The time course of idiom processing

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Abstract

Recent neuropsychological and neurophysiological studies have suggested that the neural correlates of idiom processing are predominantly located in the left Brodmann's area (BA) 22 and, to some extent, in the prefrontal cortex. The present study explores the temporal dynamics of left prefrontal and temporal cortex in idiom processing by using repetitive transcranial magnetic stimulation (rTMS) in normal subjects.

Forty-five opaque highly familiar idioms and 45 literal sentences were used. Forty-three subjects completed 5 blocks of 18 trials (9 idioms, 9 literal sentences) corresponding to 4 stimulation conditions (left prefrontal, left temporal, vertex, no-stimulation baseline). Each subject was assigned to one of three groups, which differed in the timing of stimulation delivery.

A selective impairment in accuracy for idioms was found when rTMS was applied to the prefrontal and temporal cortex 80 ms after picture presentation, confirming the role of these regions in this task. Moreover, rTMS to the prefrontal cortex, but not to the temporal cortex, continued to affect the performance with idiomatic sentences at the later time of 120 ms. The results seem to suggest that the prefrontal region is involved in both the retrieval of the figurative meaning from semantic memory and the monitoring of the response by inhibiting alternative interpretations when a picture-matching task is used.

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Keywords: Transcranial magnetic stimulation; Idioms; Prefrontal cortex; Temporal cortex

1. Introduction

Idioms are very common in our speech and can be distinguished along a number of dimensions (Cacciari & Glucksberg, 1995; Nunberg, Sag, & Wasow, 1994), such as semantic transparency/opacity, which refers to the ease with which the motivation for their structure can be recovered (Nunberg et al., 1994), and ambiguity, meaning that many idioms (known as "ambiguous") can also be assigned a literal interpretation (e.g., "break the ice") (Cacciari et al., 2006; Colombo, 1993).

The earliest neuropsychological studies on this topic suggested a right hemisphere involvement in idiom processing, an opinion still supported by some author (see Van Lancker Sidtis, 2006); more recent experiments on aphasic patients (Cacciari et al., 2006; Nenonen, Niemi, & Laine, 2002; Papagno & Genoni, 2004; Papagno, Tabossi, Colombo, & Zampetti, 2004)

and on normal subjects using repetitive transcranial magnetic stimulation (rTMS) (Oliveri, Romero, & Papagno, 2004) have found that neurological lesions or TMS interference in the left temporal lobe can impair idiom comprehension, suggesting that the same mechanisms are involved in both literal and idiomatic comprehension. However, figurative language is also impaired in patients with probable Alzheimer's disease (AD), without language impairment (Papagno, 2001; Papagno, Lucchelli, Muggia, & Rizzo, 2003): using a string-to-picture-matching paradigm, the presence of a picture representing the literal interpretation (often a bizarre image) interferes with the correct response, similarly to the Stroop effect (MacLeod, 1991). In addition, AD patients produce literal interpretations even when asked to give an oral definition of the idiom, as did a patient with Down's syndrome (Papagno & Vallar, 2001), and similar effects have been observed with a priming paradigm in schizophrenia (Titone, Holzman, & Levy, 2002). Since this bias toward the literal interpretation appears in both picture-matching and oral definition, and also in priming, at least in the case of literally plausible idioms, it cannot be only

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ascribed to the nature of the task (Papagno & Caporali, 2007). In addition, in studies performed on AD patients and on Down's syndrome, the effect correlates with the performance on tasks assessing executive functions. fMRI studies have confirmed a prefrontal involvement in idiom processing using different paradigms (Romero Lauro, Tettamanti, Cappa, & Papagno, 2007; Zempleni, Haverkort, Renken, & Stowe, 2007). A suggested explanation (Papagno et al., 2003; Papagno, Curti, Rizzo, Crippa, & Colombo, 2006) is that the figurative meaning has to be retrieved from semantic memory and the literal meaning inhibited, with the neural correlates of inhibition/suppression being in the prefrontal cortex. If this were the case (inhibition mediated by the prefrontal cortex), one would expect the prefrontal cortex to be involved in a delayed stage, after the activation of the left temporal lobe, where the semantic information is presumably stored (Wiggs, Weisberg, & Martin, 1999).

An alternative possibility remains unexplored: the prefrontal cortex could be involved in retrieving/activating the figurative interpretation and not in inhibiting the literal one, which, particularly in the case of unambiguous idioms, would hardly emerge. One opportunity to test this hypothesis is by means of TMS, applied at different time points, in order to measure the specific temporal dynamics of circumscribed brain regions in idiom processing. This would go beyond the previous reported TMS studies by mapping the specific time of involvement of different brain regions rather than simply focusing on the involved substrates. To measure the chronometry of the interference effect, rTMS was applied over the left middle frontal gyrus (BA 9) and left superior/middle temporal cortex (BA 22) at four different time points: 0, 40, 80 and 120 ms after picture presentation.

We postulated two alternative hypotheses: (i) if the prefrontal cortex is involved in retrieving/activating the idiomatic meaning from semantic memory, rTMS effects on the temporal and frontal sites would be apparent at the same time, or even possibly first in the prefrontal cortex, followed by temporal cortex activity; conversely, (ii) if the prefrontal cortex is involved in suppressing/inhibiting the literal meaning, the effect of the prefrontal stimulation should persist at later stages when the stimulation of the temporal site has become ineffective.

