

## An fMRI study of processing novel metaphoric sentences

N. Mashal

*Bar-Ilan University, and Tel Aviv Sourasky Medical Center, Israel*

M. Faust

*Bar-Ilan University, Israel*

T. Hendler

*Tel Aviv University, and Tel Aviv Sourasky Medical Center, Israel*

M. Jung-Beeman

*Northwestern University, Evanston, IL, USA*

Due to inconsistent findings, the role of the two cerebral hemispheres in processing metaphoric language is controversial. The present study examined the possibility that these inconsistent findings may be due, at least partly, to differences in the type (i.e., words vs sentences) or the familiarity of the linguistic material. Previous research has shown that novel two-word metaphoric expressions showed stronger activation in the right homologue of Wernicke's area for the novel metaphors than for both literal expressions and unrelated word pairs. In the present study fMRI was used to identify the left (LH) and the right hemisphere (RH) neural networks associated with processing unfamiliar, novel metaphoric sentences taken from poetry, as compared to those involved in processing familiar literal sentences and unfamiliar nonsensical sentences. Across participants, several left lateralised brain regions showed stronger activation for novel metaphoric sentences than for the nonsensical sentences although both types of sentence represent unfamiliar linguistic expressions. Moreover, the metaphoric sentences elicited more activation in the left dorsolateral prefrontal cortex and the posterior middle temporal gyri than did both the literal sentences and the nonsensical sentences. The increased activation in these brain regions might reflect the enhanced demand on the episodic and semantic memory systems in order to generate de-novo verbal semantic associations. The involvement of the left posterior middle temporal gyri could reflect extra reliance on classical brain structures devoted to sentence comprehension.

---

Address correspondence to: Nira Mashal PhD, Human Neuroscience Laboratory, Department of Neurology, The University of Chicago, 5841 S. Maryland Avenue, MC-2030, Chicago, IL 60637, USA. E-mail: nmashal@uchicago.edu

Support for this work was provided by a grant from US-Israel binational science foundation (BSF, grant # 2003317) to Faust and Jung-Beeman. We would like to thank Chen Kleinman for the useful assistance in preparing the linguistic stimuli.

Although the right hemisphere (RH) involvement in metaphor comprehension has been the focus of much research, findings with regard to this issue are contradictory (for a review, see Mashal, Faust, & Hendler, 2005). Since metaphoric language may involve the use of both previously acquired familiar and newly created unfamiliar words and sentences (Cacciari & Glucksberg, 1994), the inconsistent findings may be due, at least in part, to differences in the familiarity level of the metaphors used.

The effect of the familiarity level of the linguistic stimuli is demonstrated in a behavioural study that used the divided visual field paradigm (Schmidt, DeBuse, & Seger, 2007). Schmidt et al. found a RH advantage for unfamiliar sentences containing distant semantic relationships, and a LH advantage for familiar sentences containing close semantic relationships, regardless of whether sentences were metaphorical or literal. In particular, Schmidt et al. found an RH processing advantage for less familiar metaphors (*Rain clouds are pregnant ghosts*) but an LH processing advantage for highly familiar metaphors (*babies are angels*). These results are in accordance with results obtained from Bottini et al.'s study (1994) that used the PET brain-imaging technique to study the processing of metaphoric and literal sentences. Bottini et al. reported more RH involvement when participants had to make plausibility judgements for new metaphoric sentences as compared to literal sentences. Significant greater activation for new metaphoric sentences was found in the right lateralised brain areas including the inferior temporal gyrus, right premotor cortex, and the right homologue of Wernicke's area. A recent fMRI study (Eviatar & Just, 2006) also showed that the novelty of the linguistic stimuli affects hemisphere involvement. In this study, novel ironic statements elicited higher activation in right posterior superior temporal gyrus as compared with literal sentences but familiar metaphoric sentences elicited higher activation in left IFG as well as bilateral inferior temporal cortex as compared with literal sentences.

Additional support for the claim that the familiarity level of metaphoric stimuli is a critical factor in determining hemispheric processing comes from a recent fMRI study (Mashal et al., 2005; Mashal, Faust, Hendler, & Jung-Beeman, 2007). This study used two-word expressions to investigate hemispheric processing of familiar and unfamiliar metaphoric and literal language. In this investigation literal familiar expressions were represented by meaningful word pairs (i.e., *loyal friend*), literal unfamiliar word pairs were represented by unrelated word pairs (i.e., *laundry moon*), familiar metaphoric expressions were represented by conventional metaphors (e.g., *iron fist*), and unfamiliar metaphoric expressions were represented by novel metaphoric expressions taken from poetry (e.g., *caged cry*). Mashal et al. found that processing novel metaphoric word pairs recruits a special network consisting of the right homologue of Wernicke's area, Broca's area, left and right insula, and left and right premotor areas. When

participants processed novel metaphoric expressions as compared to conventional metaphors, significant activation was found at right posterior superior temporal sulcus (PSTS), right inferior frontal gyrus (IFG), and left middle frontal gyrus (MFG). Following these results, a divided visual field study that used two types of unfamiliar word combinations, novel metaphoric two-word expressions, and unrelated word pairs was conducted (Mashal & Faust, 2008). Participants were presented with the stimuli and were asked to decide whether the second word of each word pairs (which was presented to the right or to the left visual field) forms a meaningful expression with the first word (which was centrally presented). Using the signal detection model, the sensitivity of each hemisphere, i.e., the ability to discriminate between signal and noise, was calculated. "Signal" was represented by the unfamiliar metaphoric expressions whereas "noise" was represented by the unrelated word pairs. Thus, sensitivity referred to the ability to discriminate unfamiliar meaningful from unfamiliar meaningless expressions. It has been shown that, compared with the LH, the RH is more sensitive to novel metaphoric expressions, beyond the tendency of the participants to respond that an unfamiliar expression is meaningful.

These results point to the special role of the RH in processing distant word meanings (Anaki, Faust, & Kravetz, 1998; Beeman, 1998; Faust & Lavidor, 2003; Faust & Mashal, 2007; Jung-Beeman et al., 2004; Mashal & Faust, 2008; Mashal et al., 2005, 2007). The findings of these studies suggest an enhanced role for the RH in the comprehension of distantly related or unfamiliar metaphoric word pairs, which is related to the unique ability of the RH to maintain activation of distantly related meanings. This interpretation is consistent with the fine-coarse semantic coding theory (Beeman, 1998), suggesting that while the LH fine semantic coding has a clear advantage for most linguistic processes, the RH coarse semantic coding is critical when consideration of more than one plausible meaning or the sustained activation of a wide range of word meanings is required. The fine-coarse semantic coding theory (Beeman, 1998) corroborates with the graded salience hypothesis (GSH, Giora, 1997, 2003), postulating that nonsalient meanings, i.e., meanings that are not coded in the mental lexicon be they literal or metaphorical, will be processed by the RH cognitive mechanisms. According to the GSH, the familiarity level of the linguistic stimuli is the factor that determines the salience level of the stimuli more than other factors (conventionality, prototypicality, and frequency). The salient meaning of a linguistic expression refers to its familiar meaning, i.e., a meaning that is prominent, coded in the mental lexicon, and more accessible than the less salient one. For example the metaphoric meaning of a conventional metaphor (e.g., *iron fist*) is more salient (i.e., familiar, and more accessible) than its literal interpretation (e.g., a fist made of iron). The integration of the coarse semantic coding theory with the GSH implies that while salient,

closely related meanings are processed mainly by the LH, the RH activates and maintains nonsalient meanings.

However, some recent fMRI studies demonstrated an LH advantage regardless of the familiarity of the metaphorical sentences (Rapp, Leube, Erb, Grodd, & Kircher, 2004; Stringaris, Medford, Giampetro, Brammer, & David, 2007) or bilateral pattern of hemispheric activation (Ahrens et al., 2007). Ahrens et al. (2007) found different neural correlates for the processing of literal and both conventional and novel-anomalous metaphoric sentences. Processing novel metaphoric (“Their capital has a lot of rhythm”) compared with literal sentences (“He studied in the library the whole day”) increased activation in the frontal and temporal gyri bilaterally. The comparison between the novel and conventional metaphoric (“The framework of this theory is very loose”) sentences elicited activation in the left fusiform gyrus and left IFG, as well as bilateral activation in the middle frontal gyrus and precentral gyrus. RH activation for this contrast was found in the superior frontal gyrus and the inferior occipital gyrus. Rapp et al. (2004) used novel metaphorical (“the lover’s words are harp sounds”) and literal (“the lover’s words are lies”) sentences, and found stronger activation for the metaphorical sentences in the triangular and the opercular part of the left inferior frontal gyrus (IFG) and left temporal pole, but no significant differences in the RH homologues.

