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Functional anatomy of idiomatic expressions

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Abstract

Idiomatic expressions (IE) are groups of words whose meaning is different from the sum of its components. Neural mechanisms underlying their processing are still debated, especially regarding lateralization, main structures involved, and whether this neural network is independent from the spoken language. To investigate the neural correlates of IE processing in healthy Spanish speakers.Twenty one native speakers of Spanish were asked to select one of 4 possible meanings for IE or literal sentences. fMRI scans were performed in a 3.0T scanner and processed by SPM 12 comparing IE vs. literal sentences. Laterality indices were calculated at the group level. IE activated a bilateral, slightly right-sided network comprising the pars triangularis and areas 9 and 10. In the left hemisphere (LH): the pars orbitalis, superior frontal, angular and fusiform gyrus. In the right hemisphere (RH): anterior insula, middle frontal, and superior temporal gyrus. This network reveals the importance of the RH, besides traditional LH areas, to comprehend IE. This agrees with the *semantic coding* model: the LH activates narrow semantic fields choosing one single meaning and ignoring others, and the RH detects distant semantic relationships, activating diffuse semantic fields. It is also in line with the *configuration hypothesis*: both meanings, literal and figurative, are executed simultaneously, until the literal meaning is definitively rejected and the figurative one is accepted. Processing IE requires the activation of fronto-temporal networks in both hemispheres. The results concur with previous studies in other languages, so these networks are independent from the spoken language. Understanding these mechanisms sheds light on IE processing difficulties in different clinical populations and must be considered when planning resective surgery.

Keywords FMRI · Idioms · Neuroanatomy · Language · Figurative · Spanish

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Introduction

Figurative language is not just an ornamental or poetic resource; instead, it is omnipresent in everyday communication as a powerful conceptual tool, with different degrees of complexity (Pollio et al. 1977; Gibbs 1993; Bottini et al. 1994; Bowdle 2005; Gibbs Jr and Colston 2006; Thoma and Daum 2006; Vulchanova et al. 2019). Idiomatic expressions (IE) are an important part of the language and culture of a society. Like many other languages in the world, the Spanish language uses many IE, which are highly dependent on the culture of the people, IE are very often characteristic and specific to a language. This means that they cannot generally be translated literally and / or directly into another language. Noteworthily, there are no fMRI studies of figurative language processing in Spanish, the third most spoken language in the world, with 330 million native speakers. Previous research on IE has used stimuli in languages of different linguistic families, such as English (Hillert and Buračas

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2009; Kana et al. 2012), Italian (Papagno et al. 2002; Lauro et al. 2008; Papagno and Romero Lauro 2010) or Japanese (Shibata et al. 2007), among others. A linguistic family is a group of languages with a common historical origin and phylogenetically related, that is, they seem to derive from an older language or proto-language (mother language). The languages of the same family share common words or grammatical characteristics, which in turn are vastly different from those of other families. Brain responses use similar neural machinery to understand literal language, regardless of cross-language differences, something similar is expected to happen when dealing with idioms (Bookheimer 2002; Small 2008; Price 2010).