2. Material and methods

2.1. Participants

A total of 43 neurologically normal native Italian speakers (17 males and 26 females), aged between 20 and 30 years (mean = 24.71), participated in the experiment after providing written informed consent. All of them were right-handed with a mean score on the Edinburgh Handedness Inventory of +98% (Oldfield, 1971) and had normal or corrected-to-normal vision. The study was approved by the local Ethical Committee. We decided not to stimulate both sites at all four different time intervals in the same subject, in order to minimize the number of stimulations received by each participant. Therefore, participants were randomly assigned to one of three experimental conditions (see below).

2.2. Stimuli

Forty-five idioms (see Appendix A) with a low degree of transparency (mean 3, DS S.D.0.6) were selected. They were rated as highly familiar by a group of
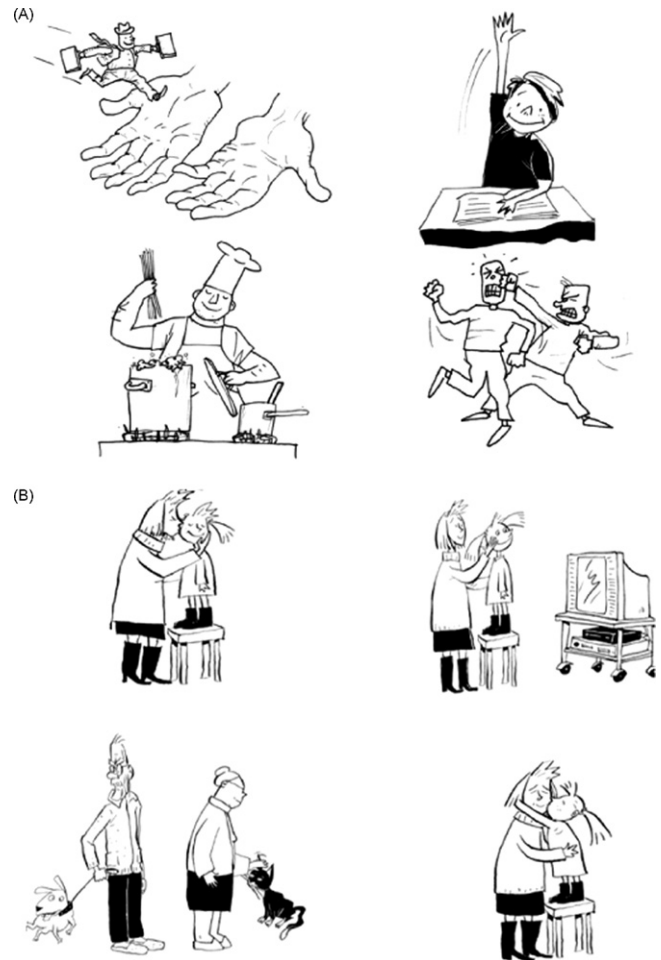

Fig. 1. Examples of the alternatives for idiomatic (A) and (B) literal sentences.

101 healthy native Italian speakers (39 males and 62 females, aged between 22 and 65 years) from different regions of the country. They were unambiguous, meaning that either their literal interpretation was unlikely or it was ill formed or both. The degree of transparency was checked by asking 30 healthy subjects (mean age 26), who did not participate in the TMS experiment, to rate how easily the meaning of the idiom could be deduced from the concrete image evoked by the sentence: a score ranging from 0 to 5 was assigned, where "0" meant "not at all" and "5" "entirely". For each idiom, four line-drawing pictures were created: one representing the idiomatic interpretation, a second representing the literal interpretation as well as possible, a third corresponding to an unrelated situation and a fourth representing a situation described by a sentence which included the content word following the verb in the idiom (for example in the case of the idiom "to come to the hands" meaning "to fight", an alternative was represented by a boy lifting his hand. We will refer to this type of error as "single word") (see Fig. 1A). We checked the relatedness of the picture corresponding to both the literal and idiomatic interpretation by asking 30 native Italian speakers healthy subjects (not included in the study) to rate how well the pictures matched the sentence read by the examiner. A score ranging from 0 to 7 was assigned, where 0 meant "not at all" and 7 "perfectly". The mean score was 2.66 (range 0.8–5.5; S.D. ±1.06) for literal pictures and 6.02 (range 4.5–7, S.D. ±0.65) for idiomatic targets. Idiomatic targets therefore were rated as significantly more related to the idiom strings than literal foils [$t(44) = 15.22$, $p < 0.001$]. Idioms were presented in a syntactically simple construction (in the previous example "the boy is coming to the hands").

Forty-five literal sentences, matched in length and syntactic structure to the idioms, were selected (examples are: the man is leaving the feathers/the woman is kissing the girl, for idiomatic and literal sentences, respectively). For each sentence, four pictures were presented; one was correctly described by the

sentence (for example "the woman is kissing the girl"), one corresponded to a sentence including the same actors involved in a different action ("the woman is caressing the girl"), one corresponded to a sentence in which the agent and the theme were reversed ("the girl is kissing the woman") and one corresponded to an unrelated situation (see Fig. 1B).

The stimuli for each block were chosen after a pilot experiment performed in a baseline condition to balance the mean RTs across the blocks. The pilot experiment was run on 29 subjects (14 males and 15 females; mean age 23.2, S.D. ±1.13, mean education 16, S.D. ±2 years—therefore matched for age and educational level to the TMS experiment participants), none of whom took part in the TMS experiment. A fixation point appeared on the screen for 1 s, followed by the sentence, which remained on the screen for 2 s and was followed by four pictures, which remained on the screen until the subject's response.