Thus, although according to Rapp et al. (2004) only the LH is recruited for the processing of novel metaphorical sentences, or conventional metaphoric sentences (Stringaris et al., 2007), Ahrens et al.’s (2007) results suggest that both hemispheres play a role in comprehending unfamiliar metaphoric sentences. Thus, the role of the RH in processing novel metaphoric sentences is still not fully understood.

Results obtained from studies with brain-damaged patients also yielded conflicting results. In two studies with left hemisphere damaged (LHD) and right hemisphere damaged (RHD) patients, findings suggested some dissociation between visuo-verbal and verbal tests of metaphor processing. In both studies participants listened to sentences containing conventional metaphoric expressions (i.e., *a heavy heart can really make a difference*) and were presented with four pictures that were related either to the metaphoric or the literal meaning of the sentences, or to a single word in the sentence. In the visuo-verbal task, the patients were asked to point to the picture that best represented the meaning of the sentence. RHD patients preferred the pictures related to the literal meaning of the sentence to those related to the metaphoric interpretation. However, they were able to explain verbally the metaphoric meaning of the sentences (Rinaldi et al., 2004; Winner & Gardner, 1977). This traditional view, that the RH plays a central role in metaphoric processing, was challenged by recent studies with brain-damaged patients. Findings of other studies (Zaidel, Kasher, Soroker, & Batori, 2002)

failed to support the claim that the RH has a unique role in metaphor processing. In one of these studies (Giora, Zaidel, Soroker, Batori, & Kasher, 2000), a large sample of RHD and LHD patients were presented with conventional metaphors (e.g., “broken heart”) with no plausible literal meaning, and were asked to provide oral verbal explanations. RHD patients did not show a selective bias towards the literal interpretation.

Hemispheric interaction during language comprehension may be affected not only by the metaphoricity or familiarity of the linguistic stimuli (metaphoric vs literal; familiar vs unfamiliar), but also by level of linguistic expression. Thus, a single word, two-word expressions, word triads, sentences, or discourse may show different patterns of hemispheric dominance (for reviews, see Chiarello, 2003; Faust, 1998) since each of these contexts supports a different, increasingly complex level of semantic representation. Thus, although findings on the neural correlates of metaphor processing at the word level generally support the view that the RH is involved when unfamiliar metaphoric word-level combinations are accessed (Anaki et al., 1998; Faust & Mashal, 2007; Mashal & Faust, 2008; Mashal et al., 2005, 2007), studies that looked at hemispheric differences for language processing at the sentence level tend to show a LH advantage (for reviews, see Chiarello, 2003; Faust, 1998). Sentence processing necessarily involves the syntactic combination and modification of word meanings to yield a higher level meaning representation. This process seems to be heavily dependent on A LH message-level processing mechanisms, although recent studies have shown some message-level processing in the RH too (e.g., Faust, Bar-Lev & Chiarello, 2003; Chiarello, 2003; Faust, 1998; St. George, Kutas, Martinez, & Sereno, 1999). Previous sentence priming research (for reviews, see Chiarello, 2003; Faust, 1998) indicates that different mechanisms are responsible for sentence context effects on word recognition in the two hemispheres. Thus, during sentence comprehension, the LH uses both word-level and message-level processing mechanisms, whereas the RH relies mainly on intralexical-level information, i.e., information that is based on the semantic relations between single words appearing in the sentences. In addition, it appears that the RH can use intralexical-level processing mechanisms without being constrained by the structural and conceptual restrictions imposed by the sentence message level. On the one hand, this unique ability could potentially be advantageous for the flexible, multifaceted processing of unfamiliar word combinations such as novel metaphoric two-word expressions both in isolation and when embedded in a larger sentence context. On the other hand, the comprehension of unusual lexical combinations within a sentence may require the LH message-level mechanisms. This is because the unfamiliar lexical information must be interpreted in a way that is consistent with the whole sentence message and become part of an integrated meaning representation for the

entire sentence. Thus, the extent to which the LH and the RH are involved in processing sentences that contain unfamiliar metaphoric word combinations, such as those taken from poetry, is still a relatively open question.

The current study was motivated by our previous findings (Mashal et al., 2005, 2007), which showed higher activation for the novel two-word metaphoric expressions than for both the unrelated word pairs and the literal two-word expressions in the right homologue of Wernicke's area. The present study used the fMRI technique to examine whether the above findings with regard to word pairs generalise to sentences. Specifically, it compared brain activation for unfamiliar metaphorical sentences taken from poetry (i.e., "My mother was a silence lock") both to familiar literal sentences (i.e., "My brother was a loyal friend") and unfamiliar nonsensical sentences (i.e., "My dog was a happy pencil"). Thus, the novel metaphoric, literal, and nonsensical sentences of the current study replace the novel metaphoric, literal, and unrelated two-word expressions of Mashal et al.'s study (2005, 2007). If the RH advantage in processing unfamiliar metaphoric meanings extends to sentences, then the comparison between the two types of unfamiliar sentences (i.e., the novel metaphors and the nonsensical sentences) is expected to show stronger activation for the novel metaphoric than for the nonsensical sentences in RH areas, specifically in the right homologue of Wernicke's area. To the best of our knowledge, none of the neuroimaging studies using metaphoric stimuli compared brain activation patterns for unfamiliar metaphorical sentences with unfamiliar nonsensical sentences (for a summary of findings from previous hemispheric studies of metaphor processing, see Kacinik & Chiarello, 2007).

An alternative hypothesis concerning the involvement of the RH and the LH neural networks in the processing of novel metaphoric sentences was derived from the classical view that sentence processing is heavily dependent on the LH (e.g., Capek et al., 2004; Caplan, 2001; Cutting et al., 2006; Faust, 1998; Just, Carpenter, Keller, Eddy, & Thulborn, 1996; Kang, Constable, Gore, & Avrutin, 1999; Ni et al., 2000) regardless of sentence familiarity and metaphoricity. According to this hypothesis, an exclusive reliance on the LH, especially at the left inferior frontal gyrus (IFG), superior/middle temporal gyrus (STG/MTG), and the inferior parietal lobule for all types of sentences, was predicted.

## METHOD

### Participants

A total of 15 neurologically normal participants (nine male), who were right-handed (yielding a laterality quotient of at least +80 on the Edinburgh Inventory, Oldfield, 1971) and all native Hebrew speaking, took part in the

study. Mean age was 25 (*SD* 2.3, range: 22–28) years. The study protocol was approved by the Tel-Aviv Medical Center Human Science Ethics Committee. All participants received a detailed explanation of the study and gave written informed consent. Participants were paid for their participation.

## Experimental stimuli

A total of 25 four-word Hebrew sentence triads served as stimuli (i.e., 75 sentences). Each triad contained one novel metaphoric (NM) sentence taken from original Hebrew poetry, a literal (LIT) sentence, and a nonsensical (NS) sentence (see Appendix). By metaphoric sentence we mean a sentence that could not be understood via word-by-word analysis but instead by grasping its figurative meaning. Our metaphoric sentences included metaphoric phrases where the two words comprising the phrase were either adjacent (e.g., “moon ripens” in “The moon ripens the tree’s branches”) or separated (e.g., “time leaves” in “Time does not leave a testament”). Sentences were matched for syntactic structure according to the metaphoric sentence. The matching (literal and nonsensical) sentences were constructed so that they contained the same parts of speech (i.e., verb, adjective, adverb, noun) in the same order. In addition, the literal and the nonsensical sentences were built in a way that every concrete/abstract word in the NM sentence was replaced by a matching concrete/abstract word. Poetical sentences were selected as stimuli if they could be judged as having a negative or a positive meaning (as will be described below).

A total of 19 judges, who did not participate in the study, were asked to rate 111 sentences for the understandability, familiarity, imageability, and metaphoricity on scales ranging from 1 to 5 (1 = low, 5 = high), and the related content (positive or negative sense) from which 75 sentences were chosen as stimuli for the experiment (Table 1). All 75 sentences were within 1 standard deviation from the mean on the imageability rating scale (for the use of this method, see Stringaris et al., 2007). As expected, metaphorical sentences were 1 SD above the mean on the metaphoricity rating scale. Nonsensical sentences were 1 SD below the mean on the understandability rating scale. Literal sentences were 1 SD above the mean on the familiarity scale.

