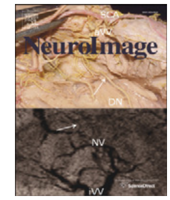
NeuroImage 59 (2012) 3502–3513

Contents lists available at SciVerse ScienceDirect

NeuroImage

journal homepage: www.elsevier.com/locate/ynimg



When do you grasp the idea? MEG evidence for instantaneous idiom understanding

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ARTICLE INFO

Article history:
Received 21 June 2011
Revised 24 October 2011
Accepted 3 November 2011
Available online 10 November 2011

Keywords:
Action words
Idioms
MEG
Sentence comprehension

ABSTRACT

We investigated the time-course of cortical activation during comprehension of literal and idiomatic sentences using MEG and anatomically guided distributed source analysis. Previous fMRI work had shown that the comprehension of sentences including action-related words elicits somatotopic semantic activation along the motor strip, reflecting meaning aspects of constituent words. Furthermore, idioms more strongly activated temporal pole and prefrontal cortex than literal sentences. Here we show that, compared to literal sentences, processing of idioms in a silent reading task modulates anterior fronto-temporal activity very early-on, already 150–250 ms after the sentences' critical disambiguating words ("kick the *habit*"). In parallel, the meaning of action words embedded in sentences is reflected by somatotopic activation of precentral motor systems. As neural reflections of constituent parts of idiomatic sentences are manifest at the same early latencies as brain indexes of idiomatic vs. literal meaning processing, we suggest that within ¼ of a second, compositional and abstract context-driven semantic processes in parallel contribute to the understanding of idiom meaning.

Introduction

Current theories of language and conceptual processing assume that word and sentence meaning is grounded in the brain systems for action and perception (Barsalou, 2008; Gallese and Lakoff, 2005; Pulvermüller, 2005). This position implies that sensorimotor systems provide structure and content for single words and literal sentences whose meaning can be derived from the meaning of their word elements. Crucially, this approach also suggests that sensorimotor systems play an equally important role in the derivation of the meaning of abstract sentences. That bodily action and interaction with the world is important for language understanding was recently confirmed by a series of experiments documenting the interwoven functionality of the brain's action and language systems (Hauk et al., 2008a; Pulvermüller and Fadiga, 2010). Neuroimaging data revealed somatotopic activation of the precentral cortex when subjects perceived words and sentences semantically related to bodily actions involving the face, arms or legs (Hauk et al., 2004; Kemmerer et al., 2008; Pulvermüller et al., 2001; Tettamanti et al., 2005). A range of TMS (Transcranial Magnetic Stimulation) studies also revealed modulation of motor cortex excitability during action word processing (Buccino et al., 2005; Papeo et al., 2009; Sato et al., 2008). Papeo et al. (2011) showed contextual modulation of such motor excitability, being present for hand-related action verbs presented in first person but not, or significantly less, in third person; modulation by context of category-specific semantic brain activity has long been emphasised (for review, see Pulvermüller, 1999, p. 266). Semantic somatotopic activation was even found when subjects read idiomatic sentences including action-related words, so that in the comprehension of the sentence "She grasped the idea" the arm region of the sensorimotor system became strongly active after the sentence disambiguating word ("idea"), whereas the leg region was most strongly sparked during comprehension of "She kicked the habit" (Boulenger et al., 2009; see also Desai et al., 2011 for similar findings). These results show that, when processing idiomatic sentence meaning, semantic information about constituent parts of these sentences, especially of their action verbs, is manifest in the brain response, thus suggesting a compositional contribution of these elements to meaning of the whole sentence. Challenging results have however been reported in other neuroimaging studies. Raposo et al. (2009) for instance failed to replicate the finding of motor somatotopy for idioms containing words related to arm and leg actions (see also Aziz-Zadeh et al., 2006). However, given that brain responses to action

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doi:10.1016/j.neuroimage.2011.11.011

words embedded in idioms were targeted[1] and sequential probability of strings was not controlled in this study, it is difficult to separate effects of cloze probability, idiomaticity and action-related semantics, thus making it difficult to assess whether the mentioned study successfully addressed the brain basis of action idioms. Using TMS, Cacciari et al. (2011) showed modulation of motor system excitability during reading of literal, fictive and metaphorical motion sentences but not of idiomatic motion sentences. Here again, methodological differences could, at least partly, explain the discrepancies between the results. Whereas similar action verbs and/or sentence contexts were used for idiomatic and literal sentences by Boulenger et al. (2009; e.g. "Anna *caught* the sun/fish" respectively) and Desai et al. (2011; e.g. "The church *bent* the rules"/"The bodyguard *bent* the rod" respectively), action words and preceding contexts included in idiomatic sentences (e.g. "Il lavoro *giunge* in porto fra difficoltà") were different from those included in metaphorical (e.g. "La fatica *viene* in punta di piedi sempre") and literal sentences (e.g. "Carla *corre* a casa con la spesa") in Cacciari et al. (2011). Hence, while the Raposo et al. study failed to target the point in time of idiom comprehension, Cacciari et al.'s absence of motor activation for idioms may be related to subtle semantic differences between the words embedded in idioms and literal sentences. The brain basis of action idioms does therefore still appear as unresolved.

A main part of pre-existing data supporting semantic embodiment comes from fMRI investigations. However, it is well-known that the sluggish nature and low time-resolution of BOLD responses, and neurometabolic imaging more generally, makes it impossible to draw firm conclusions on the temporal dynamics of cognitive processes under investigation. Moreover, as it has been pointed out repeatedly, the fMRI activation map in itself leaves it unclear whether motor system activation emerges in the rapid on-line comprehension process or rather is part of a late response following comprehension, for example a post-understanding inference or epiphenomenal second-order process (Boulenger et al., 2006; Kemmerer and Gonzalez-Castillo, 2010; Kiefer and Pulvermüller, in press; Pulvermüller, 2005). It has, in fact, been suggested that motor activity during action word processing is not related to semantic processing per se but that it is triggered because subjects adopt a strategy of imagining/simulating the movement with the body parts used to perform the actions depicted by words (Tomasino et al., 2007, 2008). Critically, "on the disembodied cognition hypothesis, activation of the motor system in tasks that do not 'require' motor system activation must be regarded as ancillary to, and inconsequential for, semantic analysis. Such motor system activation would be akin to the role that the activation of the 'salivary system' in the Pavlovian dog plays in recognizing the bell — i.e., nothing" (Mahon and Caramazza, 2008, p.68). As these authors are well-aware, pre-existing evidence demonstrating a causal influence of motor systems TMS on the processing of action-related language falsifies such an approach and the only option therefore seems to be to integrate sensorimotor semantic systems into a mixed embodied plus "symbolic" or amodal systems account (see also Pulvermüller, 2005 and Patterson et al., 2007). In such a "hybrid" model, it still needs to be determined whether, if amodal "symbolic" and sensorimotor embodied systems are called into action together, one might possibly "drive" the other. In Mahon and Caramazza's version of such a model, the symbolic system would be the master and the sensorimotor circuits the slave, thus suggesting temporal priority of the former. If abstract-contextual and embodied-sensorimotor semantic processes occur strictly in parallel (Boulenger et al., 2009; Pulvermüller et al., 2009), we would expect near-simultaneous emergence of the brain correlates of contextual and sensorimotor semantics. To decide between these competing hypotheses on the spatio-temporal activation pattern of sensorimotor embodied and amodal symbolic brain systems, fMRI studies are not sufficient. More precise temporal information is necessary to elucidate the time-course of brain processes underlying the comprehension of language semantically related to actions. We here use whole-head high-density MEG (MagnetoEncephaloGraphy) which, with its well-known fine-grained temporal precision (milliseconds), is ideally suited for deciding the critical question about WHEN the motor system and putative cortical correlates of amodal symbolic systems become active for the first time.