2.3. rTMS procedure

TMS was carried out by means of a Magstim SuperRapid magnetic stimulator connected to four booster modules and a standard figure-of-eight shaped coil with an outer winding diameter of 70 mm (Magstim Company, Whitland, UK) that generates 2.2 T as a maximum output. Before the experiment, individual resting excitability thresholds of stimulation were determined by stimulating the left motor cortex and inducing a visible contractions evoked by a single TMS pulse in the contralateral first interosseus dorsalis muscle. The threshold was defined as the minimum intensity which induced a visible contraction in the tested muscle, as agreed by two experimenters on at least three trials. The stimulation intensity used during the experiment was set at 110% of each subject's threshold. The mean stimulation intensity (as a percentage of the maximum machine output) was 49.6% (S.D. ±3.98, range 39–60) for the first group, 52.6% (S.D. ±2.98, range 42–63) for the second group and 53.4% (S.D. ±2.67, range 45–62) for the third group, which is well within guidelines on safety of rTMS

(Wassermann, 1998). Participants tolerated rTMS well and did not report any adverse effects.

During the experiment, rTMS was delivered using a train of five pulses with a frequency of 10 Hz (i.e. lasting a total of 400 ms). The coil was placed tangentially to the scalp with the handle pointing posteriorly roughly parallel to the subject's midsagittal plane.

Participants wore a tightly fitting Lycra bathing cap on which the positions of Cz (vertex), and other locations from the International 10/20 EEG system were reproduced. The cap was positioned such that the Cz marking corresponded to the individual's measured Cz, thus ensuring that the position of the reference points was constant across subjects. The scalp positions for stimulation were determined for each participant by using the SofTaxic Evolution navigator system (E.M.S., Bologna, Italy) a frameless stereotaxic image guidance system. This system consists of a graphic user interface and a 3D Fastrak digitizer (Polhemus Inc., Colchester, USA), and has three receivers and one stylus. Three of these receivers were firmly placed on the subject's head, in order to rule out inaccuracy due to head movements. The stylus was used to register craniometric landmarks (nasion, inion and two pre-auricular points) on subject's head. This neuronavigational system has precision in the order of millimeters (Bastings et al., 1988). The SofTaxic Navigator system therefore permitted the computation of an estimated volume of MRIs of the head, in order to guide the TMS coil positioning in our subjects. The estimated MRIs were automatically calculated by means of a warping procedure, operating on a generic MRI volume (template) on the basis of a set of about 50 points, digitized from the subject's scalp. The mean (±S.D.) accuracy of the estimated MRIs was of 4.06 (±1.54) mm (as indicated by the EMS), that is minor or comparable to the spatial resolution of the TMS at motor threshold intensity (Herwig et al., 2001).

In our experiment the location of the stimulation sites was on average centred on Talairach co-ordinates $X = -37$, $Y = 42$, $Z = 35$ (Brodmann's area 9) and $X = -57$, $Y = -11$, $Z = 8$ (Brodmann's area 22) (Talairach & Tournoux, 1988)
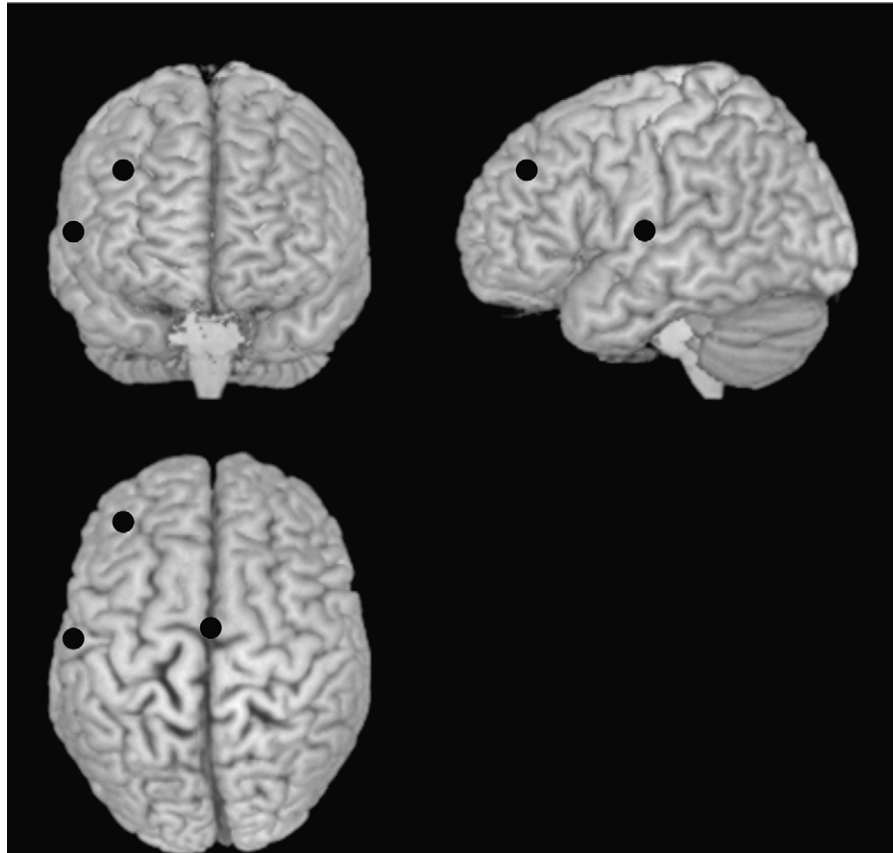

Fig. 2. Lateral, anterior and superior surface view of a 3D brain reconstruction showing the localisation of the stimulation sites (black dots) as identified using the SofTaxic system. Cz was defined as a point midway between the inion and the nasion and equidistant from the left and right inter-trachial notches.