In addition, one-way ANOVA with the three types of sentences was performed for metaphoricity,  $F(2, 48) = 113.58, p < .001$ , understandability,  $F(2, 48) = 73.11, p < .001$ , imageability,  $F(2, 48) = 92.34, p < .001$ , and familiarity,  $F(2, 48) = 156.18, p < .001$ . Metaphoric sentences were rated as more metaphoric than both LIT and NS sentences ( $p < .001, p < .001$ , respectively), less understandable than the LIT sentences ( $p < .001$ ) but more understandable than NS ( $p < .001$ ), less imaginable than LIT ( $p < .001$ ) but

TABLE 1  
Pretest scoring

<i>Type of sentence</i>	<i>Metaphoricity</i>	<i>Understandability</i>	<i>Familiarity</i>	<i>Imageability</i>
LIT	2.03	4.82	3.76*	4.27
NM	4.24*	3.88	2.02	3.32
NS	2.76	1.60*	1.38	1.85
Mean ( <i>SD</i> )	3.01 (1.11)	3.43(1.47)	2.39 (1.14)	3.15 (1.53)

Pretest scoring of the literal sentences (LIT), novel metaphoric sentences (NM), and nonsensical sentences (NS) in the metaphoricity, understandability, familiarity, and imageability scale (1–5). Last row summarises the overall average and *SD*. \* = 1 *SD* scoring below or above the total average.

more imaginable than NS ( $p < .001$ ), and less familiar than LIT ( $p < .001$ ) but more familiar than NS ( $p < .001$ ).

Sentences were also rated on the valence scale (1 = very negative meaning, 5 = very positive meaning). Sentences with valence ratings between 2.75 and 3.25 (i.e., valence of  $3 \pm 0.25$ ) were excluded in order to avoid neutral meaning and hence delayed response times for the task. The mean valence was 2.99, 2.92, 2.95 for the literal sentences, metaphorical sentences, and nonsensical sentences, respectively (i.e., balanced positive and negative contents). For example, the literal sentence “Flowers wilted in the garden’s flowerbed” was rated as a sentence with negative meaning (2.26 on the valence scale), whereas the novel metaphoric sentence “The sunrise wears the trees’ veil” was rated as a sentence with positive meaning (3.5 on the valence scale).

Experimental conditions were also matched for word frequency, using an Internet database (<http://word-freq.mscc.huji.ac.il/index.html>) for Hebrew words.

## Experimental design

In this study we used a block design and the experimental task included silent reading of four word sentences followed by a semantic judgement task. Participants were instructed to read each presented sentence silently and decide as quickly as possible whether they thought the sentence had a positive or a negative meaning. In order to ensure that participants read the sentences and were trying to comprehend them, they were asked to indicate their decision by pressing one of two response buttons. They were told that although some of the sentences were nonsensical they could still assign them positive or negative meaning. For example, although the sentence “The swimmer glides the keyboard’s sea” is nonsensical, it induces a positive



meaning (“swimmer” and “sea” may induce a positive connotation and hence a positive meaning), whereas the sentence “Foliage does not hurry nonsense” induces a negative meaning (“not” and “nonsense” induce a negative meaning). The participants were told that there is no right or wrong answer and that we were interested in their subjective judgement. For this reason accuracy rate was not measured.

Block design fMRI experiments have the power to detect haemodynamic changes occurring in response to extended durations of repeated cognitive processes, in comparison to a “baseline” block, thus allowing the haemodynamic response and associated BOLD signal to saturate. A significant disadvantage of block design is that the task and, in some cases, expected response are predictable, and thus prone to potential confounds such as anticipation or other strategies. However, in the present study the responses were not predictable (trials requiring “yes” and “no” responses were randomly intermixed within each block); moreover, there were no reaction time (RT) trends either within or across blocks. The use of an implicit rather than explicit task (e.g., semantic judgement) during scanning not only prevents participants from developing strategic responses but also prevents the induction of additional executive processes. It has been shown that using explicit as opposed to implicit task activates more left inferior frontal gyrus (e.g., Hasson, Nusbaum, & Small, 2006; Suzuki & Sakai, 2003). In addition, in a debriefing session following the experiment, all participants reported that they fully cooperated in performing the task (deciding if the sentence has a positive or negative meaning) as required, and were surprised to hear that some of the sentences were taken from poetry, thus indicating that the participants were concentrating on the task and not on the type of the sentence.

The experiment started with 2000-ms instruction screen. Each block (duration 22 s) contained 5 sentences with 5 blocks for each condition, resulting in 15 blocks, separated by 14 s of fixation (baseline), a total of 284 volumes acquired over a period of 9 minutes and 28 seconds. Each sentence was presented for 2200 ms followed by 2200-ms fixation. The 2200-ms presentation duration for each sentence was selected in order to avoid synchronisation between the start time of volume acquisition ( $TR = 2$  s) and stimuli presentation. Sentences were presented using Presentation software (Neurobehavioural Systems, Inc; <http://nbs.neuro-bs.com>), and projected via an LCD projector (EPSON MP 7200) onto a translucent tangent screen located on the head coil in front of the participant’s eyes. All sentences were presented in black uppercase Arial font on a grey background.

Participants were trained prior to performing the fMRI experiment with sentences not included in the online study. They were told that some sentences might be meaningless.

## Image acquisition

Imaging measurements were performed on a 3T GE G3 scanner (GE, Milwaukee, WI, USA) located at the Wohl Institute for Advanced Imaging in the Tel-Aviv Sourasky Medical Center. All images were acquired using standard quadrature head coil. A 3D T1 SPGR sequence was performed in order to allow for a volume statistical analysis of signal changes during the experiment and to facilitate later coordinate determinations. Acquisition parameters for the SPGR were: TR/TE = 30/3 ms, flip angle of  $12^\circ$  with resolution of  $0.97 \times 0.97 \times 1 \text{ mm}^3$ .

The Functional T2\*-weighted images were acquired using gradient echo echo-planar imaging pulse sequence (TR/TE/flip angle = 2000/35/90) with FOV of  $200 \times 200 \text{ mm}^2$ , and acquisition matrix dimensions of  $64 \times 64$ . A total of 29 contiguous axial slices with 3.5 mm thickness and 0 mm gap were prescribed, based on a sagittal localiser, covering the whole brain.

## Data analysis

fMRI data were processed by applying the BrainVoyager software package (version 4.9; Brain Innovation, Maastricht, The Netherlands). Prior to statistical tests, raw data were examined for motion and signal artefacts. Preprocessing included 3D motion correction, linear trend removal, and high pass filtering (filtering out the lowest three frequencies). The first nine functional volumes (i.e., 18 s), before signal stabilisation, were excluded from analysis. Functional images were then superimposed on 2D anatomical images, and incorporated into 3D data sets through trilinear interpolation. The complete data set was transformed into Talaraich space (Talaraich & Tournoux, 1988).

Functional analysis was performed for each participant using a general linear model GLM (Friston et al., 1995). Task-related activation was defined in correlation to predictors of the used protocol. To account for a haemodynamic response, predictors were shifted with lag of 6 s. This shift was selected to result in maximised correlation between individual blood oxygen level dependent (BOLD) signal intensity time course and predictors. Voxel-wise t-maps were constructed for each of the participants as a first-level analysis and then carried to a second-level analysis to test for significant group effects using the random effects model. This two-level strategy takes into account the inter-participant variance (as opposed to inter-scan variance) in order to provide a better estimation for the average activation of a given population (Holmes & Friston, 1998). Whole-brain random effects analysis was applied to the GLM of the group of our participants. Two contrasts were performed: novel metaphoric sentences vs

nonsensical sentences (i.e., NM > NS) and novel metaphoric sentences vs literal sentences (i.e., NM > LIT). In addition, in order to depict brain activation specifically associated with processing novel metaphoric sentences more than literal and nonsensical sentences, a conjunction analysis was performed: novel metaphoric sentences > nonsensical sentences AND novel metaphoric sentences > literal sentences ( $p < .05$ , uncorrected). Voxels demonstrating significant effect were further analysed using individual parameter estimates (beta weights). The parameter estimates are derived from the linear model of the study:

$$Y(t) = \beta_1 X_1(t) + \beta_2 X_2(t) + \beta_3 X_3(t) + c + e$$

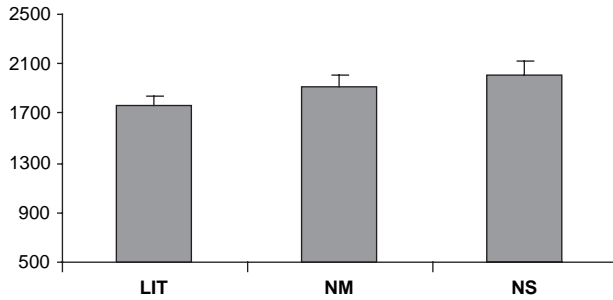
where  $Y(t)$  is a time-dependent vector of intensity values of the data,  $X_1(t)$ ,  $X_2(t)$ ,  $X_3(t)$  are the three different model waveforms corresponding to the NM, LIT, and NS time-courses respectively,  $\beta_1$ ,  $\beta_2$ , and  $\beta_3$  are the corresponding parameter estimate for  $X_1(t)$ ,  $X_2(t)$ , and  $X_3(t)$ , respectively,  $c$  is a constant that corresponds to the baseline intensity value in the data, and  $e$  is the error in the model fitting. Thus, a large  $\beta_1$  value indicates that a particular voxel responds more strongly to model  $X_1$  (i.e., to the time course of the NM condition) than the other models (i.e., time course of the LIT and NS condition), etc. Analysis of the parameter estimates was performed using STATISTICA software (version 5).