We note that the bulk of evidence argues against the possibility that motor-area activity is a simple by-product of the comprehension process and emerges only after semantic processing. First, neurological diseases affecting the motor system reduce the processing efficiency of action-related words (Bak et al., 2001; Boulenger et al., 2008a). Second, magnetic stimulation of arm or leg motor cortex changes specifically the processing speed of action words semantically related to arm or leg movements, thus documenting a causal effect of motor system activity on the processing of specific semantic sub-categories of action words (Pulvermuüller et al., 2005a). Third, motor activation in action-related brain regions correlates with lexical and semantic properties of action words (Hauk et al., 2008a, 2008b; Pulvermüller et al., 2005b), a feature which further argues against an epiphenomenon role. Fourth, EEG (ElectroEncephaloGraphy) and MEG results documented rapid semantic somatotopic activation in action word comprehension. Within 150–250 ms after the point in time when action words presented in isolation could first be identified unambiguously, the brain response showed differential activation of sensorimotor areas (Hauk and Pulvermüller, 2004; Pulvermüller et al., 2001; Pulvermüller et al., 2005b; Shtyrov et al., 2004; van Elk et al., 2010). At the same early time, a functional influence of action word processing on overt motor movements could be demonstrated (Boulenger et al., 2006, 2008b; Nazir et al., 2008). This early time-course of language-motor interactions is consistent with embodied semantic theories that claim immediate access to sensorimotor knowledge in word comprehension and is difficult to reconcile with the idea that semantically related motor activations are secondary to semantic processes elsewhere in the brain (Pulvermüller, 2005; Pulvermüller and Fadiga, 2010). However, pre-existing work still did not address one of the most important predictions of embodied semantic models, namely that instantaneous sensorimotor activations documented for action words and sentences, for example "*Mary caught the fish*", are also brought about in the comprehension of idiomatic sentences, where direct action reference may be obscured or absent, as for example "*Mary caught the sun*". Critically, if the figurative meaning of idioms that include action words recurs to the same action schemata also effective in the comprehension of literal language (Barsalou, 2008; Gallese and Lakoff, 2005), differential activation of motor cortex should be present early, within 250 ms, when subjects understand idioms that contain for example arm- or leg-related words. We here ask whether semantically-specific activation in the motor system emerges early and how its time-course relates to that of brain indexes of figurative vs. literal language processing.

The present study further tackles the more general issue of figurative language processing which we commonly use to express our

[1] Raposo et al. (2009) used sentences such as "The spiteful critic *trampled* over Sarah's feelings", triggering fMRI responses to (here italicised) *action words* rather than to the (here underscored) critical words disambiguating idiomatic sentences. Note that with the expression kitchen floor at its end, the sentence would not be idiomatic, so the brain response brought about by *trampled* cannot be interpreted to reflect idiomatic sentence processing. Thus, although it had been the authors' intention that "each sentence contained a phrase before the verb whose role was to disambiguate the meaning of the verb (i.e. whether or not it was related to body movements)", their example sentences show that this strategy was not successful (that is, disambiguation happened with "feelings/kitchen floor", but not with "*trampled*"). Thus, it appears that Raposo et al. have missed the critical point of idiom comprehension in their sparse imaging design.

ideas and thoughts. Two main theories have been proposed to explain idiom comprehension: the *constructionist approach* holds that idioms are stored and processed as complex forms, similar to entries in a lexicon for whole constructions, and separate from their constituent words (see, for example, Goldberg, 2003; Langacker, 1991; Swinney and Cutler, 1979).[2] Gibbs (1984) argued that people do not engage in linguistic analysis of idiomatic expressions at all and that they can directly access idiom meanings while completely bypassing the literal ones, although data from his group also indicated a contribution of constituent verbs to figurative idiom meaning (Hamblin and Gibbs, 1999). Thus, in the constructionist perspective, both single lexical items and complex constructions are viewed to be semantically stored and accessed in parallel, also simultaneous with any other context integration processes (Pulvermüller et al., in press). On the other hand, *compositional theories of semantic processing* postulate that sentence meaning is computed from the semantics of a sentence's constituent words, and that also in the case of idioms, individual words make a significant contribution to sentence meaning (Davidson, 1967; Titone and Connine, 1999). As an example, the "configurational hypothesis" (Cacciari and Tabossi, 1988) views idioms as represented as configurations of words, not lexical units, and posits that, in the computation of idiom meaning, individual constituents of the sentence play a role. Idioms are processed literally until a key word is encountered that prompts recognition of the idiomatic nature of the string and activation of its figurative interpretation, with this interpretation being coloured by key words in the construction. Based on the observation of semantic somatotopic activation during reading of action-word-containing idioms, we (Boulenger et al., 2009) previously provided evidence for compositional mechanisms, however without ruling out whole-form storage constructional accounts. Here, using MEG, we determine when brain reflections of motor schemata associated with composite action words emerge relative to those of access to idioms as abstract constructions. Immediate activation of action-related brain regions that precedes or parallels activation of regions involved in figurative sentence processing will lend support to compositional theories as it would suggest that sentences' constituent parts contribute to the computation of the whole sentence meaning. A general brain activation difference between idiomatic and literal sentences will substantiate the claim that these types of semantics have different brain bases. As mentioned in the context of the embodied/amodal debate, findings of brain correlates of both word-semantics and sentence-level idiomaticity would allow us to cast light upon the relative activation time-courses and could therefore also have implications for the temporal orchestration of compositional and constructional semantic processes.

Materials and methods

Participants

Eighteen healthy right-handed English native speakers (10 females) aged 19–45 years participated in the study. They had no record of neurological diseases, vision or hearing problems, and reported no history of drug abuse. All subjects gave their written informed consent to participate in the experiment and were paid for their participation. Ethical approval was obtained from the Cambridge Local Research Ethics Committee.

Stimuli

The materials consisted of seventy-six pairs of idiomatic and literal English sentences. Most of the idioms were semantically opaque, so that their meaning could not be derived from their constituent words alone. Half of the sentences included an arm-related action verb (e.g., "John scraped the barrel", "John picks her brain" and "Mary caught the sun" vs. "John scraped the table", "John picks her fruit" and "Mary caught the fish") while the other half included a leg-related action verb (e.g., "Pablo kicked the bucket", "Anna walked a tightrope between the situations" and "Pablo jumped on the bandwagon" vs. "Pablo kicked the ball", "Anna walked a mile between the towns" and "Pablo jumped on the armchair"; see Appendix for the complete stimulus set). Four experimental conditions were thus compared: arm-related idiomatic (n = 38), arm-related literal (n = 38), leg-related idiomatic (n = 38) and leg-related literal (n = 38) sentences. Sentence length varied from 3 to 7 words and was matched across the four conditions. The critical words of the sentences (e.g., "bucket" and "ball"), which disambiguated the sentences as either idiomatic or literal, were matched using the CELEX lexical database for relevant psycholinguistic variables. Arm- and leg-related action words were matched along the same variables (Table 1). The two types of sentences were further matched for syntactic structure (i.e. only the critical words differed between idiomatic and literal conditions) and cloze probability. Cloze probability was estimated by asking 12 native English speakers (different from those who participated in the study) to complete the sentence fragments, not containing the critical words, with the first word/group of words that came to their mind (each subject had to give 3 answers). Results of this rating revealed that mean cloze probability of our idiomatic sentences (7.9%) did not significantly differ from that of literal sentences (5.1%, $p > .1$, n.s.). Six further literal sentences including action-related or mental/state verbs were used as probe stimuli, interspersed with the main test sentences, in a simple motor response task (see Procedure below).