(see Fig. 2). In the frontal and temporal stimulation conditions, the coil was positioned so that the virtual cathode was overlying the relevant sites stated.

2.4. Experimental task

A sentence-to-picture-matching task was performed on a personal computer with a 19 in. screen using E-Prime software (Version 1.2, Psyc. Tools Inc.). Subjects were seated in a lit room at a distance of approximately 70 cm from the computer screen. Before starting the experiment, the subjects completed a block of eight practice trials (four idiomatic and four literal sentences). During the practice block, the TMS coil was placed near the subject, and trains of stimulation were delivered with the same intensity and timing as in the subsequent experimental trials, in order to accustom them to the scalp sensation and noise produced by the stimulator. The practice block was followed immediately by the experimental blocks where the TMS coil was fixed in position at the relevant site. Each subject took part to an experimental session consisting of four blocks [three stimulated scalp positions: left BA 9, left BA 22, one vertex (Cz) control site and a baseline condition without stimulation]. In the first group of subjects (6 males and 9 females, mean age 24.5, S.D. ±6.3, range 20–29) rTMS was delivered 80 ms after picture presentation on BA 9 (F80), and 0 and 40 ms on BA 22 (T0 and T40, respectively). In the second group (7 males and 9 females, mean age 25.5, S.D. ±6.4, range 21–30) rTMS was delivered 40 ms after picture presentation on BA 9 (F40), 40 and 80 ms after picture presentation on BA 22 (T40 and T80, respectively). In the third group (4 males and 8 females, mean age 25, S.D. ±5.6, range 21–29) rTMS was delivered 120 ms after picture presentation on BA 9 (F120) and 40 and 120 ms on BA 22 (T40 and T120, respectively).

For the vertex condition, in the first group of subjects the coil was positioned approximately parallel to the floor, with the handle pointing back and the virtual cathode overlying Cz. In the others two groups the coil was tilted of 90° so that it was perpendicular to the floor. Both conditions reproduced the scalp sensation and the noise associated with the discharge of the coil, but in the second, because of the orientation of the coil, no stimulation is likely to have reached the brain, thus acting effectively as a sham condition. We decided to change the orientation of the coil to reduce the overall number of magnetic stimuli delivered in each experimental session. The analyses on subjects' performance in the vertex stimulation condition indicated that no differences were present between groups, suggesting that performance was not affected by the coil orientation.

Each experimental block consisted of 18 trials – 9 with idioms and 9 with literal sentences – randomly intermixed. A fixation point appeared for 1000 ms, followed by a written string, either idiomatic expression or literal sentence, which remained on the screen for 2000 ms. The sentence was followed by four pictures, that remained until the subject indicated, as quickly as possible, which picture matched the sentence, by pressing one of four buttons spatially mapped so that each of them corresponded to the location of the chosen picture on the computer screen (upper right/ upper left/ lower right/ lower left). The subjects responded with four fingers, the index and middle fingers of both hands. Index fingers corresponded to lower pictures (left and right) and middle fingers corresponded to the upper pictures (left and right). The position of the correct response was counterbalanced across trials.

2.5. Data analysis

RTs were excluded from the analysis if the subject responded incorrectly or if they fell outside ±2S.D. from the mean for each condition and type of sentence. An ANOVA with sentence (two levels: idiomatic versus literal sentences) and condition (five levels) as factors was run on number of errors and RTs. Planned comparisons were performed. In addition, in the case of idiomatic sentences, an ANOVA was run on type of errors with condition (site/time of stimulation) and error type (three levels: literal, single word, unrelated) as factors. The level of significance was set at 0.05.

3. Results

The results are shown in Fig. 3. The performance of the three groups of participants did not differ in the baseline and vertex condition.
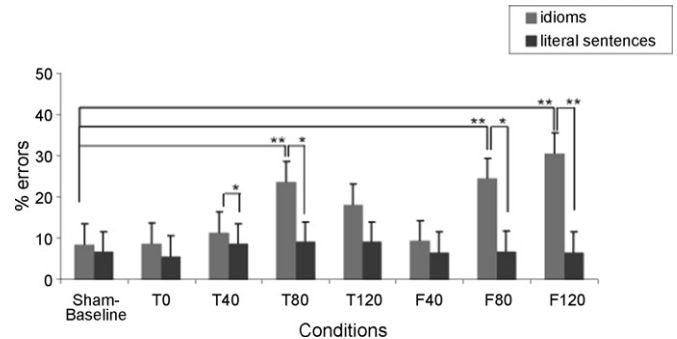

Fig. 3. Average errors number (percentage) after rTMS, sham and in the baseline condition. *Significant differences at p level < 0.05 and **significant differences at p level < 0.001. Vertical bars represent the standard error of the means.