## RESULTS

### Behavioural results

The participant's behavioural performance was recorded via Presentation. Figure 1 shows the overall reaction time for each condition (novel metaphoric sentences = NM, nonsensical sentences = NS, and literal sentences = LIT). Repeated measures ANOVA for RTs measures were found to be statistically different from each other,  $F(2, 28) = 18.04$ ,  $p < .001$ , with participants showing the shortest RTs to LIT, and the longest RTs to NS.

We also tested response patterns for each block, separately for each condition, to rule out the possibility that participants anticipated the nature of the sentences in each block. Each block comprised five sentences from the same type. Some of the sentences had positive meaning and some had negative meaning (as was determined in a pretest). For each participant the average RT for each of the five blocks was calculated. Then a one-way repeated-measures ANOVA, with block as the independent variable, was performed. For the NM blocks, no significant differences were found ( $p > .3$ ). For the LIT and the NS blocks,  $p$  was marginally significant ( $p > .08$  and  $p > .06$ , respectively). Thus, Tukey LSD post-hoc analysis was performed. The results indicated that the third block of the LIT condition



**Figure 1.** Reaction times (RTs) and *SE* of 15 participants for the literal sentences (LIT), novel metaphorical sentences (NM), and nonsensical sentences (NS). Tukey HSD post hoc analysis revealed faster RTs for LIT than both NM ( $p < .01$ ) and NS ( $p < .001$ ), and faster responses for NM than NS ( $p < .05$ ). Error bars denote standard error.

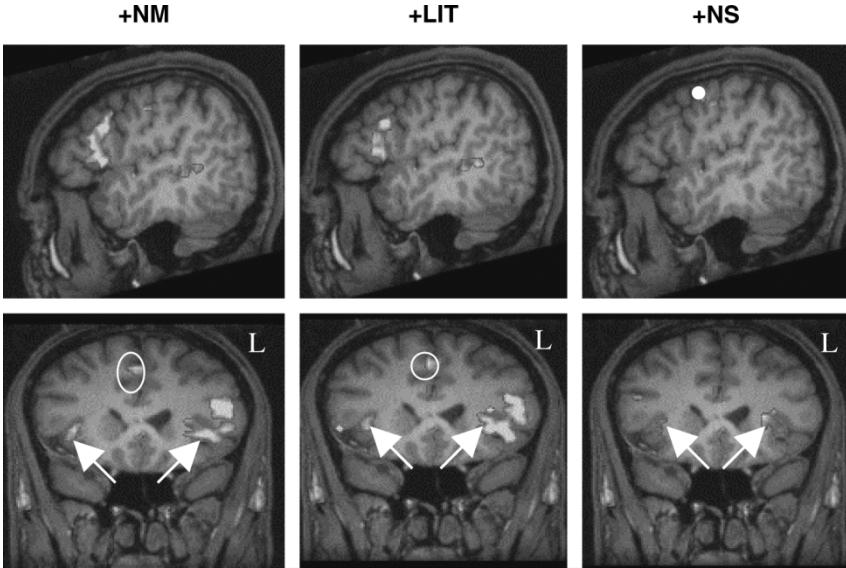
was faster than the last (fifth) block ( $p < .05$ ). For the NS blocks, Tukey LSD post-hoc analysis revealed that the fourth block was faster than the first and the second blocks but was slower than the last block ( $p < .05$ ). Those results, together with the fact that participants were surprised to hear after completing the experiment that some of the sentences were metaphorical, suggest that participants were not aware to the sentence types.

## fMRI results

Each experimental condition was compared to baseline (fixation) using the random effect model for the group of the 15 participants at the level of  $p < .0001$ , uncorrected (Figure 2). Similar clusters of activation were observed for the NM and the LIT in left MFG, middle temporal gyrus (MTG), left and right insula, left inferior frontal gyrus (IFG), and the supplementary motor area. NS showed weaker activation in those brain areas as compared with both NM and LIT. In order to study more precisely the differences between NM and both LIT and NS, two individual contrasts (NM > NS and NM > LIT) were performed.

Using the random effect model for the group of the 15 participants, the contrast NM > NS elicited significant activation in four left-brain regions ( $p < .001$ , uncorrected): angular gyrus; anterior MTG; posterior middle MTG; and posterior cingulate gyrus extended to the precuneus (Table 2).

Repeated measures ANOVA for the fMRI parameter estimates revealed significant main effect in the angular gyrus,  $F(2, 28) = 57.48$ ,  $p < .001$ , anterior MTG,  $F(2, 28) = 7.4$ ,  $p < .01$ , posterior MTG,  $F(2, 28) = 18.52$ ,  $p < .0001$ , and cingulated gyrus/ precuneus,  $F(2, 28) = 74.33$ ,  $p < .001$ . Tukey HSD post hoc analysis revealed significant stronger activation for NM and



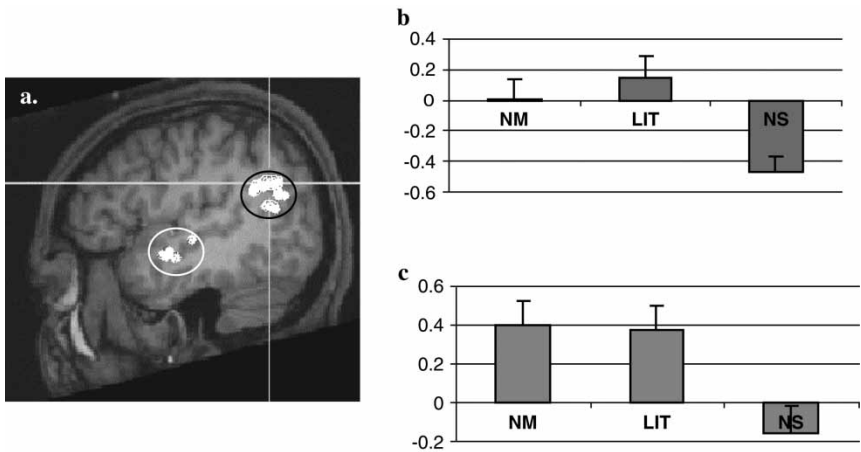
**Figure 2.** Activation maps of random effect analysis obtained from 15 participants ( $p < .0001$  uncorrected;  $t > 6$ ), showing significant activation for the contrast novel metaphoric sentences (+NM; first column), literal sentences (+LIT; second column), and nonsensical sentences (+NS; third column) vs baseline. First row shows sagittal section of two clusters in LH (IFG/MFG and MTG). Second row shows coronal section of the left and right insula (white arrow), left IFG (black arrow), and the supplementary motor area (white circle).

LIT than NS in the angular gyrus ( $p < .001$ ,  $p < .001$ ; respectively) and in anterior MTG ( $p < .01$ ,  $p < .01$ ; respectively). Parameter estimates and Talaraich coordinates for the centre of activations are demonstrated in Figure 3. Tukey HSD post hoc analysis revealed significant stronger

TABLE 2  
Whole brain analysis

	BA	x	y	z	Cluster size
<i>NM &gt; NS</i>					
Angular gyrus	39	-47	-59	25	280
Anterior middle temporal gyrus	21	-46	-6	-10	250
Posterior middle temporal gyrus	21	-54	-41	-1	236
Posterior cingulate Gyrus/precuneus	31	-10	-50	29	280
<i>NM &gt; LIT</i>					
Middle frontal gyrus	9/46	-44	18	30	332

Whole Brain Analysis for the two contrasts that are significant at  $p < .001$ , uncorrected. NM = novel metaphoric sentences; NS = nonsensical sentences; LIT = literal sentences. BA = Brodmann area. x, y, z = the centre of the activation in Talaraich coordinates (Talairach & Tournoux, 1988).