After the MEG experiment, the same group of 18 participants had to evaluate the sentences on action-relatedness and idiomaticity by answering the following questions using a 5-point scale (1 = not at all; 5 = very much): (1) Is the meaning of the sentence related to an action that you could perform with your hands/arms/fingers? (2) Is the meaning of the sentence related to an action that you could perform with your feet/legs? (3) Does the sentence have a figurative/idiomatic meaning? Rating results confirmed that our arm- and leg-related literal sentences were more strongly associated with arm and leg actions respectively (average ratings = 4.59 and 4.7 respectively) than arm- and leg-related idiomatic sentences (average ratings = 1.92 and 1.44 respectively, $p < .001$) and that our idioms were actually perceived as having a figurative meaning (average rating = 4.65) compared to literal sentences (average rating = 1.44, $p < .001$). A further rating study was performed to determine whether concreteness/abstractness ratings dissociated between literal and idiomatic sentences ("Is the meaning of this sentence concrete or abstract?" rated on a 5-point scale). Results showed clearly that idiomatic sentences were rated as more abstract than literal ones (average values were 2.44 vs. 4.25 respectively; $F(1, 10) = 58.47$, $p = .001$).

Procedure

Sentences were presented word by word, each for 500 ms (word-to-word stimulus onset asynchrony, SOA = 500 ms), in lowercase letters at the centre of a computer screen. The SOA between critical words of two consecutive sentences was fixed (6.6 s) and the

[2] In one variant of such an approach, called the "lexical representation hypothesis" (Swinney and Cutler, 1979), the computation of literal and idiomatic meanings is assumed to be initiated simultaneously upon occurrence of the first word in the idiomatic string. Individual words in the literal string would thus be accessed immediately, as would be the representation for the entire idiomatic construction. However, the lexicalized idiomatic meaning would become available before the computation of semantic relationships between constituent words in the literal interpretation of the sentence, which, according to this proposal, can only follow single word access. In the same sense, our present results do not provide evidence for a delayed processing of literal sentences and therefore we do not further discuss this proposal in detail below.

Table 1
Psycholinguistic characteristics of critical words and of arm- and leg-related action words included in the idiomatic and literal sentences.

	Critical words			Action words		
	Idiomatic	Literal	ANOVA	Arm	Leg	ANOVA
WORD FQ	83.8 (93)	80.8 (91)	*ns*	15.25 (10)	22.58 (27)	*ns*
LEMMA FQ	143.7 (169)	117.9 (119)	*ns*	93.75 (86)	113.33 (139)	*ns*
LETT	5.55 (1.8)	5.51 (1.5)	*ns*	4.67 (1.1)	4.17 (0.7)	*ns*
SYLL	1.59 (0.7)	1.53 (0.7)	*ns*	1 (0)	1 (0)	*ns*
BIGR	39,137 (13,419)	40,133 (12,368)	*ns*	32,984 (17,388)	23,052 (17,378)	*ns*
TRIG	4811 (3096)	5126 (3788)	*ns*	4859 (6144)	1892 (1780)	*ns*
ORTH NEIGH	5.34 (5)	5.35 (5.8)	*ns*	7.08 (5.7)	7.67 (4.4)	*ns*

Mean values of word frequency (WORD FQ; per million), lemma frequency (LEMMA FQ; p/m), length in letters (LETT), number of syllables (SYLL), bigram frequency (BIGR), trigram frequency (TRIG), and number of orthographic neighbours (ORTH NEIGH) are reported for idiomatic and literal critical words of the sentences, and for arm- and leg-related action verbs (standard deviations are reported in brackets). *P*-values for ANOVAs (by items) are reported.

intersentence interval (ISI; i.e. time-interval between the offset of a sentence and the onset of the next sentence), during which a fixation cross remained on the screen, varied between 2.6 and 5.1 s (mean = 4.04 s). Action verbs appeared on average 1.2 s before critical word onset (SD 485 ms). Such long delay and jitter were introduced to ascertain that any neurophysiological effects elicited by the critical word could not be explained as a direct consequence of action word presentation per se. Participants were asked to read sentences attentively but silently, without moving lips or articulators, and to carefully look at sequences of symbols that could also be displayed. They were told to attend to the meaning of each sentence and to be prepared to respond to test questions probing their comprehension. To this end, they occasionally had to answer simple yes/no questions about probe sentences, randomly interspersed between critical sentences, by pressing one of two buttons either with their left index or middle finger. For instance, after reading "John believes in ghosts", they had to answer "yes" to the question "Does John believe in ghosts?". Note that subjects did not know which sentences were probes so that they had to expect questions after each sentence, keeping their attention on the visual sentence input. Stimuli were presented in a randomised order with E-Prime software (Psychology Software Tools, 2001).

MEG recording

Brain's magnetic activity was continuously recorded using a 306-channel Vectorview MEG system (Elekta Neuromag, Helsinki, Finland) with pass-band 0.10–330 Hz and 1 kHz sampling rate. To enable the removal of artefacts due to head movements, the position of the subject's head with respect to the recording device was tracked throughout the experiment using continuous head position identification (HPI). To this aim, magnetic coils were attached to the head and their position (with respect to a reference system determined by 3 standard points: nasion, left and right pre-auricular) was digitised using the Polhemus Isotrak digital tracker system (Polhemus, Colchester, VT). To allow the off-line reconstruction of the head model and co-registration with MR structural images, an additional set of points randomly distributed over the scalp was also digitised. Four EOG electrodes were further placed laterally to each eye (horizontal EOG) and above and below the left eye (vertical EOG) to monitor eye movements during the recording.

MEG data processing

Pre-processing

For each subject, MEG channel and condition, we applied the following pre-processing steps:

(i) The continuous raw data from the 306 channels where pre-processed off-line using MaxFilter software (version 2.0, Elekta Neuromag, Helsinki) which minimises possible effects of magnetic sources outside the head as well as sensor artefacts using a Signal Space Separation (SSS) method (Taulu and Kajola, 2005; Taulu et al., 2004). SSS was applied with spatio-temporal filtering and head-movement compensation which corrected for within-block motion artefacts.
(ii) Using the Minimum Norm Estimates Suite (MNE, Martinos Center for Biomedical Imaging, Massachusetts General Hospital, Boston, MA), average event-related fields (ERFs) starting 100 ms before critical word onset and ending 800 ms after offset were computed from the pre-processed data for each sentence condition. Epochs containing gradiometer, magnetometer or EOG peak-to-peak amplitudes larger than 2000 fT/cm, 4000 fT or 150 μV respectively were rejected. These average responses were low-pass filtered (40 Hz) and baseline corrected (from 100 ms before critical word onset to word onset).

Cortical surface reconstruction

For each subject, T1-weighted magnetic resonance images (MRIs) were acquired on a 3-T Siemens Tim Trio scanner (TR = 2 s, TE = 30 ms). The skin surface was segmented and tessellated. The cortical surface was decimated to include 10,242 vertices in each hemisphere for the purposes of source estimation (Dale et al., 1999; Fischl et al., 1999). A single-layer boundary element model (BEM) of the inner skull surface (Hämäläinen and Sarvas, 1989; Mosher et al., 1999) was created to perform the forward model calculations. FreeSurfer software package (Martinos Center for Biomedical Imaging) was used in the above reconstruction procedures.

Source analysis

Using the MNE suite, the digitised points from the Polhemus were co-registered to the skin surface. The forward solution was created using the decimated cortical surface and the single layer BEM. The noise covariance matrix was used to whiten the forward matrix and the data (Lin et al., 2006; Lütkenhöner, 1998). Dipole orientation was unconstrained. The cortical sources of the MEG signals were estimated using a distributed model, the L2 minimum norm estimate (Hämäläinen and Ilmoniemi, 1984). This was done for each subject, sentence condition and time-point. The data from each individual's source analysis were analysed in a common registered cortical space. To examine effects of specific conditions, a dynamic Statistical Parametric Map (dSPM) was used (Dale et al., 2000). dSPM utilises the MNE to create an *F*-like statistic (the square root of the *F* statistic) comparing the signal to the noise. Local current sources are calculated for and displayed on an average cortical surface (anatomical average of all brains of participants in the present study).

