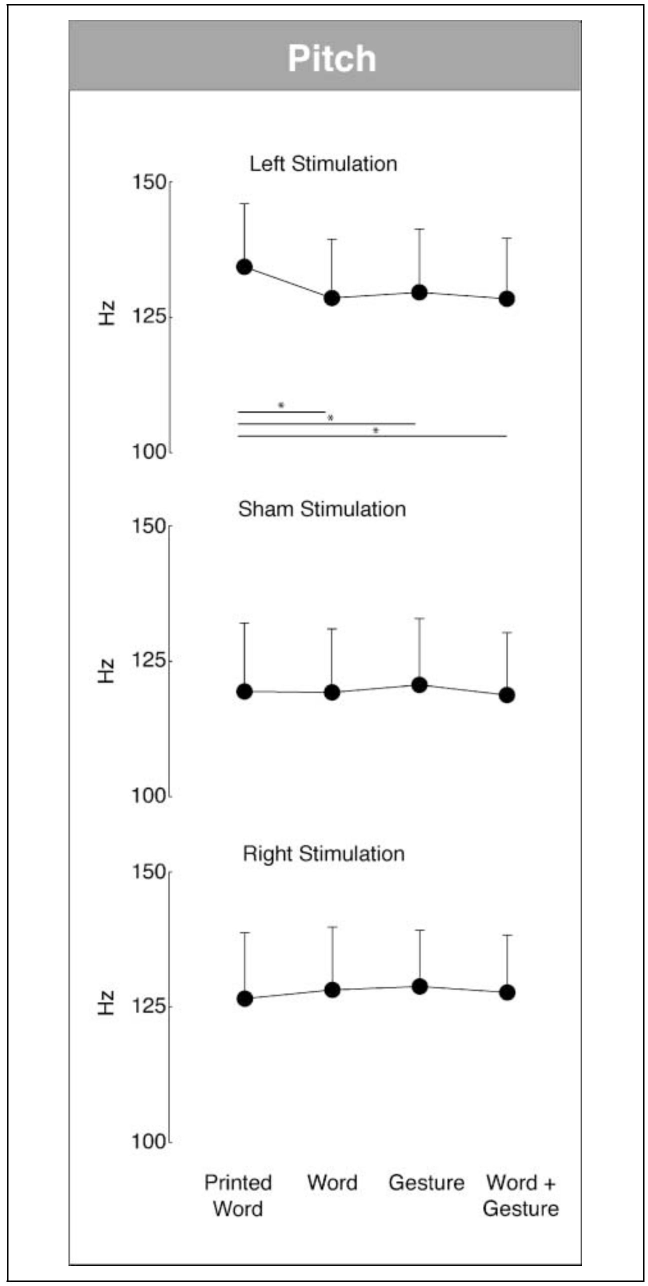

Figure 4. Effects of the modalities of stimulus presentation on the pitch of the verbal responses after left hemisphere, right hemisphere, and sham rTMS in Experiment 1. Conventions as in Figure 3.

predicted an interference effect of the gesture on the word after sham and right stimulations, which had to be removed after the left stimulation.

Methods

Participants

A new sample of six Italian right-handed (according to the Edinburgh Inventory, Oldfield, 1971) male volunteers (age 21–37 years) participated in the study. They were screened to rule out any history of neurological, psychiatric, medical problems, and contraindications to TMS (Wassermann, 1998). Before the experiment, they all signed consent forms approved by the Ethics Committee of the Medical Faculty of the University of Parma.

Transcranial Magnetic Stimulation

We performed rTMS over the frontal region of the left cortex, over the symmetrical sites of the right cortex, and sham stimulation over the same sites as those over