Research on figurative language initially focused on metaphors (Black 1979; Bottini et al. 1994; Rapp et al. 2004; Bowdle 2005; Sotillo et al. 2005; Lee and Dapretto 2006; Stringaris et al. 2007; Shibata et al. 2007; Schmidt and Seger 2009; Bohrn et al. 2012), and later included other forms of non-literal expressions, such as idioms or proverbs (Bobrow and Bell 1973; Swinney and Cutler 1979; Kempler et al. 1988, 1999; Cacciari and Tabossi 1988, 2014; Gibbs Jr et al. 1989; Gibbs 1993; Nunberg et al. 1994; Tabossi and Zardon 1995; Titone and Connine 1999; Papagno et al. 2002; Titone et al. 2002; Oliveri et al. 2004; Papagno and Genoni 2004; Huber-Okrainec et al. 2005; Lee and Dapretto 2006; Caillies and Butcher 2007; Fogliata et al. 2007; Zempleni et al. 2007; Lauro et al. 2008; Mashal et al. 2008a; Bélanger et al. 2009; Hillert and Bura 2009; Hillert and Buračas 2009; Vespignani et al. 2009; Schettino et al. 2010; Vulchanova et al. 2011; Cacciari et al. 2018; Kulkova and Fischer 2019; Citron et al. 2019). *Idiomatic expressions* (IE) are a particular type of non-literal language, formed by sequences of words without compositional meaning (Nunberg et al. 1994; Gibbs Jr and Colston 2006; Gibbs Jr 2008; D'Ouakil 2012; Cacciari and Tabossi 2014). The IE meaning does not derive from its components for example: "to wash your hands" actually means "to avoid your responsibility" (Nunberg et al. 1994; Cacciari and Tabossi 2014). IE have different degrees of transparency and ambiguity, depending on the distance between the figurative and literal meaning. An IE is considered *opaque* if its meaning is not derived from the evoked image or the constituent words. On the contrary, IE are *transparent* if the metaphorical and literal sense are close. There are different degrees of "figurativeness" (or conventionalization of meanings) Therefore, some authors hypothesized that the recognition of figurative language might not be dichotomous, but rather a continuum without strict boundaries between literal and non-literal language (Rumelhart 1979; Dascal 1989; Gibbs 1993; Cacciari and Glucksberg 1994).

IE can be understood as such when detecting a syntactic or semantic deviation in a sentence. Some assertions can be interpreted in several alternative ways: literal, figurative, or even both simultaneously, depending on the context. For example, "John is a hungry wolf," could mean either that a person named John can eat a lot, or that the hungry wolf's name is John. Moreover, if a phrase is literally false in a given context, it might mean it is a figurative expression (Black 1979; Ortony 1980; Glucksberg 1991, 1998).

Several theories tried to figure out the psycholinguistic processing of IE:

The Graded Salience Hypothesis (Giora 1997, 2007) posits that the interpretation of an IE depends on the salience of its meaning (an IE is more salient when it is more conventional, more familiar, more frequent, more prototypical). The most salient meaning has priority, for example, if a word has two meanings, the most salient in a specific context would be considered first. There is a continuum of saliences, from non-coded (most salient, processed *on the fly*) to coded (less salient, requiring more complex processing). A new interpretation of an IE requires first to consider the most salient meaning and, once it is rejected, reinterpreting it.

Conversely, the *Configuration Hypothesis* proposed by Cacciari & Tabossi (1988) suggests that there is no such reinterpretation of both meanings. Idioms are initially processed literally until a "key" word is recognized and the idiomatic meaning is activated. Then both meanings, literal and figurative, are executed simultaneously, until the literal meaning is definitively rejected and the figurative one is accepted.

The *fine versus coarse* semantic coding model (Jung-Beeman 2005) states that the right hemisphere (RH) weakly activates broad semantic fields, while the left hemisphere (LH) activates narrow semantic fields. The LH, then, chooses one single meaning and ignores irrelevant competitors. Instead, the RH can detect distant semantic relationships by activating larger but diffuse semantic fields.

The newest neuropsychological model of IE representation (Papagno and Romero Lauro 2010) postulates that IE undergo a linguistic analysis first, with two possible interpretations (literal or figurative), one of them (or both) are rejected based on the context. IE with a more salient meaning activate the LH, while non salient, literal interpretations of IE require RH recruitment. Moreover, prefrontal areas in both hemispheres retrieve the figurative meaning and inhibit the literal one.

The neural mechanisms by which people understand figurative expressions have been studied by different neurophysiological and neuroimaging techniques. Scientific literature on the neural correlates of IE processing as revealed with converted fMRI is still scant. While everyone agrees that certain frontal, temporal, and parietal areas participate in the network involved, there is no absolute agreement about the role of each hemisphere in the processing of IE. Even more, specific areas of activation may differ slightly depending on the paradigm used. Some investigators postulate that the