Statistical analysis

To compare the effects of Idiomaticity of the sentences and Body Part reference of the action verbs they included, the values produced by the MNE of each condition were subjected to statistical comparisons. Five sequential 50-ms time-windows ranging from 100 ms to 350 ms after critical word onset were selected. The source space was divided in 9 regions of interest (ROIs) which were chosen following our fMRI results on idioms including action words (Boulenger et al., 2009) and on previous studies on action word and idiom processing (Hauk et al., 2004; Romero-Lauro et al., 2007). Most of these ROIs were previously shown to (i) be strongly activated during reading of idiomatic sentences compared to literal sentences and (ii) relate to semantic somatotopy to arm- and leg-related sentences. The following ROIs were manually drawn on the average left-hemisphere cortical surface across all subjects (see Table 2 for corresponding Brodmann areas and MNI coordinates of the centre of ROIs): inferior frontal gyrus (IF), superior/middle temporal gyrus (ST), temporal pole (TP), angular gyrus (AG), dorsolateral prefrontal cortex (PF), arm premotor/motor region (MA), leg premotor/motor region (ML), inferior temporal cortex (IT) and occipital cortex (OCC). As initial analysis revealed that activity in IT and OCC did not distinguish between conditions, these regions were not included into the main statistical analysis. Note also that an analysis on smaller motor ROIs restricted to arm and leg motor cortex confirmed the results presented. Mean current amplitudes extracted for each time-window, ROI, condition and subject were subjected to a 4-way repeated measures analysis of variance (ANOVA) with factors Time (100–150 ms, 150–200 ms, 200–250 ms, 250–300 ms, 300–350 ms), ROI, Idiomaticity (idiomatic vs. literal) and Body Part (sentences containing arm- vs. leg-related action words). Significant effects are reported in the text only if they survived Greenhouse–Geisser correction for sphericity violations.

Capitalising on the fine temporal resolution MEG offers, a further fine-grained time-course analysis (1) estimated the earliest points in time when the idiomatic/literal status of the sentences and the body-part reference of action words included in the sentences affected the activation strength of relevant ROIs and (2) directly compared the earliest onset latencies of idiomaticity and body part effects with each other. For each subject, source estimates for two critical conditions were subtracted from each other: the contrast between idiomatic vs. literal sentences was calculated for the ROIs TP and PF, and that between sentences containing arm-related vs. leg-related words was computed for the precentral ROIs MA and ML. A test was then performed time-point by time-point to assess whether the resultant subtraction curve was significantly different from the baseline (−100 ms to critical word onset; using the SD of the baseline). The first of 10 consecutive significant time-points was identified as the first point in time when the critical conditions differed from each other. The “earliest time-points of divergence” found for the idiomatic/literal and for the arm/leg contrasts were then compared between ROIs and contrasts using t-tests.

Results

Silent reading of arm- and leg-related idiomatic and literal sentences elicited rapid spreading of cortical activation within a distributed neural network. Within 250 ms of the critical word distinguishing between literal or idiomatic meaning of a sentence (e.g., “she caught the *sun*” vs. “she caught the *fish*”, “he kicked the *habit*” vs. “he kicked the *statue*”), neural activity spread from the visual occipital cortex to anterior areas in temporal and frontal cortex. First activation peaks (note that cortical sources build up earlier than the point in time when they reach their maximum of activity) were seen in the occipital cortex at 165 ms, in the inferior temporal cortex (IT) at 170 ms, the angular gyrus (AG) at 180 ms and in the dorsolateral prefrontal cortex (PF) at 180 ms. After a further slight delay, activation also peaked in the temporal pole (TP; 235 ms), the precentral gyrus (motor/premotor cortex, arm and leg regions, MA and ML; 250 ms) and the superior temporal (ST; 250 ms) and inferior frontal gyrus (IF; 265 ms; Fig. 1).

50-ms time-windows analysis

To test activity dynamics related to Time, Idiomaticity of the sentences, and Body Part reference of the action verbs they included, along with the interactive effects of these variables, activity in 7 regions of interest (ROIs; Table 2) was compared between arm/leg-related idiomatic/literal sentences in 5 sequential 50-ms time-windows ranging from 100 to 350 ms following critical word onset. A 4-way ANOVA (Time × ROI × Idiomaticity × Body Part) revealed significant main effects of Time ($F(4, 68) = 10.40$, $\varepsilon = 0.592$, $p = 0.001$), indicating generally strongest brain activation from 150 ms to 300 ms post-stimulus (maximal activity in the interval 200–250 ms), and of ROI ($F(6, 102) = 61.24$, $\varepsilon = 0.329$, $p = 0.001$), due to stronger activity in TP and AG compared to other regions. The interaction of the factors Time and ROI was also found to be significant ($F(24, 408) = 5.83$, $\varepsilon = 0.243$, $p = 0.001$), as activity in AG and TP was

Table 2
Regions of interest (ROIs) in the left hemisphere in which time-course of activation during literal and idiom sentence reading was examined.

ROI	Label	Brodmann areas	MNI coordinates	
Occ	Occipital cortex	BA 17/18/19	−25 −89 4	Dale et al. (2000) Dhond et al. (2001)
AG	Angular gyrus	BA 39	−40 −61 27	Humphries et al. (2007) Lau et al. (2008)
ST	Superior temporal cortex	BA 22/41/42	−45 −35 1	Dale et al. (2000) Friederici et al. (2003)
IT	Inferior temporal cortex	BA 21/37	−57 −42 −9	Dhond et al. (2001) Marinkovic et al. (2003)
TP	Temporal pole	BA 38	−50 −1 −26	Binney et al. (2010) Romero-Lauro et al. (2007)
IF	Inferior frontal cortex	BA 44/45 + BA9/47	−45 11 17	Bookheimer (2002) Friederici et al. (2003)
PF	Dorsolateral prefrontal cortex	BA 9	−20 38 32	Fogliata et al. (2007) Pulvermüller and Hauk (2006)
MA	Arm motor/premotor cortex	BA 4/6	−51 −6 43	Boulenger et al. (2009)
ML	Leg motor/premotor cortex	BA 4/6	−25 −17 64	Hauk et al. (2004) Tettamanti et al. (2005)

For each ROI, the label, corresponding Brodmann areas (BA) and MNI coordinates (at the centre of ROI) are reported. Previous studies where the ROIs were found to be active in the processing of idioms, action words, or language in general are also mentioned.

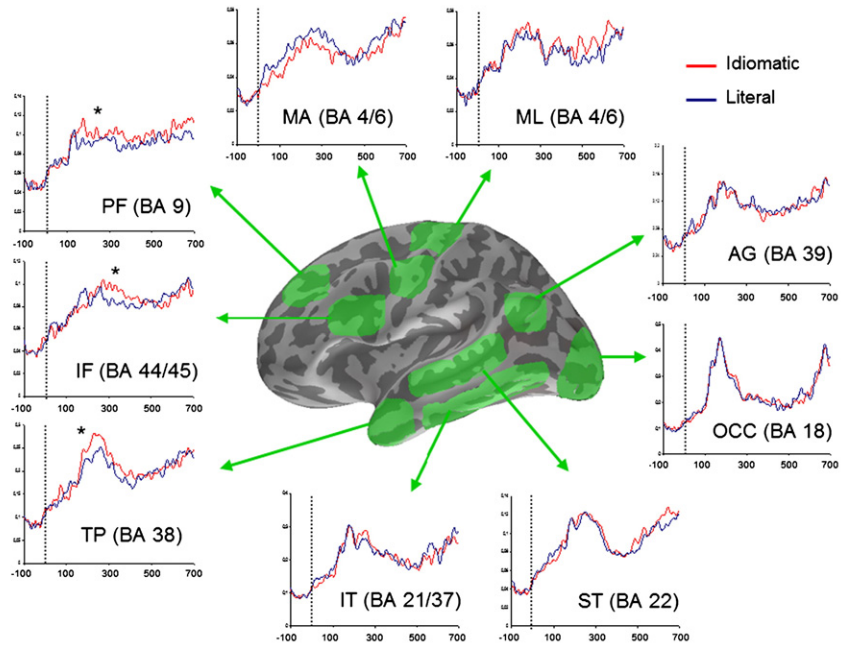

Fig. 1. Time-course of cortical activation in each region-of-interest (ROI) for idiomatic and literal sentences. The nine predefined ROIs (see Table 1 for more details about ROIs) are represented in green on an "inflated" view of the left cortical hemisphere. For each ROI, time-course of activation is reported from 100 ms before critical word onset to 700 ms after onset for idiomatic (red) and literal sentences (blue). The vertical dotted line indicates critical word onset. MA = left motor/premotor arm region; ML = left motor/premotor leg region; IF = left inferior frontal cortex; ST = left superior temporal cortex; TP = left temporal pole; PF = left dorsolateral prefrontal cortex; AG = left angular gyrus; IT = left inferior temporal cortex; OCC = left occipital cortex. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

enhanced, respectively, in the intervals 150–250 ms and 200–300 ms post-stimulus onset compared with earlier and later time-windows. In contrast, activation strength in the other ROIs rose within the first 100 ms after critical stimulus onset but did not change significantly between 100 and 350 ms.