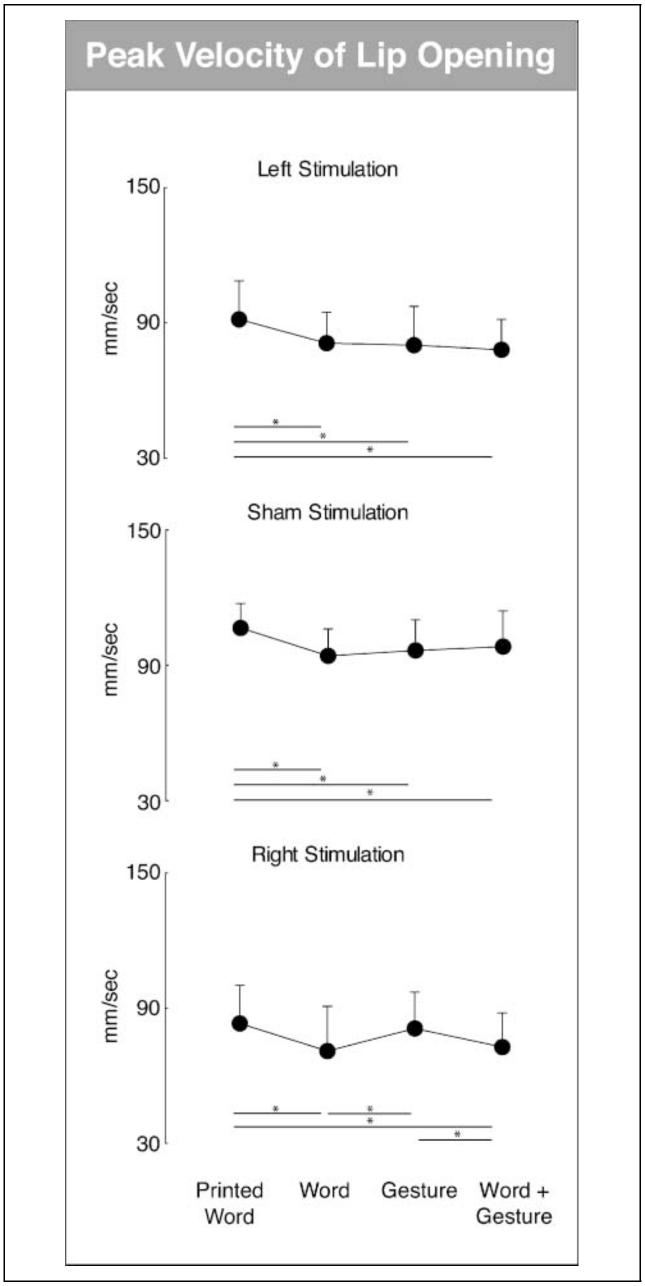

Figure 5. Effects of the modalities of stimulus presentation on peak velocity of lip opening during verbal responses after left hemisphere, right hemisphere, and sham rTMS in Experiment 1. Conventions as in Figure 3.

the left cortex. The interval between two successive stimulation sessions was at least 1 week. In addition, the order of stimulation (sham vs. left vs. right) was counterbalanced across participants. Both the technique and the procedure of stimulation were the same as in Experiment 1. The location of the OP muscle on the left motor cortex was, on average, 6.2 ± 1.5 cm lateral and 0.5 ± 0.5 cm anterior as compared to Cz (Figure 2A). The mean intensity was 60 ± 6% of the maximum stimulator output. We evoked a nonmotor SA over the left cortex and excluded any SA on the symmetrical site of the right cortex before rTMS. Before sham stimulation, we evoked a nonmotor SA on the same site and with the same intensity and procedure as the left rTMS. Successively, we did not evoke SA with the apparatus used for the sham stimulation.

Apparatus and Stimuli

The apparatus was the same as in Experiment 1. The stimuli could be words or symbolic gestures or colored spots. The words could be either the same communication signals as in Experiment 1, namely, CIAO [tʃao], NO [nɔ], and STOP [stɔp], or names of colors: GIALLO (yellow, [dʒɑl:o]), ROSA (rose, [rɔzɑ]), and ROSSO (red, [ros:o]). Note that the initial vowels (i.e., /ia/ and /o/) were the same for the two categories of words. The gestures were always those corresponding to CIAO, NO, or STOP. The modality of stimulus presentation varied in each of six successive blocks of trials. In the first two modalities (modalities of printed word; Figure 6A and D), a printed word of the communication signal category (CIAO, NO, or STOP) and of the color category (GIALLO, ROSA, or ROSSO) was presented on the PC display. In the third and fourth modalities, short videoclips showed the half body of the actress (face: 3° × 4.5° of visual angle) pronouncing either the communication words (communication word modality; Figure 6B), or the names of the colors (color word modality; Figure 6E). In the fifth modality, she executed the gestures (gesture modality; Figure 6C). These modalities were the same as in Experiment 1. In the sixth modality, the actress executed the gesture, and, in addition, when the hand palm was visible, a spot colored by yellow, red, or rose appeared on the hand palm and lasted all along the salient phase of the gesture (i.e., the oscillation phase of CIAO and NO, and the stationary phase of STOP—gesture-and-color modality; Figure 6F). Other modalities of stimulus presentation were not used in order to avoid an excessive number of stimulations in each experimental session. On the other hand, these modalities of stimulus presentation were sufficient to test the hypothesis of the experiment.

Procedure

The participants were required to pronounce the word corresponding to the stimulus presented with different modalities as in Experiment 1. In the gesture-and-color modality, the participants were required to pronounce the word corresponding to the presented color instead of that corresponding to the presented gesture. The blocks of trials were quasi-counterbalanced across participants. Each stimulus was quasi-randomly presented five times, yielding a total of 15 trials per block. In the gesture-and-color modality, the three colors were presented twice, coupled with each of the three gestures.