A 5×2 ANOVA was conducted in each group with condition and sentence (literal versus idiomatic) as within-subject factors. In the first group (conditions: F80, T0, T40, vertex and baseline) the ANOVA on number of correct responses showed a significant main effect of sentence [$F(1, 14) = 35.48$, $p < 0.001$], with participants producing more errors with idioms than with literal sentences. There was also a significant main effect of condition [$F(4, 56) = 5.83$, $p = 0.001$], with a higher number of errors when rTMS was applied over F80 as compared to baseline and vertex. The interaction, sentence by condition, was also significant [$F(4, 56) = 4.98$, $p = 0.004$]. Post hoc analyses showed that rTMS applied at F80 reduced accuracy for idioms compared to the baseline ($p < 0.001$), with a specific significant increase in errors on idioms compared to literal sentences ($p < 0.001$). Also rTMS at T40 induced significantly more errors on idioms than on literal sentences ($p = 0.04$).

In the case of RTs, there was a significant effect of sentence [$F(1, 14) = 73.69$, $p < 0.001$] and condition [$F(4, 56) = 11.96$, $p = 0.001$] and the interaction was also significant [$F(4, 56) = 4.85$, $p = 0.006$]. RTs significantly decreased after stimulation, participants being significantly faster with literal than idiomatic sentences. All paired comparisons proved to be significant, as compared to the baseline but not to the vertex condition.

In the second group (conditions: F40, T40, T80, vertex and baseline), the ANOVA on number of correct responses showed a significant effect of sentence [$F(1, 15) = 6.68$, $p = 0.021$], with participants producing more errors with idioms than with literal sentences. The effect of condition was also significant [$F(4, 60) = 3.42$, $p = 0.019$], with a higher number of errors when rTMS was delivered at T80. The interaction, sentence by condition, was significant [$F(4, 60) = 3.42$, $p = 0.019$]. Post hoc analyses showed that rTMS applied at T80 significantly reduced accuracy on idioms as compared to the baseline ($p = 0.01$) and vertex rTMS ($p = 0.006$); in addition, rTMS applied at T80 and F40 produced a significant reduction in accuracy in idiom as compared to literal sentences ($p = 0.008$ and $p = 0.043$, respectively).

The ANOVA on the average RTs showed no main effect of sentence [$F(1, 15) = 1.65$, $p = 0.22$], while condition [$F(4, 60) = 4.15$, $p = 0.005$] was significant, as was the interaction [$F(4,

$60) = 19.84$, $p = 0.0001$]. All comparisons with the baseline, but not with the vertex condition, proved to be significant.

In the third group (conditions: F120, T40, T120, vertex and baseline), in the case of accuracy, the main effect of sentence [$F(1, 11) = 14.85$, $p = 0.003$] and condition [$F(4, 44) = 8.90$, $p < 0.001$] were significant, as was their interaction [$F(4, 44) = 8.19$, $p = 0.001$]. Post hoc analyses showed that rTMS applied at F120 reduced accuracy for idioms as compared to the baseline ($p < 0.001$) and vertex rTMS ($p = 0.001$); rTMS at F120 also reduced accuracy in idiom as compared to literal sentence comprehension ($p < 0.001$). In contrast, rTMS at T120 did not affect accuracy for either idiom or literal sentence comprehension, as compared to the baseline and vertex rTMS. rTMS at F120 did not produce any effect on literal sentence comprehension. In the case of RTs, there was a significant effect of sentence [$F(1, 11) = 14.49$, $p = 0.003$] and condition [$F(4, 44) = 13.78$, $p < 0.001$]. The interaction was also significant [$F(4, 44) = 17.01$, $p < 0.001$].

We further analyzed error type in the conditions showing a significant effect on accuracy. The interaction type of error x condition was not significant, namely baseline/F80 [$F(2, 28) = 2.76$, $p = 0.08$], baseline/F40/T80 [$F(4, 60) = 1.42$, $p = 0.24$], baseline/F120 [$F(2, 22) = 0.9$, $p = 0.44$], with no effect of error type ($p = 0.09$), suggesting that number of errors significantly increased, but that there was no difference in error type distribution.

4. Discussion

Previous rTMS (Oliveri et al., 2004; Rizzo, Sandrini, & Papagno, 2007), as well as neuropsychological studies on aphasic patients (Papagno et al., 2004, 2006), have shown that both the frontal and temporal cortices are involved in idiom comprehension. However, no information is available on the timing of idiom processing: one suggestion is that the prefrontal cortex is involved in inhibiting/suppressing the literal meaning; therefore, we would expect frontal activity to persist even after the temporal activity has ceased. This was precisely what happened, supporting our second hypothesis.