Importantly, the factors Time, ROI and Idiomaticity led to a significant 3-way interaction ($F(24, 408) = 2.85$, $\varepsilon = 0.332$, $p = 0.006$) which is displayed in Fig. 2a. This complex interaction revealed that idiomatic/literal status of a sentence was manifest in spatially and temporally specific brain activations. The interaction was due to

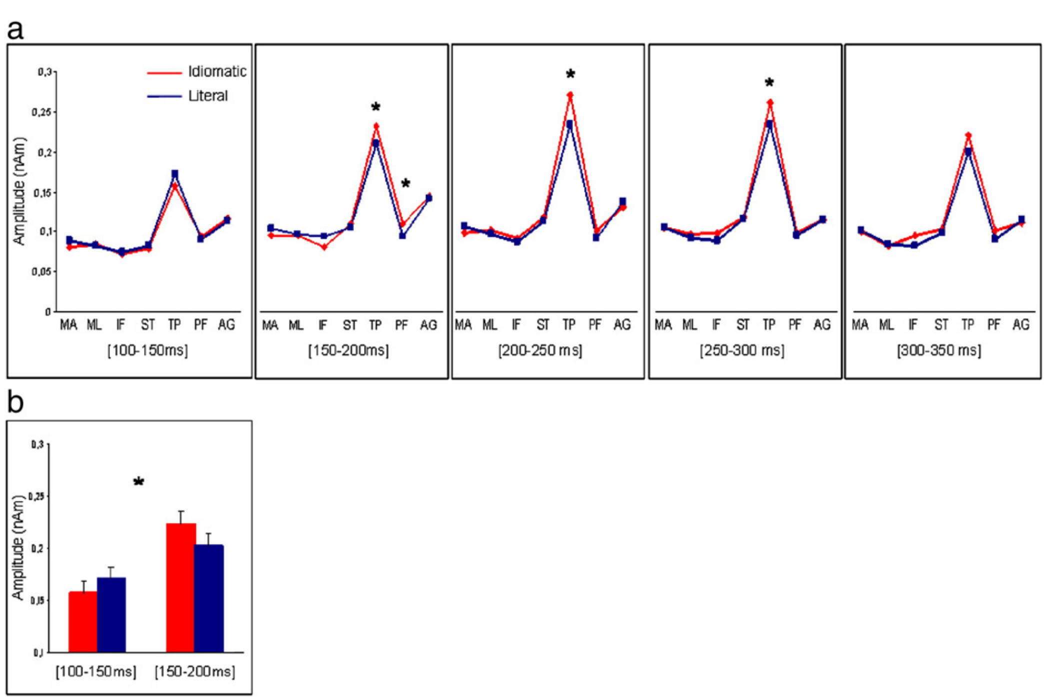

Fig. 2. ROI activations for idiomatic and literal sentences across time. (a) Amplitudes of MNE source current values summed over predefined ROIs are reported for each of the 7 selected ROIs for idiomatic (red) and literal sentences (blue) in five 50-ms time-windows (from 100 to 350 ms after critical word onset). MA = left motor arm region; ML = left motor leg region; IF = left inferior frontal gyrus; ST = left superior temporal cortex; TP = left temporal pole; PF = left dorsolateral prefrontal cortex; AG = left angular gyrus. Asterisks indicate significant differences ($p<.05$) between conditions. (b) Cross-over interaction ($p = .017$) in the left temporal pole in the first two time-windows of analysis (100–150 ms) and (150–200 ms) during reading of idiomatic (red) and literal (blue) sentences. Bars represent standard errors of differences. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

stronger idiomaticity effects in the temporal pole (TP) and prefrontal cortex (PF) compared with other ROIs. Interestingly, in the first two time-windows (100–150 ms and 150–200 ms), activation in TP revealed a significant Time × Idiomaticity interaction ($F(1, 17) = 6.93$, $p = 0.017$; Fig. 2b): TP tended to respond more strongly to literal sentences than to idioms at very early time-points (100–150 ms, although the Idiomiaticity contrast did not reach significance in this very early time window), whereas later on (150–200 ms), the reverse contrast was significant, showing stronger activity for idiomatic sentences ($F(1, 17) = 5.28$, $p = 0.035$). A similar interaction was also observed in PF ($F(1, 17) = 6.81$, $p = 0.018$) and an even clearer interaction between the same factors (Time, Idiomaticity) emerged when the 2 ROIs (TP and PF) were entered into one analysis ($F(1, 17) = 9.27$, $p = 0.007$). In addition, the inferior frontal cortex (IF) first activated more strongly to literal than to idiomatic sentences (150–200 ms; $F(1, 17) = 5.27$, $p = 0.035$), however seemingly with a slight delay upon that in TP and PF. When entering data from all three ROIs, where significant idiomaticity effects were found, into a new analysis of the earliest two time-intervals (100–150 and 150–200 ms), a significant 3-way interaction emerged between the factors Time, ROI and Idiomaticity ($F(2, 34) = 9.11$, $\varepsilon = 0.633$, $p = 0.004$), documenting different region-specific time-courses of the neurophysiological differences between figurative and literal sentences. Note that the early