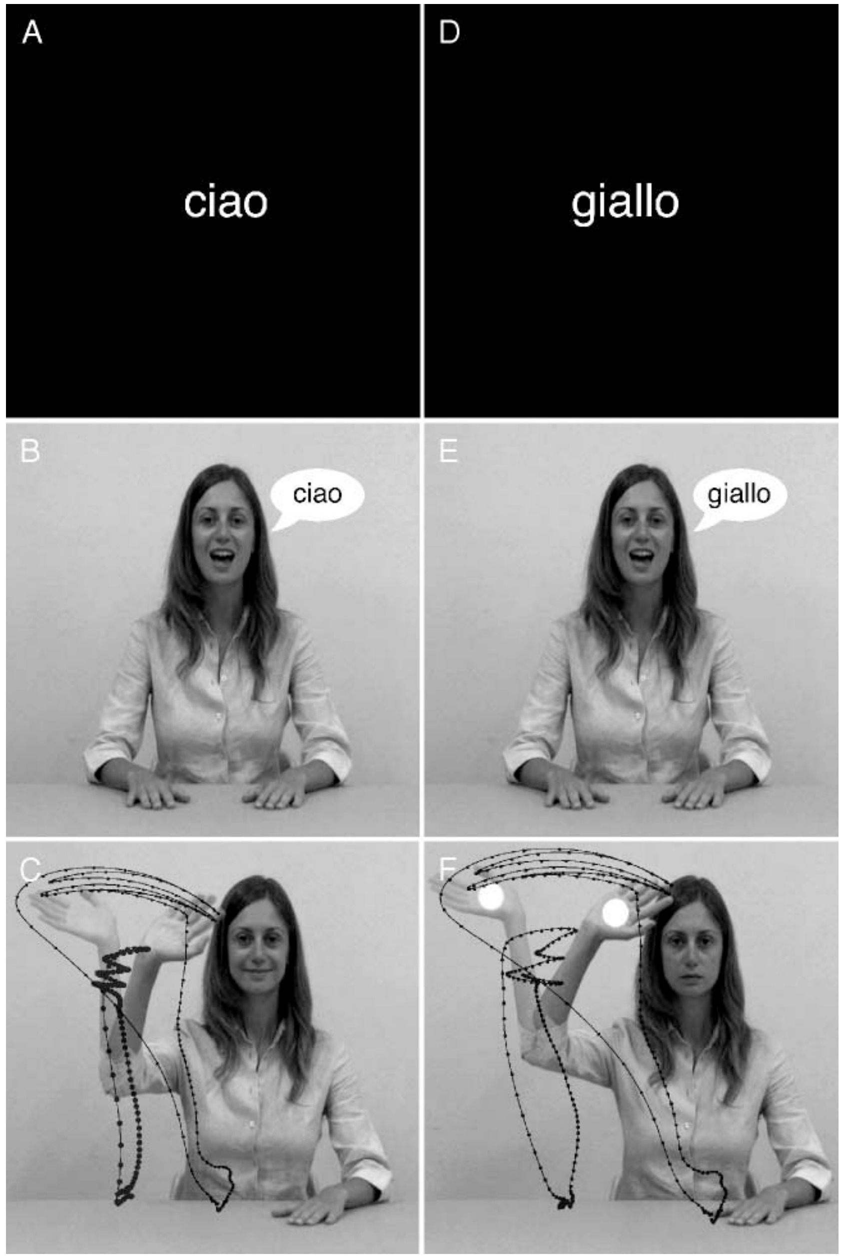

Figure 6. Modalities of stimulus presentation in Experiment 2. (A, D) Printed words; (B, E) spoken words; (C) gesture; (F) gesture and color. Only the CIAO communication signal and the stimulus "yellow" (the word GIALLO and the yellow spot) are presented. In each panel one frame of the presented videoclip is shown. In C and D two different frames are superimposed. Black lines indicate the index finger and wrist path. Circles show the spatial positions of the markers placed on the index finger and wrist during gesture execution. Kinematics data were collected in a separate session using the SMART motion capture system.

This yielded a total of 18 trials. Each block of trials was preceded from rTMS.

Data Recording

The recording technique for voice and lip movements was the same as in Experiment 1. We measured the same parameters as in Experiment 1, as well as the response time (RT), that is, the time elapsed from the end of stimulus presentation to the beginning of the lip opening.

Data Analysis

The voice and kinematics parameters were analyzed by ANOVAs in which the within-subjects factors were stimulation (left vs. right vs. sham), presentation modality (printed word vs. spoken word vs. gesture or gesture-and-color), word category (communication vs. color), and word (CIAO vs. NO vs. STOP and GIALLO vs. ROSA vs. ROSSO). In all analyses, paired comparisons were performed using the Newman–Keuls procedure. The significance level was fixed at $p < .05$.

Results

Figure 2A (gray circles) shows the left hemisphere stimulation sites, in relation to the international 10–20 system, where nonmotor SA was evoked (Stewart et al., 2001). Mean intensity of stimulation was 66 ± 1.0% of maximum stimulator output. Location was, on average, 10.9 ± 1.6 cm lateral and 3.1 ± 0.4 cm anterior with respect to Cz.