RH is more important than the LH for IE processing (Van Lancker and Kempler 1987; Winner and Gardner 1993; Bottini et al. 1994, 2007; Kempler et al. 1999; Goel and Dolan 2001; Sotillo et al. 2004; Coulson and Wu 2005; Faust and Mashal 2007; Pobric et al. 2008; Alba-Ferrara et al. 2011; Schmidt et al. 2011; Rapp et al. 2012). In fact, many studies report greater RH brain activity compared to LH while subjects perform higher-level language tasks, such as understanding metaphors, irony, idioms (Winner and Gardner 1977, 1993; Bottini et al. 1994, 2007; Faust and Mashal 2007; Pobric et al. 2008; Schmidt et al. 2011), decoding complex and social emotions from prosody (Alba-Ferrara et al. 2011), or understanding jokes (Goel and Dolan 2001; Coulson and Wu 2005), among other pragmatic, higher order language skills (Mashal et al. 2008a). Repetitive transcranial magnetic stimulation (rTMS) offers the opportunity to interrupt temporarily and selectively the activity of a specific area. Using this technique, Pobric et al.(2008) found a role of the posterior part of the superior temporal gyrus of the RH in novel metaphor comprehension, suggesting that the RH creates a significant non-literal expression from the individual meanings of two seemingly unrelated concepts. Sotillo et al (2004) used Event- Related Potentials (ERP) to demonstrate that middle and superior temporal RH areas have an important role in figurative language processing. Kempler et al. (1999), studied patients with RH or LH damage and found that LH damaged patients performed poorly in novel sentences comprehension, although they performed well when processing IE. On the other hand, RH damaged patients had difficulties processing IE but were unimpaired when processing novel sentences. The contribution of the RH in complex language and communication skills was also supported by other behavioral studies in patients with RH damage, as these patients frequently present a wide range of deficits in discourse, lexical-semantic, prosodic, and pragmatic processing (Winner and Gardner 1977; Kempler et al. 1999; Coulson and Van Petten 2007; Faust and Mashal 2007; Johns et al. 2008; Ferré et al. 2011, 2012; Abusamra et al. 2012, 2014; Lomlomdjian et al. 2017).

Nevertheless, a large amount of evidence, especially from clinical studies, challenged the RH hypothesis. Several investigators showed that LH is essential to understand IE (Papagno 2001; Papagno et al. 2002; Nenonen et al. 2002; Oliveri et al. 2004; Papagno and Genoni 2004; Fogliata et al. 2007; Papagno and Caporali 2007; Bélanger et al. 2009; Cardillo et al. 2018; Arcara et al. 2019). Left temporal rTMS significantly interfered with accuracy and reaction times when processing IE (Papagno et al. 2002; Oliveri et al. 2004). It is assumed that to understand IE, a certain lexical integrity is required. In fact, IE understanding is severely impaired in aphasic patients with LH damage. Moreover, patients with LH damage tend to interpret unambiguous IE as literal, (Hillert 2004; Papagno et al. 2004, 2006; Cacciari et al. 2006). Stringaris et al (2007) used fMRI to demonstrate the role of the LH in understanding conventional English non-literal utterances. Several authors have pointed out that, as the expression becomes increasingly complex, RH counterpart areas are recruited in addition to classic LH language areas, such as frontal and lateral temporal regions. (Faust and Mashal 2007; Yang et al. 2009; Schmidt and Seger 2009; Bohrn et al. 2012; Rapp et al. 2012). It should be noted that fMRI studies often show areas associated, but not crucial, for a task, as it is a correlational technique in nature (Alba-Ferrara et al. 2012).