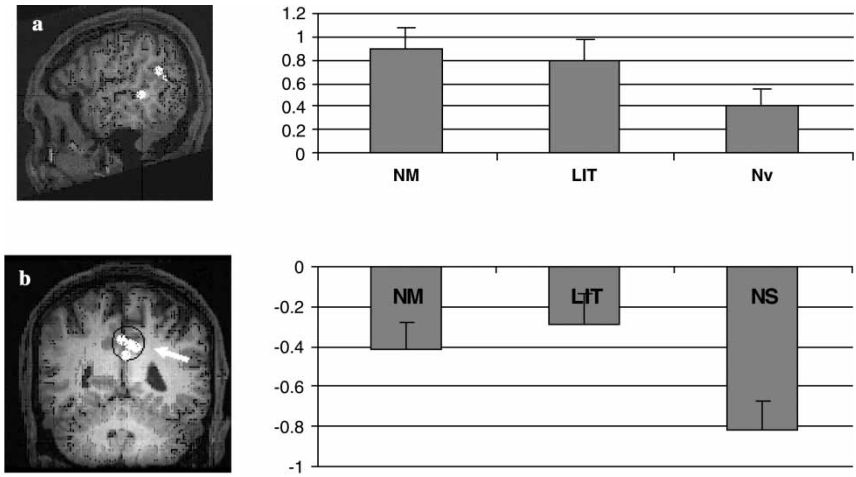


**Figure 3.** (a) Statistical parametric map of NM > NS ( $p < .001$  uncorrected;  $t > 4.4$ ) in the left angular gyrus (black circle) and anterior middle temporal lobe (white circle). (b) Mean parameter estimates of activation in the left angular gyrus. (c) Mean parameter estimates of activation in anterior temporal lobe. Error bars denote standard error. NM = novel metaphoric sentences; NS = nonsensical sentences; LIT = literal sentences.

activation in posterior middle temporal gyrus for NM and LIT than for NS ( $p < .001$ ;  $p < .001$ ; respectively) (Figure 4a). Beta weights in posterior cingulate gyrus/precuneus were found negative in the three conditions (i.e., deactivation compared with rest). Tukey HSD post hoc analysis indicates that parameters estimates of the NS were significantly more negative than both NM ( $p < .001$ ) and LIT ( $p < .001$ ) (Figure 4b).

The contrast NM > LIT ( $p < .001$ , uncorrected) elicited significant activation in left middle frontal gyrus (MFG). Repeated measures ANOVA for the beta estimates revealed a significant main effect,  $F(2, 28) = 4.9$ ,  $p < .05$ . Tukey HSD post hoc analysis revealed significantly stronger activation for the NM compared to LIT in the MFG ( $p < .05$ ) (Figure 5).

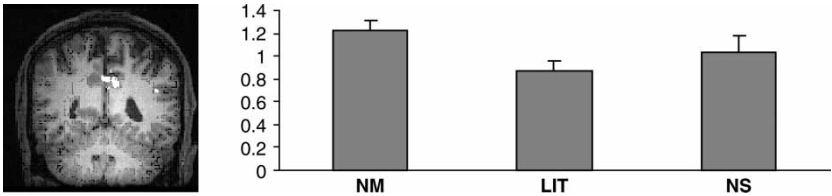
The conjunction analysis of NM > NS and NM > LIT did not reveal significant activation at the level of  $p < .001$  (as applied for the separate contrasts). Since conjunction analyses find out the overlapping regions among a set of contrasts, it is more difficult to obtain activation at the level of the individual contrasts. However, when we examined the data using a more lenient threshold of  $p < .05$ , significant activation was found in left MFG—BA 9; centre of activation at  $(-40, 14, 27)$  Talaraich coordinates; 245 voxels—and left posterior MTG—BA 21;  $(-54, -44, 2)$ ; 177 voxels. These areas overlap with the brain regions that were found in the separate contrasts NM > NS and NM > LIT.



**Figure 4.** Statistical parametric maps (left) ( $p < .001$  uncorrected;  $t > 4.4$ ) and mean parameter estimates of activation (right) for the contrast NM > NS in (a) left posterior middle temporal gyrus (white circle) and (b) left posterior cingulate gyrus extended to the precuneus (black circle). Error bars denote standard error. NM = novel metaphoric sentences; NS = nonsensical sentences; LIT = literal sentences.

**Covariate analysis**

Since RTs were significantly different between conditions, we performed a secondary functional analysis with RT as a covariate in order to test whether the sentence type differences would persist. Repeated measures ANCOVA for the fMRI parameter estimates was performed in each of the brain regions that showed a significant difference in the ANOVA (MFG; angular gyrus; anterior MTG; posterior MTG; and posterior cingulate gyrus extended to the precuneus). Results indicate that those regions still show significant differences between the conditions, suggesting that the correlation between the signal change and the RTs is not a potential source of bias (variability of the beta weights, which is attributable to the RTs). These



**Figure 5.** Statistical parametric map of the contrast NM > LIT ( $p < .001$  uncorrected;  $t > 4.4$ ) and mean parameter estimates of activation in middle frontal gyrus (white circle). Error bars denote standard error. NM = novel metaphoric sentences; NS = nonsensical sentences; LIT = literal sentences.

results are in line with the finding that although it took longer to process the UR than both the NM and LIT, NS did not elicit higher activation anywhere in the brain than both NM and LIT.

## DISCUSSION

The present study used the fMRI technique to identify the cortical systems recruited for the processing of novel metaphoric sentences taken from poetry. Previous behavioural and neuroimaging research revealed unique RH involvement in processing novel metaphoric two-word expressions (Faust & Mashal, 2007; Mashal & Faust, 2008; Mashal et al., 2005, 2007). The present study tested whether this RH advantage generalises to sentences. Specifically, it compared brain activation for unfamiliar metaphorical sentences taken from poetry to both familiar literal sentences and unfamiliar nonsensical sentences. The few studies that investigated the brain mechanisms involved in the processing of metaphoric sentences have yielded conflicting results. Whereas one study showed an LH involvement in the processing of novel metaphoric sentences (Rapp et al., 2004), the findings of other studies suggest either that both hemispheres or mainly the RH are recruited for the processing of these sentences (Ahrens et al., 2007; Bottini et al., 1994; Schmidt et al., 2007). Thus, two alternative hypotheses were tested. According to one hypothesis, exclusive reliance on the LH for the comprehension of all types of sentences was expected, whereas according to the alternative hypothesis, in addition to the LH involvement, the RH should also contribute to the processing of novel metaphoric sentences. The findings of the present study support the predictions of the first hypothesis, indicating that the comprehension of unfamiliar metaphorical sentences relies on a LH processing mechanisms.

Two important findings emerged from the present study. Most prominent is the observation that while the neural networks involved in the processing of literal and novel metaphorical sentences overlap, there is an enhanced activation in the left MFG and the MTG for the processing of novel metaphoric sentences. The second main finding is that although both the novel metaphoric sentences and the nonsensical sentences consisted of novel combinations of words (Table 1), brain activation for novel metaphoric sentences was higher than that for nonsensical sentences everywhere (i.e., the opposite contrast, NS > NM, did not elicit significant brain activation). This pattern of results suggests that readers rely on the same LH neural systems when reading potentially meaningful sentences, whether they are novel metaphoric or literal (Figure 2). In addition, these findings show that NM are not perceived as nonsensical sentences and in terms of brain activation,



unfamiliar metaphoric sentences are processed differently than unfamiliar nonsensical sentences.

The findings of the present study are consistent with the results of much previous research that tested brain processing of complete sentences. A wide range of studies investigated the neural correlates of sentence processing, and have consistently reported more LH than RH activation (e.g., Capek et al., 2004; Cutting et al., 2006). The relevant areas in the LH consist of the IFG, superior/middle temporal gyrus (STG/MTG), and the inferior parietal lobule (e.g., Caplan, 2001; Caplan, Alpert, Waters, & Olivieri, 2000, Caplan et al., 2002; Just et al., 1996; Kang, Constable, Gore, & Avrutin, 1999; Ni et al., 2000). These left-lateralised brain areas seem to be sensitive to sentence complexity as well (e.g., Carpenter, Just, Keller, Eddy, & Thulborn, 1999; Constable et al., 2004). Taken as a whole, the findings of previous research indicate that portions of Wernicke's area, the angular gyrus (AG), the SMA, and the adjacent cortices, in particular the left middle temporal regions, are critical for sentence comprehension (for reviews, see Demonet, Thierry & Cardebat, 2005; Sakai, Hashimoto, & Homae, 2000; Xu, Kemeny, Park, Frattali, & Braun, 2005).