RTs were significantly reduced in all conditions, including vertex, as compared to the baseline. This effect has been observed before with TMS (Marzi et al., 1998), and can be explained by a non-specific inter-sensory facilitation phenomenon (see Nickerson, 1973 for a review). Therefore, the main findings relate to accuracy: rTMS interfered with the task when delivered 80 ms after picture presentation at both sites, frontal and temporal, suggesting that they were both involved at the same time points. However, when stimulation was delivered 120 ms after picture presentation, only the prefrontal stimulation was found to have a significant effect on accuracy. The fact that literal sentence comprehension was not affected by prefrontal stimulation at any time allows us to conclude that the prefrontal cortex is not simply involved in a multiple choice task, but has a specific role in idiom interpretation. This possibility seems to be supported by fMRI data (Romero Lauro et al., 2007): making yes/no judgments about literal and idiomatic sentences yielded a similar network of activity, involving the language area of the left hemisphere; in addition, a left superior and inferior frontal gyri activation was specifically found in processing idiomatic sentences. Alternative explanations could be suggested: for example, one could argue that idioms are more difficult than literal sentences and this requires a prefrontal recruitment. The fact that no difference was found without stimulation between the two tasks, idiomatic versus literal sentence comprehension ($p = 0.806$, $p = 0.333$ and $p = 0.111$, in the first, second and third group, respectively), rules out this possibility. An alternative interpretation could be that the prefrontal cortex is involved in entertaining rather than suppressing the multiple meanings enticed by the stimuli, while suppression is involved only with meanings entirely unrelated to the derivation of the appropriate one, as shown by Faust and Gernsbacher (1996). The literal meaning could be considered as less salient than the idiomatic meaning and therefore there could be no need for it to be suppressed, since the more salient meaning is accessed faster and reaches sufficient levels of activation before the less salient one (Giora, 1997; Laurent, Denhières, Passerieux, Iakimova, & Hardy-Baylé, 2006). But F80 and F120 stimulation significantly increased the total (not a specific type) number of errors, supporting the hypothesis of a lack of inhibition of irrelevant responses. In addition, the presence of a picture depicting the literal interpretation has proved to interfere with the correct answer and to correlate with executive functions in several studies (see, for example, Papagno et al., 2003, 2006), since participants are specifically instructed to choose the figurative interpretation. Single-word errors proved to be as frequent as literal errors, suggesting that people may activate the "literal" senses of individual words, at least when they recognize the individual parts of decomposable idioms as having independent figurative meanings: it would be interesting to check in a future study if this activation concerns only decomposable idioms (Gibbs, Nayak, & Cutting, 1989), since decomposability was not checked in the present study.

The presence of a prefrontal stimulation effect persisting at 120 ms suggests a suppression/inhibition mechanism: the idiom meaning is retrieved from the temporal lobe, but there are competing, potentially correct, alternatives. The "single-word" picture includes at least one concrete element of the sentence. The literal representation exactly corresponds to the sentence, in other words what is said and what is meant coincide, at variance with the idiomatic one. There is one way only to represent the literal interpretation, while the idiomatic meaning can have alternative representations and people can have different opinions on how to represent it; the choice of the idiomatic, abstract, alternative is more demanding than the concrete, literal one. On the contrary, in the case of a literal string only one picture matches the sentence, which has a concrete meaning, and there is only one way to represent it. Accordingly, rTMS reduced accuracy in the case of idioms, but not of literal sentences. Suppression has a crucial role in many aspects of language (Gernsbacher & Robertson, 1999). It is defined as a general, cognitive mechanism, the purpose of which is to attenuate the interference caused by the activation of extraneous, unnecessary or inappropriate information, either external, such as when we conduct a conversation in a noisy place, or internal, such as when we have to

deal with competing meanings of a word or phrase. Suppression seems to have a role in the task we described: the coordination of different interpretations with the meaning of the picture is required only in the case of idiom comprehension. In the case of literal sentence, the meaning of the picture needs to be matched with one interpretation only. The prefrontal cortex might mediate the inhibition of the alternative meanings in favour of the correct one.

Finally, two more possibilities seem plausible: first, it could be that normal subjects retrieve the figurative meaning of idioms in the course of reading the target sentences, before the 2000 ms have elapsed and what is interrupted is the reactivation of figurative meaning and matching this to the correct visual representation in presence of distractors: in this case, the role of the prefrontal cortex would come into play during the secondary task (picture-matching). Although this possibility cannot be excluded, it is not clear why, if this were the case, no effect was found when rTMS was delivered at F0, T0 and F40, compared to the baseline, since the reactivation of the meaning should occur immediately. In addition, a retention or re-activation of meaning to perform the matching task would concern also literal sentences, with a consequent interfering effect at least on the temporal site (if not on the prefrontal, due to the lack of a potentially correct alternative). This was not the case.

Second, a generalized facilitation induced by stimulation could result in a speed accuracy trade-off, since RTs decreased in all the explored conditions. However, this explanation seems also unlikely, since the accuracy decrement concerned only idioms.

The results of this experiment need to be confirmed with further studies assessing idiom comprehension with different tasks and methodologies, avoiding pictorial material and delivering rTMS when the "key word" of the idiom is presented. In addition, the lack of any effect on literal sentences needs to

be explored: we can interpret this as due to the task being too easy, with the temporal stimulation occurring well beyond the time needed to comprehend the sentence, coupled with the fact that probably a more posterior stimulation in the frontal lobe (Broca's area) would have produced an interference, as it has been demonstrated that sentence comprehension relies on the integrity of that specific area (see, for example, Fiebach, Vos, & Friederici, 2004).

A last comment needs to be done: the problem of what are we really measuring with metalinguistic tasks concerns any kind of task, even single word comprehension. Nevertheless, in rTMS experiments it is not always possible to use the same paradigms, as those applied in psycholinguistic experiments. It should be noted, however, that the present conclusions are not based on a single result, but on a set of related results that, we argue, converge to support one interpretation of the processes involved in idiom comprehension, as it has been suggested when interpreting a patient's performance (Caramazza, 1986). Therefore, converging evidence using different methodologies and tasks will strengthen the results concerning the respective role of the temporal and prefrontal cortex in idiomatic language processing, accepting that no single experiment is definitive, but assuming that a sufficiently rich and coherent body of data will place major constraints to rule out alternative hypotheses.