Finally, most studies showed a bilateral neural network, or failed to support exclusive RH involvement (Gibbs Jr and Nagaoka 1985; Tompkins et al. 1992; Chobor and Schweiger 1998; Gagnon et al. 2003; Rapp et al. 2004, 2012; Jung-Beeman 2005; Mason and Just 2006; Lee and Dapretto 2006; Ahrens et al. 2007; Stringaris et al. 2007; Zempleni et al. 2007; Pobric et al. 2008; Papagno and Romero Lauro 2010; Bambini et al. 2011; Bohrn et al. 2012; Hagoort and Levinson 2014; Carotenuto et al. 2018). Neuroimaging studies in healthy subjects, in any linguistic task, reveal a predictable activation of the left hemisphere, specially of the inferior frontal gyrus, medial temporal gyrus and prefrontal areas. However, with non-literal language tasks, such as metaphors or idiomatic expressions, there is an additional activation of anatomically equivalent areas of the RH (Papagno et al. 2002; Rapp et al. 2004; Zempleni et al. 2007; Hillert and Buračas 2009; Schmidt and Seger 2009; Price 2010). Schmidt et al. (2011) proposed that factors such as familiarity or the difficulty of non-literal sentences would determine the degree of the RH recruitment. Mashal and Faust (Faust and Mashal 2007; Mashal et al. 2008a) showed that the RH underlies literal, non-salient interpretations of IE, while ambiguous IE with salient meanings are processed by the LH. So, in case of LH damage, the less salient interpretation is activated by the RH, and the IE is understood literally. Zempleni et al. (2007) used fMRI and a task with ambiguous and unambiguous idioms to suggest a bilateral neural network underlying IE comprehension, as opposed to the exclusive participation of the RH. Papagno and Lauro (2010) also proposed a bilateral network, predominantly left-sided, activating simultaneously temporal and frontal areas, but also BA 9 (prefrontal) in both hemispheres to suppress the literal interpretation and to monitor the response.

In addition to that question, others remain unanswered: although the current trend is to consider IE processing as dependent on a bilaterally distributed neural network comprising the posterior part of the superior temporal gyrus, as well as parietal and frontal areas, some studies still point to a predominance of one or the other hemisphere. At last, these data would allow us to compare the different models and see which one provides the best explanation of the neural processing of IE. We predict that there will be a RH predominance when processing IE, on top of the typical left areas activated for a linguistic task, the RH will be strictly associated to figurative language comprehension. The present fMRI study focuses on how healthy subjects process IE in Spanish and which anatomical networks underlie such task.

Materials and Methods

Participants

Twenty-one native speakers of Spanish (11 males), with a mean age of 32.6 years (range: 19–48) were recruited for this protocol from the School of Medicine of the University of Buenos Aires. All subjects were right-handed as revealed by the Edinburgh Handedness Inventory (Oldfield 1971), had a mean education level of 16 years, met the usual criteria for MRI scanning (no metallic implants, no claustrophobia, etc.), were neurologically healthy (without known neurological or psychiatric conditions, without psychotropic substances consumption at the time of the assessment) and reported a good visual acuity. Participants gave informed consent to take part in the study, which was approved by the institutional review board of the Hospital Roffo of Buenos Aires in agreement with the Declaration of Helsinki ethical standards. The participants did not receive financial compensation for their participation in the experiment.

General neuropsychological evaluation

Besides assessing hemispheric dominance, the following tests were administered in order to rule out cognitive impairment or psychiatric conditions: the Edinburgh manual dominance questionnaire (Oldfield 1971), WAT (Word Accentuation Test) (Del Ser et al. 1997), Direct/Inverse Digit span from the Wechsler Memory Scale (Weschler and Stone 1945), Spanish version of the Beck Depression Inventory (Brenlla and Rodríguez 2006) and the State and Trait Anxiety Inventory in Spanish (Buela-Casal et al. 2011).

Stimuli

We designed a *sentence to word* matching task, taking as a model the tasks originally designed in Italian language by Papagno and Caporali (2007) and Proverbio et al. (2009). The task in Spanish has already been validated by Lomlomdjian et al. (2017).

Stimuli consisted of 35 idioms (18 non-ambiguous and 17 ambiguous) and 35 literal sentences, selected from a pool of 312 adapted stimuli previously tested in behavioral experiments (Lomlomdjian et al. 2017). Idioms were collected and designed according to their familiar use across Argentina. Idiomatic expressions were "ambiguous" if a literal interpretation was possible (i.e. "The chairman washed his hands'', as it could be interpreted to absolve himself from responsibility or literally wash his hands), or "non-ambiguous", if the literal interpretation was unlikely (i.e. "Her cousin lost her head" could be interpreted as to act emotionally or irrationally, but was unlikely to be interpreted as an actual beheading). Literal expressions had only one possible meaning (i.e. "Her cousin lost his wallet"). Each idiomatic and literal expression was paired with four word options: i) a correct one representing the idiomatic or literal meaning, ii) an option semantically related to the key structure of the sentence, and iii) two unrelated options. An example of translated expressions, for the IE: "my uncle screwed up", the options are: (1) error (2) leg (3) treatment (4) goal, with the first two options being related to the meaning, and the second two unrelated to the sentence. In the case of a literal expression like "my cousin worked all night" the options are: (1) effort (2) smoothness (3) darkness (4) triangle, being the first and third options the related ones.