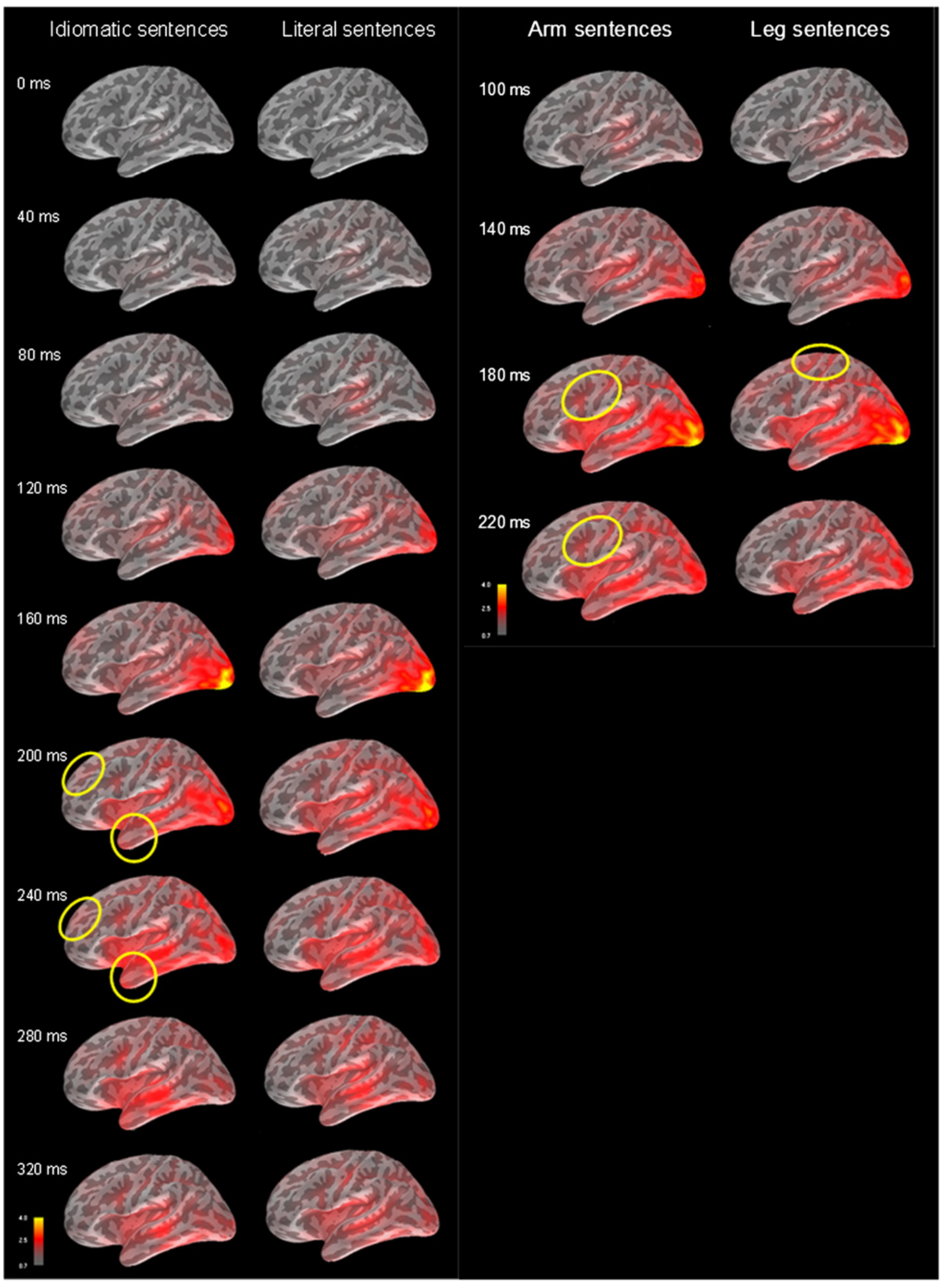

Fig. 3. Dynamic Statistical Parametric Maps (dSPMs) of local cortical activation dynamics elicited by arm- and leg-related idiomatic and literal sentences calculated over the subject group. The panel on the left contrasts dSPMs for idiomatic and literal sentences. The time-scale is in milliseconds after the onset of the critical word. Activation differences in the temporal pole (TP) and in the prefrontal cortex (PF) are highlighted by yellow circles. Stronger activity in TP was found for idioms at 150–250 ms. The panel of the right shows dSPMs for arm- and leg-related sentences (collapsed over idiomatic and literal ones). Yellow circles highlight the stronger activation for arm-related sentences in the arm motor/premotor region and for leg-related sentences in the leg motor/premotor region at ~180 ms after critical word onset. Activations are shown on an “inflated” view of the left cortical hemisphere of the average over the brains of all experiment participants. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

dynamics seen in TP (first trend towards literal > idiomatic, then idiomatic > literal) re-occurred with a slight delay in IF cortex (see Fig. 1).

Crucially, a significant Time × Body Part interaction also emerged ($F(4, 68) = 2.86$, $\varepsilon = 0.868$, $p = 0.037$), indicating dissociations of activation time-courses between sentences including arm- and leg-related action words, regardless of whether they were literal or idiomatic in meaning, and over the 7 ROIs and 5 time-intervals. When directly comparing activity for arm and leg sentences in each ROI separately, significant differences were found in the arm precentral cortex (MA) in the intervals between 200 and 350 ms ($F(1, 17) = 5.06$, $p = 0.038$), indicating stronger activity for arm than for leg sentences, but not in any other region. The opposite tendency in the leg precentral cortex was observed but did not reach significance. No interaction involving both semantic factors – Idiomaticity of the sentences and Body Part reference of their composite action words – was found.

Fig. 3 illustrates the time-courses of cortical activation elicited by idiomatic and literal sentences (panel on the left), and by sentences including arm- and leg-related action words (panel on the right), by displaying snapshots of activity patterns revealed by dynamic Statistical Parametric Maps (dSPMs).

Time-point by time-point analysis

Taking advantage of the main strength of MEG, we further scrutinised the dynamics of semantic brain activation by determining the earliest time-points of divergence between idiomatic and literal sentences in TP and PF, and between arm- and leg-related sentences in arm and leg precentral ROIs (MA and ML). This meticulous analysis revealed that the difference in spatiotemporal patterns between sentences including arm- and leg-related action words was significant in arm precentral cortex at 165 ms and in leg precentral cortex at 173 ms. In prefrontal cortex and temporal pole, the earliest idiomaticity effects were seen at 170 and 185 ms, respectively. Unlike the larger time-bins described above, these earliest time-points of divergence of the Idiomaticity and Body Part effects did not significantly differ between each other for any pair of ROIs examined.

A further analysis computing the Idiomaticity main effect over PF and TP and that of Body Part in the premotor ROIs confirmed these time-course estimates: Significantly stronger activation to idiomatic than to literal sentences were seen in temporal pole and prefrontal cortex from 160 to 180 ms ($F(1, 17) = 5.833$, $p = 0.027$) and from 200 to 240 ms ($F(1, 17) = 7.172$, $p = 0.016$) and, similarly, in the intervals from 150 to 160 ms and from 250 to 260 ms, significant ROI × Body Part interactions emerged in MA and ML ($F(1, 17) = 6.625$, $p = 0.020$ and $F(1, 17) = 5.797$, $p = 0.028$ respectively). *Once again*, the points in time where body-part reference of action words first affected the landscape of activation in precentral cortex and where idiomaticity effects were first manifest in anterior temporo-frontal areas did not significantly differ from each other ($p > .05$). These findings therefore indicate near-simultaneous early effects – between 150 and 180 ms after the critical sentence-disambiguating word – of the idiomaticity of sentences and the embodied meaning of action words included in these sentences.

Discussion

Our results show early semantic activation (150–250 ms) to written sentences in a range of cortical regions. At early points in time (150–200 ms and onwards), idioms evoked significantly stronger activation than literal sentences in left temporal pole, Broca's region in left inferior frontal cortex as well as in left dorsolateral prefrontal cortex. Early activation in the motor system at the same early latencies (150–250 ms and onwards) was found to reflect aspects of the meaning of action words included in literal and figurative sentences alike. The short latency and dependence on semantic type of these region-specific activations are consistent with the involvement of motor schemata reflecting constituent word meaning in the semantic analysis of both literal sentences and idioms. Additional analyses of the fine-grained time-course of ROI-specific activation suggested near-simultaneous brain signatures of the semantic status of sentences (idiomatic vs. literal) and the semantic type of action words embedded in these sentences.

Idiomaticity effects

Our findings corroborate previous functional brain imaging studies showing specific involvement of anterior temporal and prefrontal regions in idiom processing (Fogliata et al., 2007; Lee and Dapretto, 2006; Rizzo et al., 2007; Romero-Lauro et al., 2007). For instance, Romero-Lauro et al. (2007) reported stronger activation in the left superior frontal and anterior middle temporal gyri along with increased effective connectivity between these regions during idiom comprehension. It was suggested that while temporal cortex may retrieve idiom meaning, prefrontal areas may suppress literal sentence interpretations. However, the functional imaging data available so far cannot, in our opinion, speak to such differential roles of frontal and temporal areas. In our fMRI study (Boulenger et al., 2009), we could confirm enhanced activity in fronto-temporal regions when reading idioms, however, these BOLD activations emerged rather late (3 s) after the critical words of stimulus sentences were presented. The apparent discrepancy between these results and the present MEG findings of rapid motor systems activation suggests that fMRI does not capture important facets of the temporal dynamics of cognitive brain processes and that using complementary neurophysiological imaging techniques is crucial for understanding the brain basis of language comprehension. As the precise temporal resolution of MEG (and EEG) methods is renowned, we believe that the temporal dynamics obtained from such study can be trusted more than those suggested by fMRI.