Figure 7 shows the effects of the rTMSs on F2. In the ANOVA the factor stimulation was not significant, whereas the interaction among stimulation, presentation modality, and word category was [$F(4,20) = 10.4$, $p < .0001$]. The results of the post hoc analyses are as follows. Concerning the communicative signal category, we found the same results as in Experiment 1. That is, after sham and right stimulations, F2 increased in the modalities of spoken word and gesture as compared to the printed word modality. After the left stimulation, F2 of the words pronounced in response to gestures was lower than F2 in the modality of spoken word presentation and did not differ from F2 in the printed word modality. Concerning the color category, a different pattern of results was found. After sham and right stimulations, F2 was lower in the gesture modality than in printed word and spoken word modalities. After the left stimulation, no significant difference among the three modalities was observed.

The analysis of the pitch parameter revealed a significant interaction between stimulation and presentation modality [$F(4,20) = 2.9$, $p < .05$], but no effect of the factor stimulation. Note in Figure 8 that the effects of the modalities of stimulus presentation on the pitch recorded in the three rTMS sessions were the same as in Experiment 1.

Figure 9 shows the rTMS effects on RT. The factor stimulation was not significant. In contrast, the interaction among stimulation, presentation modality, and word category reached significance [$F(4,20) = 3.0$, $p < .05$]. Concerning the communication signal category, after the right stimulation, RT significantly increased in spoken word and gesture modalities as compared to printed word modality. After the sham stimulation, a trend to significance was found ($p = .058$, $p = .06$). After the left stimulation, RT in the gesture modality significantly decreased as compared to the spoken word modality, and did not differ from RT in the printed word modality. Concerning the color category, RT increased in the gesture modality as compared to the printed word modality. This was statistical significant only after sham and right stimulations.

In contrast with the results of Experiment 1, peak velocity of lip opening significantly decreased after the right stimulation as compared to sham and left stimulations [$F(2,10) = 4.3$, $p < .05$, 89.3 vs. 112.5 and 111.3 mm/sec]. Moreover, the interaction between stimulation and presentation modality showed only a trend to significance [$F(4,20) = 2.6$, $p = .06$; Figure 10]. After the right stimulation, there was a trend of peak velocity

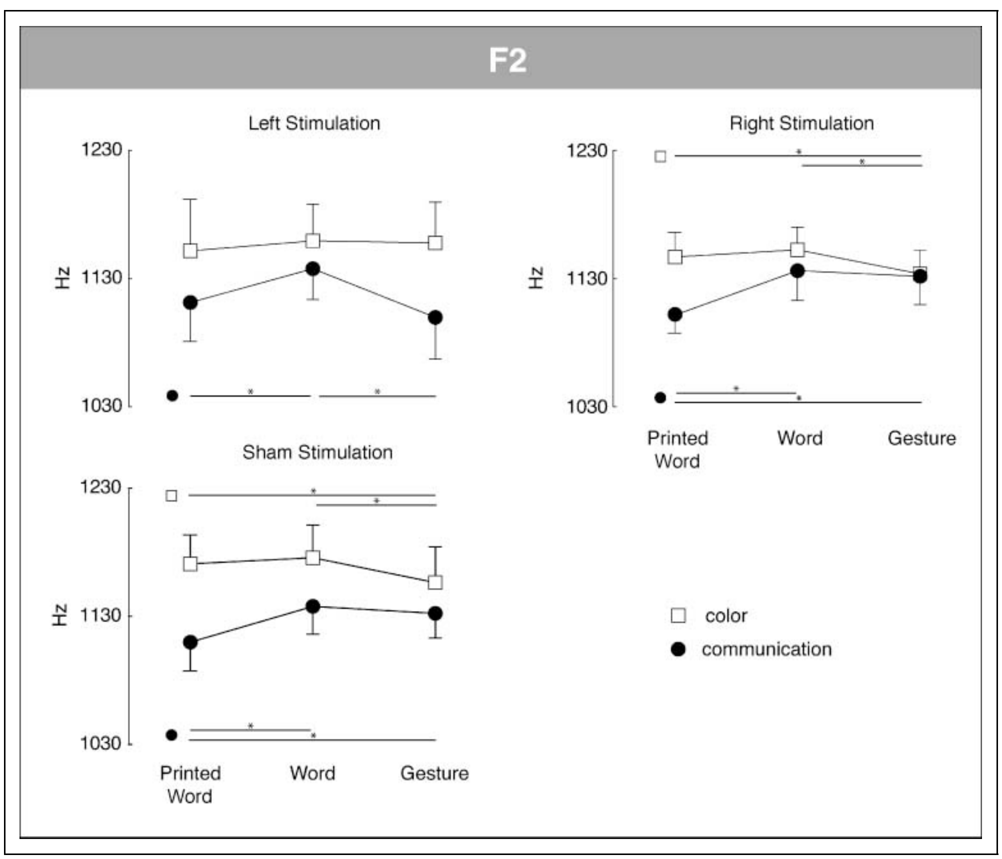

Figure 7. Effects of the modalities of stimulus presentation on vowel formant 2 (F2) of the verbal responses after left hemisphere, right hemisphere, and sham rTMS in Experiment 2. Black circles: communication signal category (CIAO, NO, STOP); white squares: color category (GIALLO, ROSA, ROSSO). Other conventions as in Figure 3.