Acknowledgements

Appendix A

Italian expressions	IF (familiarity index) (0–3)	Literal	Idiomatic
Stare in campana	2.3	To stay in bell	To be very careful
Restare con un palmo di naso	2.4	To remain with a span of nose	To be badly disappointed
Mordere il freno	2.3	To bit the brake	To champ at the bit
Tendere le orecchie	2.4	To stretch the ears	To prick up one's ears
Avere il pollice verde	2.8	To have the thumb green	To be skilled at gardening
Avere poco sale in zucca	2.6	To have few salt in pumpkin	To have noon sense in head
Essere sulla cattiva strada	2.6	To be on the bad road	To misbehave
Essere di facili costumi	2.6	To be of easy customs	To be of easy virtue
Fare fiasco	2.6	To make flask	To fail utterly
Mettersi le gambe in spalla	2.4	To put the legs on shoulder	To flee
Essere in forma	2.7	To be in shape	To be very well
Montarsi la testa	2.7	To mount the head	To pride oneself
Venire alle mani	2.3	To come to the hands	To come to blows
Avere i minuti contati	2.7	To have the minutes counted	To have very little time
Spremersi le meningi	2.5	To sqeeze one's meninges	To rack one's brain
Far cadere le braccia	2.5	To make the arms fall	To make one's heart sink to one's boots
Andare in bestia	2.6	To go in beast	To become very angry
Far venire il latte alle ginocchia	2.5	To make the milk come to the knees	To be particularly boring
Stare alle costole	2.4	To stay at the ribs	To dog someone' heels
Andare al fresco	2.5	To go in the cool	To go in jail
Essere al settimo cielo	2.7	To be at the seventh sky	To be at the seventh heaven

Appendix A (*Continued*)

Italian expressions	IF (familiarity index) (0–3)	Literal	Idiomatic
Vendere cara la pelle	2.3	To sell the skin at a hige price	To fight hard
Farsene un baffo	2.3	To make of it a moustache	To not give a damn
Essere uno stinco di santo	2.5	To be a shin bone of saint	To be an angel
Essere di manica larga	2.7	To be of large sleeve	To be indulgent
Perdere la faccia	2.5	To lose the face	To lose face
Mandare a monte	2.6	To send to montain	To make fail someone
Rimetterci le penne	2.5	To leave the feathers	To lose life
Tenere banco	2.5	To hold bench	To be a person who speaks a lot in a group of people paying attention to him
Dare i numeri	2.6	To give the numbers	To talk nonsense
Saltare la mosca al naso	1.5	To jump the fly to the nose	To get suddenly angry
Dare del filo da torcere	2.7	To give some thread to twist	To make things hard for someone
Sputare il rospo	2.7	To spit the toad	To suddenly reveal a secret
Prendere in castagna	2.4	To take in chestnut	To catch someone out
Scendere a rotta di collo	1.5	To go down breaking the neck	To go down riskily
Perdere la testa	2.7	To loose the head	To get mad
Avere il cuore in mano	2.1	To have the heart in hand	To be very generous
Non vedere l'ora	2.8	Not to see the hour	To look forward
Metterre la pulce nell'orecchio	2.5	To put the flea in the ear	To suggest something (insinuate)
Avere le mani in pasta	1.8	To have the hands in dough	To have one's finger in the pie
Stringere i denti	2.6	To tighten the teeth	To strongly pursue a goal
Essere al verde	2.9	To be at the green	To be broke
Parlare al muro	2.7	To speak to the wall	To talk to a brick wall
Prendere fischi per fiaschi	2.6	To take whistles for flasks	To misunderstand
Essere a piede libero	2.4	To be at free foot	To be on bail

References

Bastings, E. P., Gage, H. D., Greenberg, J. P., Hammond, G., Hernandez, L., Santago, P., et al. (1988). Co-registration of cortical magnetic stimulation and functional magnetic resonance imaging. *Neuroreport*, *9*, 1941–1946.

Cacciari, C., & Glucksberg, S. (1995). Understanding idioms: Do visual images reflect figurative meanings? *European Journal of Cognitive Psychology*, *7*, 283–305.

Cacciari, C., Reati, F., Colombo, M.-R., Padovani, R., Rizzo, S., & Papagno, C. (2006). The comprehension of ambiguous idioms in aphasic patients. *Neuropsychologia*, *44*, 1305–1314.

Caramazza, A. (1986). On drawing inferences about the structure of normal cognitive systems from the analysis of patterns of impaired performance: The case for single-patient studies. *Brain and Cognition*, *5*, 41–66.

Colombo, L. (1993). The comprehension of ambiguous idioms in context. In C. Cacciari & P. Tabossi (Eds.), *Idioms: Processing, structure, and interpretation* (pp. 163–200). Hillsdale: Lawrence Erlbaum.

Faust, M. E., & Gernsbacher, M. A. (1996). Cerebral mechanisms for suppression of inappropriate information during sentence comprehension. *Brain and Language*, *53*, 234–259.