Additional earlier studies have investigated the brain basis of idioms. Fogliata et al. (2007) examined the effects of repetitive TMS (rTMS) on a sentence-to-picture matching task using idioms and literal sentences. TMS was delivered, after sentence ending and subsequent to picture presentation, to the left middle temporal and prefrontal cortex, and led to impairment of idiom-picture matching. However, as TMS delivery followed sentence presentation with a substantial delay (2 s), subjects had already understood the short phrases (of 3–6 words) at the point in time when pictures were presented and subsequent TMS pulses were delivered. This feature makes it difficult to draw conclusions on TMS effects on idiom comprehension as TMS could possibly have affected post-understanding memory processes, rather than comprehension and semantic access. In contrast, the present MEG study revealed that in the first 150–250 ms after appearance of the “idiomatic key” in the string (the disambiguating *critical word*), specific brain regions, including temporal pole, dorsolateral prefrontal cortex and Broca's region, were differentially activated by idiomatic and literal sentences. Note that previous EEG studies have shown activations for idioms around 300–500 ms after critical word onset (Laurent et al., 2006; Proverbio et al., 2009). However, methodological issues such as the use of different tasks (i.e. semantic priming) and the choice of late time-windows for analysis (~320–550 ms and 500–780 ms) may explain the differences in the timings of activations with our study. We emphasise though that Proverbio et al. (2009) also found stronger brain response to idiomatic than to literal sentences in occipito-temporal regions around 250–300 ms and proposed that “there is direct access to the idiomatic meaning of figurative language, not dependent on the suppression of its literal meaning”. A study by Tartter et al. (2002) further provided evidence for activation differences between literal and metaphorical sentences already from 160 to 200 ms after critical word onset, thus suggesting that processing of figurative language recruits specific brain regions early in the course of sentence meaning computation. A range of recent studies revealed brain correlates of language comprehension at different psycholinguistic levels, thus supporting language understanding "in an instant" (for review, see Pulvermüller et al., 2009).

The stronger activation of the left temporal pole for idioms at short latency also seems in agreement with the importance of this region for semantic understanding and its crucial role in abstract meaning processing. It has indeed been proposed that the brain mechanisms for semantic circuits generalising over classes of objects and actions are located anterior and adjacent to action and object processing systems of the human brain, in prefrontal and anterior temporal cortices (see, for example, Patterson et al., 2007; Pulvermüller, 2008; Pulvermüller and Hauk, 2006). Category-specific semantic systems distributed over sensory and motor areas may therefore be complemented by centres for semantic processing, or "semantic hubs", mediating between modality-specific (sensory, motor and linguistic) brain regions and contributing to abstract meaning processing. A key finding supporting this position is that the most severe specific semantic deficit caused by brain dysfunction, the temporal variant of fronto-temporal dementia also known as Semantic Dementia, is characterised by atrophy and hypometabolism of the anterior temporal lobes associated with deficits in conceptual and semantic processing and crucially, a most severe difficulty to process abstract meanings (Snowden et al., 1989; Crutch and Warrington, 2006; Patterson et al., 2006; Jefferies et al., 2009; Pulvermüller et al., 2010; Hoffman and Lambon-Ralph, 2011; but see Yi et al., 2007; Macoir, 2009; Mattioli, 2008; Bonner et al., 2009; Papagno et al., 2009 for contrasting results regarding the so-called "reversed concreteness effect" in semantic dementia and herpes simplex encephalitis[3]). Theoretical approaches to the brain basis of abstract concepts therefore suggest that anterior temporal and possibly also prefrontal areas are most crucial for processing sentences with abstract meaning, idioms included. Consistent with this, our results, together with previous studies (Pulvermüller and Hauk, 2006; see also Binder et al. 2005 for abstract language processing), also showed strong activation to figurative language in dorsolateral and inferior prefrontal cortex, thus suggesting that both frontal and temporal areas play a role in semantic integration at abstract levels. Our present MEG results further show some activation in the angular gyrus (AG) but do not confirm an activation difference between idiomatic and literal sentence processing in that region (see Fig. 1; see Binder et al., 2009 for a discussion on the role of the angular gyrus in semantic processing). Note that previous fMRI findings (Boulenger et al., 2009; Romero-Lauro et al., 2007) showed that idiomatic sentences activated AG (along with other areas) more strongly than literal ones. The difference between the present results and these fMRI data may therefore either be caused by late activation escaping our present analysis, or the fMRI dynamics may be due to generators eliciting no or spurious MEG signals.

To our knowledge, the present study demonstrates for the first time using real-time imaging of neurophysiological activity that brain signatures of the computation of idiomatic meaning emerge at the very earliest stages of sentence processing, within 150–250 ms. At such short latencies, there is already remarkable spatiotemporal structure to the brain response: Following a trend towards stronger activation to literal sentences (which we do not give a strong interpretation here as the Idiomaticity contrast at 100–150 ms did not surpass the significance threshold), significant predominance of activity to figurative sentences emerged in anterior temporal areas and, in part, in dorsolateral prefrontal cortex; a somewhat delayed but similar dynamic pattern was present in Broca's area (IF). As a tentative suggestion, we propose that the temporally distinct activation patterns in temporal poles reflect the preliminary exploration of the semantic space of the incoming sentences, which is narrower for literal items, thus quickly converging on one interpretation, but more demanding and resource consuming – as a wider semantic space is being explored – for idioms. As the range of interpretations is wider for figurative sentences, anterior temporal and frontal activations may take longer and be more pronounced, until the stored semantic features of the whole idiomatic phrase can finally be accessed and integrated with meaning features of the words making up the sentence. Prefrontal cortex seems to follow this same dynamic pattern although with smaller activation. This convergence of cortical dynamics suggests that dorsolateral prefrontal and anterior temporal areas collaborate in the processing of idioms, possibly in linking the meaning of the whole form of the standardised parts of the idiomatic phrases (*grasp … idea*) to the very specific context-dependent meaning of these stored constructions (Goldberg, 2003; Lakoff, 1987). In parallel, semantic features of single words embedded in the sentences (over and above those of the critical words to which MEG responses were examined in detail) are processed, as documented by the differential activation in the motor system which was specific to the body-part reference of the preceding action words. Note that the present effects of sentence meaning (idiomatic/literal distinction) cannot be attributed to the "expectedness" or cloze probability of critical words, as materials had been matched for this variable. Corpus studies and a separate behavioural study of cloze probabilities looking at the tokens of the present experiment specifically supported this. Note furthermore that differential precentral activations were not elicited directly by the action words, which had occurred earlier in the sentences, on average 1.2 s ± 485 ms before critical word onset. Because of the substantial jitter between action and critical word presentations (SD = 485 ms), it is not possible that effects time-locked to the critical word onset and occurring at 150–250 ms after it were evoked by action words per se. Furthermore, any long-lasting tonic (> 1 s) neurophysiological effect of the action words per se would have been present already in the baseline before the critical word onset and would thus have been removed by the baseline correction applied. This absence of semantic somatotopy to the action words used in the present study was probably due to the fact that the same action words were used in different idiomatic and literal contexts, so that the well-known repetition effects (Dhond et al., 2005; Rugg, 1985) led to an attenuation of the fronto-central brain responses elicited by these words.