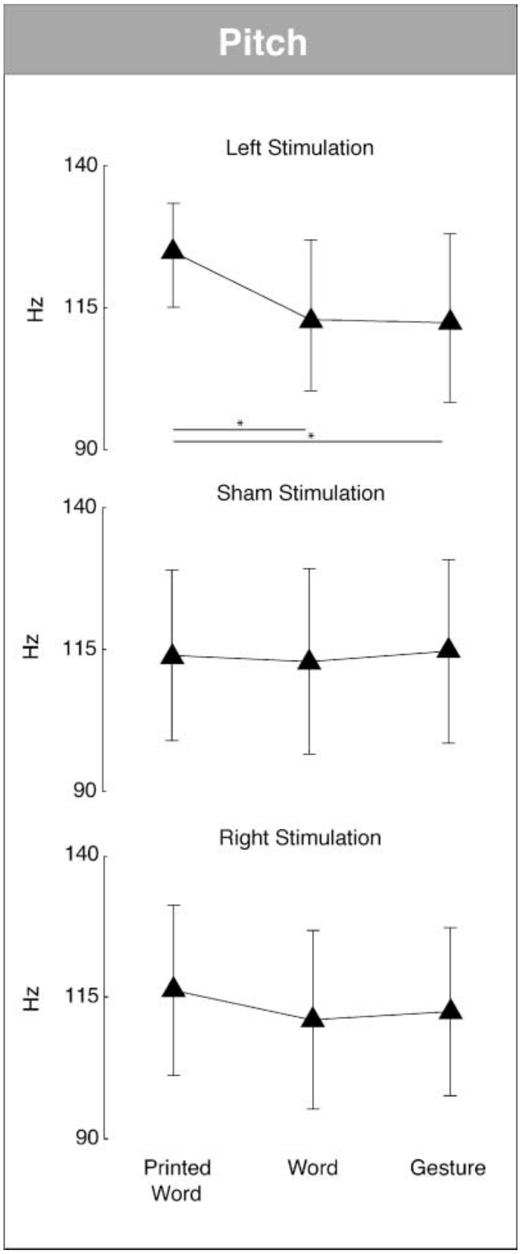

Figure 8. Effects of the modalities of stimulus presentation on the pitch of the verbal responses after left hemisphere, right hemisphere, and sham rTMS in Experiment 2. Triangles are the mean pitches of the words of both the two categories (see Results). Other conventions as in Figure 3.

to increase in the gesture modality as compared to the printed word and spoken word modalities.

DISCUSSION

The results of the sham stimulation in Experiment 1 confirm data of our previous study (Bernardis & Gentilucci, 2006). Verbal responses to words pronounced or gestures performed by the actress induced an increase in voice spectra F2 when compared with the sole reading of printed words. Moreover, whenever the participants verbally responded to the observation of the actress emitting the two communication signals simultaneously, F2 further increased as compared to the sole presentation of pronounced words or executed gestures. A similar increase was observed when participants simultaneously emitted both communication signals (Bernardis & Gentilucci, 2006). Higher F2 is consequent to tongue forward displacement (Leoni & Maturi, 2002; Ferrero, Genre, Boë, & Contini, 1979). Forward displacement may depend on the fact that the participants configured mouth articulation in the expectance of a response. This is in accordance with the observation that in nonhumans, tongue protrusion is typical of approaching relationships. For example, lip smacking, accompanied by tongue protrusion, precedes grooming actions among monkeys (Van Hooff, 1962, 1967). In other words, the presence of a speaking and/or gesturing interlocutor automatically elicited in observers the intention to a direct interaction. The command for tongue forward displacement can be explained as follows. We previously (Bernardis & Gentilucci, 2006) hypothesized that the observer, while pronouncing the word in response to arm and/or mouth gesture presentation, automatically and covertly imitated (i.e., automatically imagined) the same gesture(s), going into resonance with the interlocutor (Rizzolatti et al., 2002). The motor command to the arm (and/or to the mouth) was sent also to the tongue. The existence of double commands to the arm and tongue is supported by data of our previous studies (Gentilucci, Santunione, et al., 2004; Gentilucci, Stefanini, et al., 2004). The command to the tongue reached the threshold for the execution because the mouth was already activated to pronounce the word. The double command to both arm and tongue probably followed analysis of complex stimuli (arm gesturing or faces pronouncing words). It was probably responsible for the increase in RT in Experiment 2. The stimulus analysis could be more complex, and consequently, longer for the communication signal category than for the color category (see Figure 9). The greater complexity in the analysis might depend on aspects such as the goal/intention of the signal.