As concluded by Just et al. (1996), level of cognitive demand correlates with increased activation in the relevant brain regions. Thus, it could be anticipated that the comprehension of unusual sentences that combine the meanings of words in a rather unusual manner will show higher levels of brain activation. However, in the present study, although the nonsensical sentences were rated as less understandable than the LIT and NM (Table 1), the findings show no significant activation for NS compared with either NM or LIT. A possible explanation is that no additional effort was required in order to integrate the meanings of the words in the NS because it was relatively easy to decide that they did not form a meaningful sentence. In contrast, in those areas that are reported in the literature (for a review see Just et al., 1996) as sensitive to level of cognitive demand (AG, anterior and posterior part of MTG, and posterior cingulate), we found stronger activation for NM and LIT than for the NS (Figures 3 and 4). Our results indicate stronger activation for NM and LIT than NS in the LH anterior and posterior parts of the middle temporal lobe (Figure 3c and 4a, respectively). This stronger activation could reflect semantic activation and integration processes. According to Jung-Beeman (2005), semantic activation takes place in the posterior STG and MTG whereas semantic integration is extended to bilateral anterior parts of the temporal cortex. "Semantic activation" refers to the initial process of accessing semantic representations and first-order associations of the input word, whereas "Semantic integration" refers to the process that supports message-level interpretation (beyond the word level) and which detects, elaborates, and refines higher-order semantic relations. In line with this view, stronger

activation in posterior and anterior parts of the left MTG was found in the present study for the two experimental conditions that included meaningful sentences (LIT, NM) as compared to the experimental condition including nonsensical, meaningless sentences, which may not require semantic integration.

The increased activation in the AG for the meaningful sentences (NM, LIT), as compared with the nonsensical sentences, is consistent with findings from several other studies implicating the AG in semantic integration during sentence processing (e.g., Humphries, Binder, Medler, & Liebenthal, 2007). The AG has been implicated in a variety of cognitive processes including semantic association, selective attention, problem solving, and mental imagery (Cabeza & Nyberg, 2000). The AG is thought to be involved in mapping visually presented inputs onto linguistic representations by having functional links with Wernicke's area. In a recent fMRI study (Humphries et al., 2007) participants heard semantically congruent sentences (e.g., "the man on vacation lost a bag and a wallet") and semantically incongruent sentences (e.g., "the freeway on a pie watched a house and a window"). Results showed greater activation for semantically congruent compared to semantically incongruent sentences in the left AG. These results corroborate with our results that showed stronger activation for the meaningful as compared with the meaningless sentences in the AG, indicating a special role for the AG in processing overall sentence meaning. Our data also suggest an increased activation in the posterior cingulate/precuneus for the NM and LIT as compared with the NS. The precuneus–posterior cingulate regions have been implicated during processing of event sequences (Partiot, Grafman, Sadato, Flitman, & Wild, 1996) and in linking textual information with participants' prior knowledge (Maguire, Frith, & Morris, 1999), connecting the text with knowledge about the real world.

Our findings additionally suggest that the neural networks recruited for processing NM sentences are identical to those recruited for the processing of LIT sentences, except for the left MFG (Figure 5), which is part of the dorsolateral prefrontal cortex (DLPFC). Moreover, the only brain region that showed significantly higher beta weights for the NM as compared to LIT is the left MFG. It has long been known that the left MFG is involved in verbal episodic encoding (e.g., Buckner & Koutstaal, 1998; Dolan & Fletcher, 1997; Fletcher, Shallice, & Dolan, 1998). More precisely, functional connectivity studies (e.g., Fernandez & Tendolkar, 2001; Woodward, Meier, Tara, Cairo, & Ngand, 2006) treat the left MFG, left medial temporal lobe, and left IFG as components of an integrated episodic memory network.

Each region in this system is thought to be engaged in a different function: the MFG generates verbal relational associations, the left IFG selects the verbal relational associations maintained in working memory, and the left medial temporal lobe stores these relational associations (Woodward

et al., 2006). In line with previous research (e.g., Mayes & Montaldi, 1999; Montaldi et al., 2002; Woodward et al., 2006) the present study supports the role of the MFG in generating scenarios that enhance verbal semantic associations. The processing of novel metaphoric sentences might thus exert a higher level of demand on the episodic memory system in order to generate de-novo semantic associations. The activation in the MFG found for NM in the present study is consistent with Bottini et al.'s (1994) findings, suggesting that additional cognitive processes, such as the retrieval of information from episodic memory, are required in order to overcome the denotative violation characterising novel metaphorical language. Thus, when a reader process NM sentences the literal, denotative, interpretation is found to be inappropriate (my mother is not really a lock in "my mother was a silent lock"). Consequently, the intended metaphorical interpretation should be formed using new information from episodic memory (for example, the behaviour of distant unresponsive mothers may share some semantic features with the qualities of locks). However, the enhanced activation in left MFG does not necessarily require access to episodic memory, but could reflect retrieval from semantic memory. It is possible that one had never encountered a distant mother (thus having no episodic memory to retrieve) but could still understand a specific metaphor ("my mother was a silent lock") based on his/her semantic knowledge and the semantic overlap between distant mothers and locks. This explanation corroborates with findings obtained from many neuroimaging studies that have shown that semantic memory is typically associated with regions in the left prefrontal and temporal cortex (for review see Cabeza & Nyberg, 2000). Moreover, according to Fletcher and Henson (2001) the DLPFC (Brodmann areas 9 and 46) is involved in selecting, manipulating, and monitoring of information that is currently maintained in working memory.

Our findings are very similar to those of a recent study (Rapp et al., 2004) that investigated brain activation while participants read sentences with either metaphoric or literal meaning and performed the same valence judgement task used in the present study (whether the sentence had a positive or negative connotation). Signal changes were observed in the left posterior middle/inferior temporal (BA 37) gyrus, adjacent to the activation observed in the present study (BA 21). These findings are very similar to the present study's results in that both studies do not support a special role of the RH in processing unfamiliar NM sentences. However, the two studies differ on one crucial aspect. Whereas the familiarity of the metaphoric sentences in the present study was carefully controlled (i.e., they were judged in a pretest as highly unfamiliar), the familiarity level of the metaphoric sentences in Rapp's study was not determined in a pretest. This might explain the lack of RT differences in processing NM and LIT sentences in Rapp et al.'s study as opposed to slower RTs for processing NM than LIT in

the present study, although both studies used the same task. Hence we suggest that the additional MFG activation found in the present study reflects the use of unfamiliar metaphoric sentences.

Although the present results corroborate with the Rapp et al. findings, the present results are not consistent with those reported in the studies of Ahrens et al. (2007), Schmidt et al. (2007), and Eviatar and Just (2006). Ahrens et al. (2007) found bilateral activation in the middle frontal gyrus and the precentral gyrus, and RH activation in the superior frontal gyrus for the comparison between the anomalous and the conventional metaphors. However, the anomalous metaphoric sentences used by Ahrens et al. could actually be perceived as nonsensical sentences and not as novel meaningful metaphoric sentences, since the anomalous sentences were rated only 1.76 on the understandability scale (ranging from 1 to 7). Thus, those anomalous sentences might reflect nonsensical sentences and cannot be compared to the novel metaphoric sentences used in the present study. In the behavioural study of Schmidt et al. an RH advantage was found for the novel metaphoric sentences as compared to the conventional sentences. Schmidt et al. used a plausibility judgement task whereas the present study used a valence judgement task. The different tasks might explain the lack of RH advantage in the present study. As pointed out by Ahrens et al., deciding whether the sentence had a positive or negative meaning could have been treated by participants as a type of category test that relies on LH resources. Eviatar and Just found RH involvement (superior and middle temporal gyri) for the processing of novel ironic statement as compared to literal and conventional metaphoric sentences in an event-related fMRI study. Overall, the different tasks and methods, in addition to the different types of novel sentences (anomalous, metaphoric, ironic) that were used by Ahrens et al., Schmidt et al., and Eviatar and Just as compared to the novel metaphoric sentences of the present study can account for the inconsistent results regarding the relation between RH and novelty.