Early semantic somatotopy in idiom processing

The MEG activity elicited by the critical, sentence-disambiguating words can be related not only to the processing of these critical items themselves but, in addition, to the sentence comprehension process the critical times trigger. As aspects of the meaning of action words, namely their typical body-part relationships, were manifest in the brain response elicited by critical words, when the literal or idiomatic sentence meaning was being derived, these results are consistent with the position that referential semantic aspects of constituent action words were accessed *during* sentence meaning computation. More generally, the early motor activations to both idioms and literal sentences including action words concur with previous fMRI (Hauk et al., 2004; Kemmerer et al., 2008) and neurophysiological works (Hauk and Pulvermüller, 2004; Shtyrov et al., 2004) on concrete single action word processing, although we note that, in the present study, only sentences including arm verbs were seen to reliably recruit the arm motor region more strongly than the leg verb

[3] Results from neuroimaging studies are also controversial as while some studies reported specific activation for abstract words in the temporal poles usually affected in semantic dementia (Noppeney and Price, 2004; Binder et al., 2005; Sabsevitz et al., 2005; see also Pobric et al., 2009 for a rTMS study), others found greater activation in these regions for concrete words (Fiebach and Friederici, 2003; Grossman et al., 2002; Mellet et al., 1998; Whatmough et al., 2004).

sentences, whereas the opposite effect in the leg ROI fell short of reaching significance in the 50-ms time-window analysis. However, note that dSPMs maps and fine-grained analysis of temporal dynamics indicated such dissociations in the leg region too (Fig. 3, right panel). The present MEG results on local activation differences between both literal and idiomatic sentences containing arm vs. leg words also corroborate the spatial activation differences documented previously using fMRI (Boulenger et al., 2009), in spite of some divergence of results in the temporal domain (see discussion above). Here, we interpret these brain signatures of action words as an index of semantic access to constituent words embedded into idioms. Note that this interpretation does not require that the cell assemblies of action words ignite always in the same manner or that the core meaning of these words are being accessed whenever these items are used (for discussion, see Pulvermüller, 1999, 2003). In the positive case, semantic somatotopy can nevertheless be interpreted as an index of access to action-meaning. Also in line with our results and interpretation is the fMRI work by Saygin et al. (2010) who reported activity in area MT (in middle temporal cortex), involved in motion processing, for figurative sentences including motion verbs (see also Matlock, 2004), thus providing one more example that aspects of constituent word meaning are manifest in the brain response to abstract sentences.

Based on a recent semantic priming study, Fanari et al. (2010) argued that idiomatic meaning is available at the offset of short strings only when they are embedded in a context that biased figurative interpretation. One might therefore suggest that, since our idioms were mostly short and not preceded by biasing context, idiomatic meaning may not have been available at the point in time when critical words were presented, and that the activations observed, particularly in the precentral cortex, may therefore have resulted from the literal interpretation of (in principle idiomatic) sentences that include action verbs. Yet, given (i) the above-mentioned jitter between action words and critical words, (ii) the fact that our idioms were rated as having a figurative meaning compared to literal sentences (see Materials and methods), and (iii) the clear early neurophysiological idiomaticity effect, we believe that this alternative interpretation should be discarded. Again, we would like to call into attention that immediate strong neurophysiological differences were present between literal and idiomatic strings, thus providing neurophysiological evidence that a distinction between these otherwise matched string types has been made within the first 200 ms after presentation onset of the critical disambiguating word. The context of the experiment, in which a substantial percentage of stimulus sentences were in fact idioms, may certainly have prepared subjects that idioms might occur. We are aware that despite our efforts to get optimal material, our idioms were both ambiguous and non-ambiguous and while in some of them the critical word was the last word of the sentence, in others it was followed by a word or two, which may have slightly affected the results. However, given that (i) literal and idiomatic sentences only differed on the critical word, (ii) much effort was spent to match exactly psycholinguistic features (see Materials and methods), including sentence length and the number of items following, for example, the critical word, and (iii) idioms were rated as having a figurative meaning compared to literal sentences, the differential timing of cortical activation between the two types of sentences may be best explained by the idiomatic nature of the stimuli and not by the above-mentioned methodological features.

Relative time-course of idiomaticity and semantic somatotopy effects

An analysis of activation based on 50-ms wide time-windows revealed the first significant effects of idiomaticity contrasts in the 150–200 ms window and the first effect of semantic word type at 200–250 ms, suggesting an offset between brain processes of sentence comprehension and access to constituent word meanings. However, a more thorough analysis of the timing of activation revealed that the earliest neurophysiological differences related to semantic body-part reference of composite words and those related to the idiomatic status of the entire sentence both became first manifest statistically at 150–180 ms in precentral and anterior fronto-temporal areas, respectively. Further analyses indicated that these time-points of earliest divergence did not significantly differ between the idiomaticity and body-part contrasts. The absence of word semantics effects in precentral regions in the wide 150–200 ms window probably reflects the short-lived (~20 ms) nature of these effects already documented by earlier work (for example, Pulvermüller et al., 2005b) and confirmed by our in-depth analysis of temporal dynamics.

Altogether these findings lend support to embodied theories that view abstract semantics as grounded in the sensorimotor systems of the brain (Barsalou, 2008; Gallese and Lakoff, 2005; Pulvermüller, 2005; Pulvermüller and Fadiga, 2010). We note that it is difficult for “disembodied” theories (for discussion of such theories, see Mahon and Caramazza, 2005, 2008) to explain the early precentral activation emerging rapidly at the time when idiomatic sentence meaning can be understood, and especially the modulation of such motor system activation by the action-related meaning of words included in idioms. A full explanation of the present result pattern requires a sensorimotor semantic system extending into dorsal-stream precentral cortex, which contributes to referential semantics, and semantic processing areas in temporal pole and prefrontal cortex, which play a special role in storing non-compositional aspects of the meaning of constructions (see also Boulenger et al., 2009; Kiefer and Pulvermüller, 2011; Patterson et al., 2007; Pulvermüller et al., 2010). As some previous studies failed to show motor activation to abstract action-related single words or idioms (Raposo et al., 2009; Rüschemeyer et al., 2007), we consider our results as in need of further support, possibly paying special attention to the role of conditional probabilities of critical words in sentence contexts, a factor meticulously controlled in our present and previous studies, but not in some previous work.

Furthermore, our neurophysiological findings are consistent with simultaneous processing of compositional meaning, to which constituent words included even in idioms contribute, and of semantic access, in a non-compositional manner, to constructions stored as whole forms. We found that brain indexes of idiomatic meaning of constructions were present in anterior fronto-temporal cortex, in parallel with those of concrete motor schemata reflecting the meaning of sentence ingredients (action verbs) in motor systems. The processes of compositional meaning derivation and that of accessing idioms as stored abstract patterns may therefore occur together and potentially in parallel contribute to semantic analysis. Accordingly, our results sit comfortably with both constructional access and compositional-semantic, configurational hypotheses, implying that both the extreme views (either compositional processes-only *or* stored idiom-processing only) fall short of a full explanation of the present result pattern (see also Titone and Connine, 1999 for discussion).

Conclusions

We here demonstrate rapid brain embodied and symbolic processing of idioms, in which brain correlates of the action-related meaning of constituent parts of abstract sentences ignite within 150–250 ms after display of the critical element necessary for sentence understanding. Simultaneous with such indexes of semantic decomposition and word meaning processing, we document early emergence of anterior fronto-temporal amodal area activation distinguishing idiom processing from that of literal sentences. These neuroscience results shed light on the process of sentence comprehension, suggesting instantaneous retrieval of the meaning of whole abstract constructions (anterior fronto-temporal cortex) coloured by semantic features of their composite words (here, pre-central motor system).

Acknowledgments

We would like to thank Daniel Wakeman for his invaluable help with MEG data analysis and Clare Cook for performing the rating studies. In addition, we are grateful to Bert Cappelle, Max Garagnani and Adele Goldberg for valuable input, suggestions and discussion. This research was supported by a postdoctoral fellowship from the Fyssen Foundation to V.B., by the Medical Research Council, UK (U1055.04.003.00001.01, MC_US_A060_0034 to F.P, U1055.04.014.00001.01, MC_US_A060_0043 to Y.S.) and by the Free University of Berlin.

Appendix A. Supplementary data

Supplementary data to this article can be found online at doi:10.1016/j.neuroimage.2011.11.011.

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