The effects of the presented gesture on voicing were different depending on the congruence between pronounced word and presented gesture. In Experiment 2, the increase in F2, and consequently, an enhancement effect, was observed when both gesture and word shared the same goal (i.e., to communicate) and/or intention (i.e., to interact directly). In contrast, when the meaning of the pronounced word (name of color) was incongruent with the presented gesture, a decrease in F2 was observed. Consequently, it is possible that the observed gesture interfered with word pronunciation.

In the present study, by using the rTMS technique, we verified whether Broca's area is involved in translating

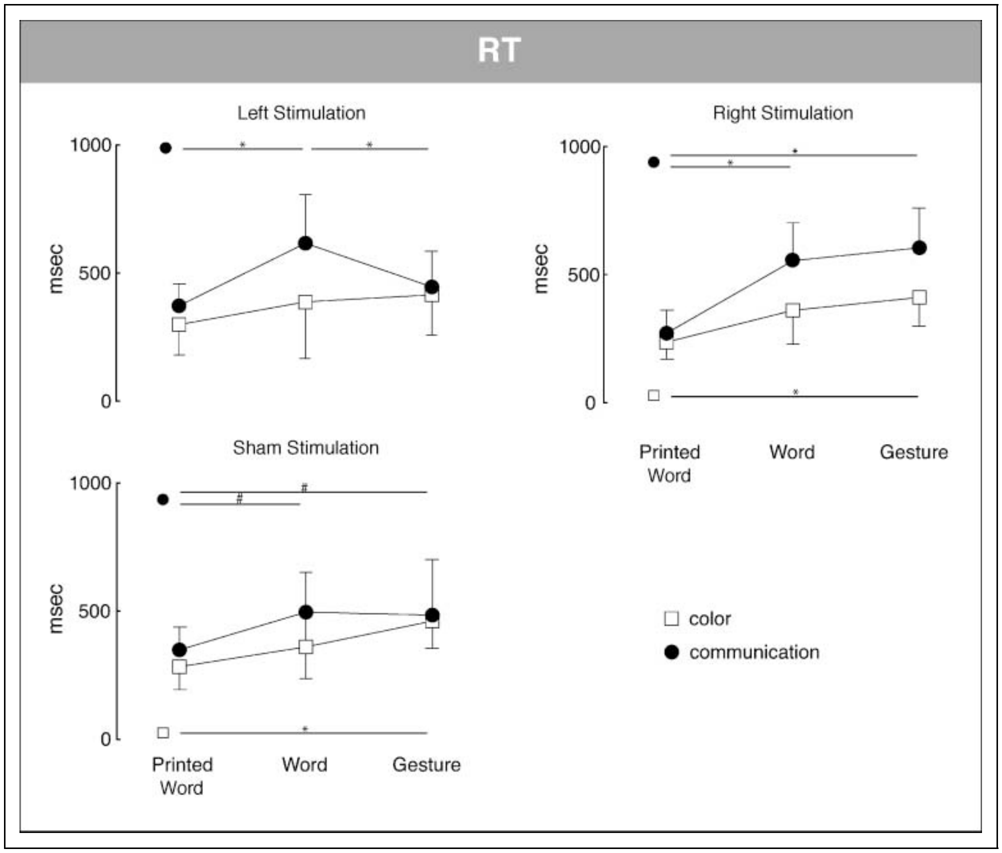

Figure 9. Effects of the modalities of stimulus presentation on RT of the verbal responses after left hemisphere, right hemisphere, and sham rTMS in Experiment 2. Horizontal bars show the significant comparisons (*$p < .05$) and the comparisons with a trend to significance ($^{\#}.05 < p < .06$) between modalities of stimulus presentation. Other conventions as in Figure 7.

aspects of gesture representations, such as goal or intention, into mouth articulation gestures. The sites of the stimulation over the left frontal hemisphere included Broca's area in both Experiments 1 and 2 (Figure 2). This is suggested by the data showing that in the rTMS sites a nonmotor SA was evoked (Stewart et al., 2001). Further evidence comes from MRI scan data showing that the most anterior and the most posterior stimulation sites were localized in BAs 44 and 45, respectively. We cannot conclude that both areas 44 and 45 were responsible for the effects induced by the stimulation because we cannot exactly establish the spreading of the stimulation in the anteroposterior direction. In other words, the posterior stimulation field might spread to BA 45, whereas the anterior one might spread to BA 44. The stimulation field could spread also to the premotor area. However, neuroimaging studies indicate that it is Broca's area that is mainly activated when representing arm-meaningful gestures (Gallagher & Frith, 2004; Buccino, Binkofski, et al., 2001; Grèzes et al., 1998; Decety et al., 1997; Grafton et al., 1996). Consequently, the stimulation effects on gesture observation (see below) were probably due to inactivation of Broca's area.