The calculated parameters estimated in the contrasts applied by the present study showed greater activation for NM and LIT than for NS in each of the activated brain regions (except the MFG which was sensitive only to the NM). In other words, as compared to meaningless sentences (NS), meaningful sentences (NM, LIT) showed enhanced activation in the left middle temporal gyrus (anteriorly and posteriorly), angular gyrus, and posterior cingulate gyrus. A wide range of neuroimaging studies has shown that the MTG is associated with sentence processing (Caplan, 2001; Caplan et al., 2000, 2002; Constable et al., 2004; Just et al., 1996; Kang et al., 1999; Ni et al., 2000; Sakai et al., 2001; Xu et al., 2005). Moreover, whereas meaningful sentences elicited significant activation in these brain areas, meaningless sentences produced de-activation (negative beta weights) in the angular gyrus, anterior middle temporal gyrus, and posterior cingulate

gyrus. Thus it seems that the brain might process meaningless sentences in an “economical” way, perhaps reducing metabolic energy in interpreting nonsensical sentences. These results are consistent with our previous findings (Mashal et al., 2005, 2007) that did not reveal stronger activation for the unrelated word pairs compared with other types of meaningful two word expressions. The fact that responses to NS were slower than responses to NM and LIT might result from the search for meaning that, in the case of NS, ends without finding a plausible meaning. However, the increased activation in the meaningful conditions may suggest that a successful search elicits more activity than a long but unsuccessful search.

It should be noted that the current experimental design, i.e., the comparison of novel metaphors to familiar literal sentences, confounds the effects of familiarity with metaphor processing. An improved design for the current study would have been one that includes additional conventional metaphoric sentences, such that the novel metaphors and conventional metaphors are both metaphoric sentences but differ only on their familiarity level. However, since sentences were strictly matched for the syntactic structure and it is impossible to construct a conventional metaphoric sentence with the same syntactic structure as that of a novel metaphoric sentence, the conventional metaphoric sentences were omitted from the current study. It is thus impossible to determine whether the increased activation for the NM as compared to the LIT is due to the novelty of the associations, to the process of making associations for (even familiar) metaphors, or both. Future studies that use novel and familiar metaphoric sentences and compare them with familiar and non-familiar literal sentences (with the same syntactic structure as the NM) may help determine whether the observed activation in left MFG is due to the metaphoricity or the familiarity level of the sentence. Furthermore, future research should also look into the effect of the implicit task on the obtained results. It might be that the same sentences would show different pattern of brain activations when passively read or when processed with a more explicit task.

In sum, the findings of the present study, which used complete sentences and showed activation in specific LH regions for NM sentences, are different from the findings of previous studies that used two word NM expressions (Mashal et al., 2005, 2007) and that showed activation in RH regions, mainly in the right homologue of Wernicke’s area. Furthermore, the present study’s findings are consistent with previous studies that investigated brain processing of sentences, and are also in line with several studies that used fMRI to identify brain areas involved in the processing of novel metaphoric sentences. Our findings thus indicate that the processing of literal sentences and novel metaphoric sentences taken from poetry relies on the same LH neural systems, but processing novel metaphoric sentences additionally shows enhanced activation in two left brain regions, the MFG in the

DLPFC and the posterior parts of the MTG. The activation of the MFG observed for the comprehension of the novel metaphoric as compared to the literal and nonsensical sentences could reflect the enhanced demand on episodic and semantic memory systems in order to generate de-novo verbal semantic associations. The involvement of the left MTG could reflect extra reliance on classical brain structures devoted for sentence comprehension. Thus, when the novel metaphorical meaning of a sentence is based on the remote associations between the individual words, as dictated by the sentence structure, processing depends on LH linguistic mechanisms including the MFG and the MTG. These findings suggest that in addition to the familiarity level, the level of linguistic stimuli, i.e., words vs sentences, and their meaningfulness, i.e., unfamiliar metaphoric vs unfamiliar nonsensical sentences, also affect patterns of brain activation.

Manuscript received 14 November 2007

Revised manuscript received 22 January 2008

First published online 16 May 2008

## REFERENCES

- Ahrens, K., Liu, H., Lee, C., Gong, S., Fang, S. and Hsu, Y. (2007). Functional MRI of conventional and anomalous metaphors in Mandarin Chinese. *Brain & Language*, *100*, 163–171.
- Anaki, D., Faust, M., & Kravetz, S. (1998). Cerebral hemispheric asymmetries in processing lexical metaphors. *Neuropsychologia*, *36*, 691–700.
- Beeman, M. (1998). Coarse semantic coding and discourse comprehension. In M. Beeman & C. Chiarello (Eds.), *Right hemisphere language comprehension: Perspectives from cognitive neuroscience* (pp. 255–284). Mahwah, NJ: Lawrence Erlbaum Associates Inc.
- Bottini, G., Corcoran, R., Sterzi, R., Paulesu, E. S. P., Scarpa, P., Frackowiak, R. S. J., et al. (1994). The role of the right hemisphere in the interpretation of the figurative aspects of language: A positron emission tomography activation study. *Brain*, *117*, 1241–1253.
- Buckner, R. L., & Koutstaal, W. (1998). Functional neuroimaging studies of encoding, priming, and explicit memory retrieval. *Proceedings of the National Academy of Sciences of the United States of America*, *95*(3), 891–898.
- Cabeza, R., & Nyberg, L. (2000). Imaging cognition II: An empirical review of 275 PET and fMRI studies. *Journal of Cognitive Neuroscience*, *12*(1), 1–47.
- Cacciari, C., & Glucksberg, S. (1994). Understanding figurative language. In M. A. Gernsbacher (Ed.), *Handbook of psycholinguistics* (pp. 447–477). New York: Academic Press.
- Capek, C. M., Bavelier, D., Corina, D., Aaron, J., Newman, A. J., Jezzard, P., et al. (2004). The cortical organization of audio-visual sentence comprehension: An fMRI study at 4 Tesla. *Cognitive brain research*, *20*, 111–119.
- Caplan, D. (2001). Functional neuroimaging studies of syntactic processing. *Journal of Psycholinguistic Research*, *30*(3), 297–320.
- Caplan, D., Alpert, N., Waters, G., & Olivieri, A. (2000). Activation of Broca's area by syntactic processing under conditions of concurrent articulation. *Human Brain Mapping*, *9*, 65–71.

- Caplan, D., Vijayan, S., Kuperberg, G., West, C., Waters, G., Greve, D., et al. (2002). Vascular responses to syntactic processing: Event related fMRI study of relative clauses. *Human Brain Mapping, 15*(1), 26–38.
- Carpenter, P., Just, M. A., Keller, T. A., Eddy, W. F., & Thulborn, K. R. (1999). Time course of fMRI-activation in language and spatial networks during sentence comprehension. *Neuro-Image, 10*, 216–224.
- Chiarello, C. (2003). Parallel systems for processing language: Hemispheric complementarity in the normal brain. In M. T. Banich & M. Mack (Eds.), *Mind, brain language* (pp. 229–247). Mahwah, NJ: Lawrence Erlbaum Associates Inc.
- Constable, R. T., Pugh, K. R., Berroya, E., Mencl, W. E., Westerveld M., Ni, W., et al. (2004). Sentence complexity and input modality effects in sentence comprehension: An fMRI study. *NeuroImage, 22*, 11–21.
- Cutting, L. E., Clements, A. M., Courtney, S., Rimrodt, S. L., Schafer, J. G. B., Bisesi, J., et al. (2006). Differential components of sentence comprehension: Beyond single word reading and memory. *Neuroimage, 29*, 429–438.
- Demonet, J. F., Thierry, G., & Cardebat, D. (2005). Renewal of the neurophysiology of language: Functional neuroimaging. *Physiological Reviews, 85*, 1–62.
- Dolan, R. J., & Fletcher, P. C. (1997). Dissociating prefrontal and hippocampal function in episodic memory encoding. *Nature, 388*(7), 582–585.
- Eviatar, Z., & Just, M. A. (2006). Brain correlates of discourse processing: An fMRI investigation of irony and conventional metaphor comprehension. *Neuropsychologia, 44*, 2348–2359.
- Faust, M. (1998). Obtaining evidence of language comprehension from sentence priming. In M. Beeman & C. Chiarello (Eds.), *Right hemisphere language comprehension: Perspectives from cognitive neuroscience* (pp. 161–186). Mahwah, NJ: Lawrence Erlbaum Associates Inc.
- Faust, M., Bar-Lev, A., & Chiarello, C. (2003). Sentence priming in the two cerebral hemispheres: Influences of lexical relatedness, word order and sentence anomaly. *Neuropsychologia, 41*, 480–492.
- Faust, M., & Lavidor, M. (2003). Convergent and divergent priming in the two cerebral hemispheres: Lexical decision and semantic judgement. *Cognitive Brain Research, 17*, 585–597.
- Faust, M., & Mashal, N. (2007). The role of the right cerebral hemisphere in processing novel metaphoric expressions taken from poetry: A divided visual field study. *Neuropsychologia, 45*(4), 860–870.
- Fernandez, G., & Tendolkar, I. (2001). Integrated brain activity in medial temporal and prefrontal areas predicts subsequent memory performance: Human declarative memory formation at the system level. *Brain Research Bulletin, 55*(1), 1–9.
- Fletcher, P. C., & Henson R. N. A. (2001). Frontal lobes and human memory: Insights from functional neuroimaging. *Brain, 124*, 849–881.
- Fletcher, P. C., Shallice, T., & Dolan, R. J. (1998). The functional roles of prefrontal cortex in episodic memory. I. Encoding. *Brain, 121*, 1239–1248.
- Friston, K., Holmes, A. P., Worsley, K., Poline, J. B., Frith, C., & Frackowiak, R. S. J. (1995). Statistical parametric maps in functional imaging: A general linear approach. *Human Brain Mapping, 2*, 189–210.
- Giora, R. (1997). Understanding figurative and literal language: The graded salience hypothesis. *Cognitive Linguistics, 7*, 183–206.
- Giora, R. (2003). *On our mind: Salience, context and figurative language*. New York: Oxford University Press.
- Giora, R., Zaidel, E., Soroker, N., Batori, G., & Kasher, A. (2000). Differential effects of right- and left-hemisphere damage on understanding sarcasm and metaphor. *Metaphor and Symbol, 15*, 63–83.
- Hasson, U., Nusbaum, H. C., & Small, S. L. (2006). Repetition suppression for spoken sentences and the effect of task demands. *Journal of Cognitive Neuroscience, 18*, 2013–2029.