Fiebach, C. J., Vos, S. H., & Friederici, A. D. (2004). Neural correlates of syntactic ambiguity in sentence comprehension for low and high span readers. *Journal of Cognitive Neuroscience*, *16*, 1562–1575.

Gernsbacher, M., & Robertson, R. (1999). The role of suppression in figurative language comprehension. *Journal of Pragmatics*, *31*, 1619–1630.

Gibbs, R. W., Nayak, N. P., & Cutting, C. (1989). How to kick the bucket and not decompose: Analyzability and idiom processing. *Journal of Memory and Language*, *28*, 576–593.

Giora, R. (1997). Understanding figurative and literal language: The graded salience hypothesis. *Cognitive Linguistics*, *7*, 183–206.

Herwig, U., Schonfeldt-Lecuona, C., Wunderlich, A. P., von Tiesenhausen, A., Thielscher, C., Walter, H., et al. (2001). The navigation of transcranial magnetic stimulation. *Psychiatry*, *108*, 123–131.

Laurent, J.-P., Denhières, G., Passerieux, C., Iakimova, G., & Hardy-Baylé, M.-C. (2006). On understanding idiomatic language: The salience hypothesis assessed by ERPs. *Brain Research*, *1068*, 151–160.

MacLeod, C. M. (1991). Half a century of research on the Stroop effect: An integrative review. *Psychological Bulletin*, *109*, 163–220.

Marzi, C. A., Miniussi, C., Maravita, A., Bertolasi, L., Zanette, G., Rothwell, J. C., et al. (1998). Transcranial magnetic stimulation selectively impairs inter-hemispheric transfer of visuo-motor information in humans. *Experimental Brain Research*, *118*, 435–438.

Nenonen, M., Niemi, J., & Laine, M. (2002). Representation and processing of idioms: Evidence from aphasia. *Journal of Neurolinguistics*, *15*, 43–58.

Nickerson, R. S. (1973). Intersensory facilitation of reaction time: Energy summation or preparation enhancement? *Psychological Review*, *80*, 489–509.

Nunberg, G., Sag, I. A., & Wasow, T. (1994). Idioms. *Language*, *70*, 491–538.

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, *9*, 97–113.

Oliveri, M., Romero, L., & Papagno, C. (2004). Left but not right temporal lobe involvement in opaque idiom comprehension: A repetitive transcranial stimulation study. *Journal of Cognitive Neuroscience*, *16*, 848–855.

Papagno, C. (2001). Comprehension of metaphors and idioms in patients with Alzheimer's disease: A longitudinal study. *Brain*, *124*, 1450–1460.

Papagno, C., & Caporali, A. (2007). Testing idiom comprehension in aphasic patients: The modality and the type of idiom effects. *Brain and Language*, *100*, 208–220.

Papagno, C., Curti, R., Rizzo, S., Crippa, F., & Colombo, M. R. (2006). Is the right hemisphere involved in idiom comprehension? A neuropsychological study. *Neuropsychology*, *20*, 598–606.

Papagno, C., & Genoni, A. (2004). The role of syntactic competence in idiom comprehension: A study on aphasic patients. *Journal of Neurolinguistics*, *17*, 371–382.

Papagno, C., Lucchelli, F., Muggia, S., & Rizzo, S. (2003). Idiom comprehension in Alzheimer's disease: The role of the central executive. *Brain*, *126*, 2419–2430.

Papagno, C., Tabossi, P., Colombo, M., & Zampetti, P. (2004). Idiom comprehension in aphasic patients. *Brain and Language*, *89*, 226–234.

Papagno, C., & Vallar, G. (2001). Understanding metaphors and idioms: A single-case neuropsychological study in a person with Down syndrome. *Journal of the International Neuropsychological Society*, *7*, 516–528.

Rizzo, S., Sandrini, M., & Papagno, C. (2007). The dorsolateral prefrontal cortex in idiom comprehension: A repetitive TMS study. *Brain Research Bulletin*, *71*, 523–528.

Romero Lauro, L. J., Tettamanti, M., Cappa, S. F., & Papagno, C. (2007). Idiom comprehension: A prefrontal task? *Cerebral Cortex*, doi:10.1093/cercor/bhm042

Talairach, E. E., & Tournoux, P. (1988). *Co-planar stereotactic atlas of human brain: Three-dimensional proportional system: An approach to cerebral imaging*. Stuttgart: Thieme.

Titone, D., Holzman, P. S., & Levy, D. L. (2002). Idiom processing in schizophrenia: Literal implausibility saves the day for idiom priming. *Journal of Abnormal Psychology*, *111*, 313–320.

Van Lancker Sidtis, D. (2006). Where in the brain is nonliteral language? *Metaphor and Symbol*, *21*, 213–244.

Wassermann, E. M. (1998). Risk and safety of ripetitive transcranial magnetic stimulation: Report and suggested guidelines from the international workshop on the safety of repetitive transcranial magnetic stimulation, June 5–7, 1996. *Electroencephalography and Clinical Neurophysiology*, *108*, 1–16.

Wiggs, C. L., Weisberg, J., & Martin, A. (1999). Neural correlates of semantic and episodic memory retrieval. *Neuropsychologia*, *37*, 103–118.

Zempleni, M. Z., Haverkort, M., Renken, R., & Stowe, L. A. (2007). Evidence for bilateral involvement in idiom comprehension: An fMRI study. *Neuroimage*, *23*, 596–603.