The main effect of the left stimulation in Experiment 1 concerned symbolic gesture representations. Differently from what was observed after sham and right stimulations, symbolic gestures when presented alone did not induce any increase in F2 of the participant's verbal responses and, in combination with spoken words, did not induce the further increase observed after sham and right stimulations. Because rTMS modified only F2, whereas the other formant (1) was unchanged, it is plausible to suppose that only some aspects of the gesture might have been interfered by the stimulation. We (see above) hypothesized that these aspects concerned the goal and the intention coded by the gesture. rTMS could interfere with the processes by which the intention or the goal of the action is understood, in other words, with understanding of the social intention coded by the communication signal.

The hypothesis that Broca's area is involved in understanding aspects of the gesture, such as goal and/or intention, is mainly supported by the results of Experiment 2. After the left stimulation, we replicated the results of Experiment 1 concerning F2 (i.e., when gesture and pronounced words were congruent). Moreover, RT decreased after gesture presentation, suggesting that some aspects of the gesture (i.e., goal/intention) were unattended. Finally, the interference effect of the observed gesture on the voicing of the incongruent verbal response was absent. This again suggests that some aspects of the gesture were unattended. We hypothesized (see above) that the observer, while pronouncing the word in response to arm gesture presentation, automatically and covertly imitated the same

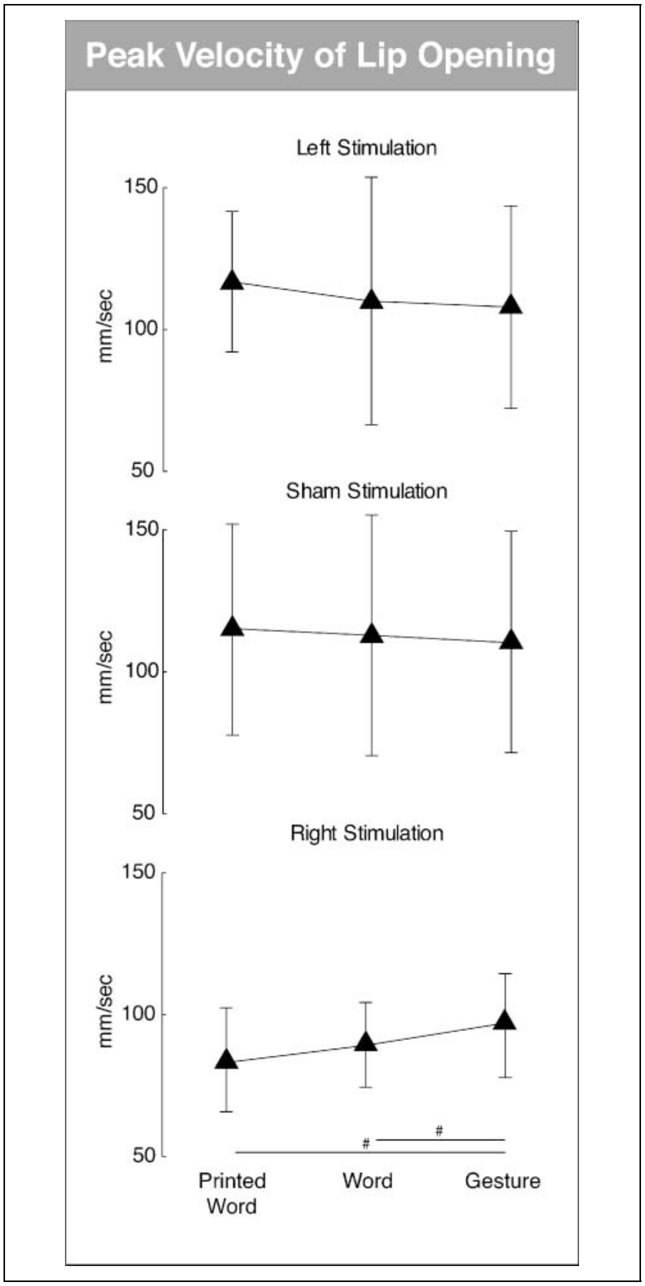

Figure 10. Effects of the modalities of stimulus presentation on peak velocity of lip opening after left hemisphere, right hemisphere, and sham rTMS in Experiment 2. Triangles are the mean peak velocity of lip opening of the words of both the two categories (see Results). Horizontal bars show the comparisons with a trend to significance ($^{\#}.05 < p < .06$) between modalities of stimulus presentation. Vertical bars: *SE*.

gesture. The motor command was sent also to the mouth. It enhanced or interfered with voicing parameters according to the congruence or incongruence between word and gesture. Because some aspects of the gesture such as the goal and/or intention were unattended, and, consequently, not understood after Broca's area stimulation, the motor command to the mouth was unable to modulate voice parameters.