- Holmes, A. P., & Friston, K. J. (1998). Generalisability, random effects, and population inference. *NeuroImage*, 7, S754.
- Humphries, C., Binder, J. R., Medler, D. A., & Liebenthal, E. (2007). Time course of semantic processes during sentence comprehension: An fMRI study. *NeuroImage*, 36, 924–932.
- Jung-Beeman, M. (2005). Bilateral brain processes for comprehending natural language. *Trends in Cognitive Sciences*, 9, 512–518.
- Jung-Beeman, M. J., Bowden, E. M., Haberman, J., Frymiare, J. L., Arambel-Liu, S., Greenblatt, R., et al. (2004). Neural activity when people solve verbal problems with insight. *PLoS Biology*, 2, 500–510.
- Just, M. A., Carpenter, P. A., Keller, T. A., Eddy, W. F., & Thulborn, K. R. (1996). Brain activation modulated by sentence comprehension. *Science*, 274, 114–116.
- Kacinik, N. A., & Chiarello, C. (2007). Understanding metaphors: Is the right hemisphere uniquely involved? *Brain & Language*, 100, 188–207.
- Kang, A. M., Constable, R. T., Gore, J. C., & Avrutin, S. (1999). An event related fMRI study of implicit phrase-level syntactic and semantic processing. *NeuroImage*, 10, 555–561.
- Maguire, E. A., Frith, C. D., & Morris, R. G. (1999). The functional neuroanatomy of comprehension and memory: The importance of prior knowledge. *Brain*, 122, 1839–1850.
- Mashal, N., & Faust, M. (2008). Right hemisphere sensitivity to novel metaphoric relations: Application of the signal detection theory. *Brain and Language*, 104, 103–112.
- Mashal, N., Faust, M., & Hendler, T. (2005). The role of the right hemisphere in processing nonsalient metaphorical meanings: Application of principal components analysis to fMRI data. *Neuropsychologia*, 43(14), 2084–2100.
- Mashal, N., Faust, M., Hendler, T., & Jung-Beeman, M. (2007). An fMRI investigation of the neural correlates underlying the processing of novel metaphoric expressions. *Brain and Language*, 100, 115–126.
- Mayes, A. R., & Montaldi, D. (1999). The neuroimaging of long-term memory encoding processes. *Memory*, 7(5–6), 613–659.
- Montaldi, D., Mayes, A. R., Barnes, A., Hadley, D. M., Patterson, J., & Wyper, D. J. (2002). Effects of level of retrieval success on recall-related frontal and medial temporal lobe activations. *Behavioural Neurology*, 13, 123–131.
- Ni, W., Constable, R. T., Mencl, W. E., Pugh, K. R., Fulbright, R. K., Shaywitz, B. A., et al. (2000). An event-related neuroimaging study: Distinguishing form and content in sentence processing. *Journal of Cognitive Neuroscience*, 12(1), 1–14.
- Oldfield, D. J. (1971). The assessment of handedness: The Edinburgh Inventory. *Neuropsychologia*, 9, 97–113.
- Partiot, A., Grafman, J., Sadato, N., Flitman, S., Wild, K., 1996. Brain activation during script event processing. *NeuroReport* 7, 761–766.
- Rapp, A. M., Leube, D. T., Erb, M., Grodd, W., & Kircher, T. T. J. (2004). Neural correlates of metaphor processing. *Cognitive Brain research*, 20, 395–402.
- Rinaldi, M. C., Marangolo, P., & Baldassari, F. (2004). Metaphor processing in right brain-damaged patients with visuo-verbal and verbal material: A dissociation (re)considered. *Cortex*, 40, 479–490.
- Sakai K. L., Hashimoto R., & Homae F. (2000). Sentence processing in the cerebral cortex. *Neuroscience Research*, 39, 1–10.
- Schmidt, G. L., DeBuse, C. J., & Seger, C. A. (2007). Right hemisphere metaphor processing? Characterizing the lateralisation of semantic processes. *Brain and Language*, 100, 127–141.
- St. George, M., Kutas, M., Martinez, A., & Sereno, M. I. (1999). Semantic integration in reading: Engagement of the right hemisphere during discourse processing. *Brain*, 122, 1317–1325.
- Stringaris, A. K., Medford, N. C., Giampetro, V., Brammer, M. J., & David, A. S. (2007). Deriving meaning: Distinct neural mechanisms for metaphoric, literal and non-meaningful sentences. *Brain and Language*, 100, 150–162.



- Suzuki, K., & Sakai, K. L. (2003). An event-related fMRI study of explicit syntactic processing of normal/anomalous sentences in contrast to implicit syntactic processing. *Cerebral Cortex*, *13*(5), 517–526.
- Talarach, J., & Tournoux, P. (1988). *A co planner stereotaxic atlas of a human brain*. Stuttgart: Thieme Verlag.
- Winner, E., & Gardner, H. (1977). The processing of metaphor in brain damaged patients. *Brain*, *100*, 717–729.
- Woodward, T. S., Meier, B., Tara, A., Cairo, T. A., & Ngand, E. T. C. (2007). Temporo-prefrontal coordination increases when semantic associations are strongly encoded. *Neuropsychologia*, *44*, 2308–2314.
- Xu, J., Kemeny, S., Park, G., Frattali, C., & Braun, A. (2005). Language in context: Emergent features of word, sentence, and narrative comprehension. *NeuroImage*, *25*, 1002–1015.
- Zaidel, E., Kasher, A., Soroker, N., & Batori, G. (2002). Effects of right and left hemisphere damage on performance of the “Right Hemisphere Communication Battery”. *Brain and Language*, *80*(3), 510–535.

## APPENDIX

Examples of FIVE triplets of sentences translated from Hebrew.

### Novel metaphoric sentences

1. In my windowpane syllables knocked repeatedly
2. We turned off the light of our intentions
3. Time does not leave a testament
4. The sunrise wears the trees' veil
5. The moon ripens in the tree's branches

### Literal sentences

1. In the park trees swayed silently
2. We calculated the hours of our shifts
3. The teacher does not leave instructions
4. The sunrise illuminates the roof's shingles
5. Flowers wilted in the garden's flowerbed

### Nonsensical sentences

1. In my blanket letters looked ceaselessly
2. We made wiser the handles of our clouds
3. Foliage does not hurry nonsense
4. The swimmer glides the keyboard's sea
5. Sunflower dips in the bread's raspberry

Copyright of Laterality is the property of Psychology Press (UK) and its content may not be copied or emailed to multiple sites or posted to a listserv without the copyright holder's express written permission. However, users may print, download, or email articles for individual use.