After the left rTMS, the pitch of words repeated in the printed word modality increased as compared to the responses to communication signals presented as word pronounced and/or gesture executed by the actress. This effect was not observed both after sham and right stimulations. It is well known that pitch is related to prosody, in particular, it increases when interrogative sense is added to the word. We reasoned that the interrogative sense could be related to uncertainty in repeating read words. This uncertainty could be consequent to left stimulation producing slight impairment in silent reading: Indeed, Broca's area is activated during silent rather than aloud reading and naming (Bookheimer, Zeffiro, Blaxton, Gaillard, & Theodore, 1995). Note that the participants in the present study were required to read silently before repeating aloud (see Methods).

rTMS of the right frontal region induced a decrease in peak velocity of lip opening, which was significant only in Experiment 2. This apparent discrepancy between the results of the two experiments may depend on the fact that the stimulation might spread caudally toward motor regions because, on average, the stimulation sites in Experiment 2 were posterior (1.4 cm) as compared to Experiment 1 (see Figure 2). However, the absence of left stimulation effect on lip kinematics suggests a different motor organization in the right as compared to the left frontal cortex. The other effect (more evident in Experiment 1 when the stimulation sites were more rostrally located) was an increase in peak velocity of lip opening of the responses to gesture presentation. Because this effect was not accompanied by a decrease in RT, the right stimulation might affect the executive phase of the mouth movement. We reasoned that, when presented with a gesture, the observer pronounced the word and covertly executed the gesture with the mirrored (left) arm (Koski, Iacoboni, Dubeau, Woods, & Mazziotta, 2003). It is well known that the simultaneous execution of two movements is slower than the execution of a single movement. Neuroimaging studies (Hanakawa et al., 2003; Kuhtz-Buschbeck et al., 2003; Gerardin et al., 2000) showed that arm movement imagination involves activation of both Broca's area and the homologue right region. Consequently, after the right stimulation, the arm gesture was not covertly executed, which in turn induced quicker word pronunciation. In contrast, in the spoken word modalities, the temporization of the word pronunciation could be strictly related to the mnemonic trace of the listened word.

The left rTMS affected mainly observation of gestures, whereas no effect was found on the verbal responses to listening of words and observation of faces pronouncing words. This result seems to be at odds with the notion that observation of speaking faces and imagination of faces expressing emotion (Buccino, Lui, et al., 2004; Leslie, Johnson-Frey, & Grafton, 2004;

for a review, see Bookheimer, 2002; Petersen, Fox, Posner, Mintun, & Raichle, 1988) activate Broca's area. Moreover, Broca's area is involved in phonological processing (Bookheimer, 2002; Demonet et al., 1992). However, it is well known that also temporal regions are involved in speech reading and phonological processing (for a review, see Bookheimer, 2002). These areas might activate motor representations of the visually and acoustically presented words. Another not alternative explanation moves from the fact that the process leading to internal motor representations probably required retrieval of lexical–semantic representations. This might be easier and more automatic for audiovisual word presentations than for visually presented gestures. In other words, the network connecting lexical–semantic representations to mouth motor representation might be richer than that connecting lexical–semantic representations to arm motor representations. Consequently, the decreased excitability of Broca's area after rTMS (Shapiro et al., 2001; Maeda et al., 2000; Pascual-Leone et al., 1999; Chen et al., 1997) could not reach the threshold to interfere visibly with the responses to audiovisual word presentation.

Observation of complex hand/arm actions without any purpose (Grèzes et al., 1998) and of symbolic gestures (Lui et al., personal communication, 2005) activates also parietal areas. Indeed, ideomotor apraxia, that is, the incapacity to represent gestures (mimed, symbolic, or meaningless) both on verbal command and/or following model presentation, is determined mainly by lesions including large sectors of the posterior parietal lobe (Haaland, Harrington, & Knight, 2000; De Renzi & Faglioni, 1996; Heilman, 1979). These findings may explain why only particular aspects rather than the general meaning of the symbolic gestures were affected by the left rTMS.

In conclusion, the data of the present study suggest that the two types of communication, word and gesture, are related at the level of translation of particular gesture aspects, such as goal (i.e., to communicate) and/or intention (i.e., to interact directly), from arm into mouth articulation postures. Our data suggest that this process is performed by a system located in Broca's area. The suggestion that aspects of gestures are translated in words within Broca's area has also implication in explaining language development in terms of evolution. Indeed, various authors (Corballis, 2002; Rizzolatti & Arbib, 1998; Amstrong et al., 1995; Hewes, 1973) have proposed that speech evolved from a primitive communication system based on gestures. Although the gestures analyzed in the present study were symbolic ones (i.e., apparently not iconic), their effects on speech were similar to those we found when syllables were simultaneously pronounced with observation/execution of actions directed to an object (Gentilucci, Santunione, et al., 2004; Gentilucci, Stefanini et al., 2004; Gentilucci, 2003; Gentilucci, Benuzzi, et al., 2001). Consequently, the system involved in speech production is related to the production of concrete actions aimed to interact with objects, as well of abstract gestures acquiring the meaning of words. A system relating actions to syllables might have evolved to a more sophisticated system relating symbolic gestures to words.

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