Stimuli were presented with E-prime software (Psychology Software Tools, Pittsburgh, PA, USA) During the task, each sentence was displayed at the top of the screen, while the four options were shown at the bottom. Participants were instructed to read and comprehend idiomatic or literal expressions and select the option that better matched the meaning of the sentence via a response box with four keys, with their right hand. Prior to entering the scanner, participants underwent a practice run of 20 trials of the task. All participants performed the practice trials accurately. During the scanning session accuracy and RT were measured. RT were computed from the onset of each trial.

Stimulus, figurative or literal, consisted of a syntactically simple sentence, with an initial identical and neutral structure (subject–verb–object, one independent clause), and a final key structure that differed according to the stimuli and determined the meaning (word or string of words). The predictability of the sentences was tested by a query performed by six neurolinguists (Lomlomdjian et al. 2017). Although in this study sentences were not split into parts for display, the length of the initial and key structure of each sentence was balanced across the type of stimuli (For further details on the stimuli and task validation see Lomlomdjian et al. (2017). Sentences and target words were matched across categories. The frequency of the words, key words of sentences and the target word options, were matched according to the CREA corpus (Real Academia Española—CREA). For each stimulus, the four target options were balanced by use frequency and word. Concreteness of the options was balanced according to the correct option. (Table 1).

Table 1 Comparison between expression categories

Expression categories	Sentences						Target options			
	Length		Word count		Frequency of use		Frequency of use		Length	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Idiom, non-Ambiguous	29.17	5.65	6.52	1.44	162.83	165.19	43.49	19.88	6.89	0.82
Idiom, ambiguous	29.57	5.20	6.43	1.29	143.17	183.37	39.17	20.91	6.94	1.36
Literal	28.03	4.87	5.90	1.01	179.48	268.15	41.35	7.09	7.29	1.25
ANOVA F value	0.948		2.889		0.309		0.493		1.357	
Df	2		2		2		2		2	
p value	0.39		0.059		0.734		0.618		0.260	

No statistical differences were found between categories

Length characters count (with spaces in case of sentences), *Word count* amount of words in the sentence; target options consists on one word, *Frequency of use* frequency of use of the key word of sentence and target words according to CREA corpus, *ANOVA* variance test, *df* degrees of freedom

Functional MRI Acquisition

Imaging was performed in a 3.0T Siemens Trio MRI scanner. A T1-weighted localizer scan was acquired to produce nine images (3 levels of cuts in three orientations) to corroborate the position of the head. Full brain MRI scans were collected using: (1) a 2D multisliced spoiled T1 sequence (2) a 3D T1 sequence (MPrage).

The T1 3D data was acquired in the sagittal plane with TR = 2 ms., TE = 3.7 ms.; inverted angle = 80, field of view (FOV) in plane = 214 × 214 mm and matrix of size 240 × 240, coding phase in antero-posterior direction and from left to right, block thickness = 128 mm, Nav = 1 (average number of signals), voxel size = 0.89 × 0.89x1.0 mm3, acquisition of bandwidth = 191.5 Hz/pixel, and parallel image (SENSE factor = 8).The images were reconstructed with an intra-plane interpolation of factor = 2 in each dimension.

Functional images were acquired through a sequence sensitive to BOLD contrast. 214 volumes were acquired, each one following the orientation AC-PC (anterior–posterior commissure). Each cut had a resolution of 64 × 64 pixels, a voxel size of 3.75 × 3.75x4 mm3, with no space between cuts and were acquired in an interleaved sequence. The volumes were recorded at a repetition time (TR) of 1.5 s, echo time (TE) of 35 ms. and a radiofrequency pulse angle of 900. 214 whole brain volumes (4 dummies) were acquired at the beginning of the run. The whole run lasted 5:21, and the whole session had a duration of around 25 min.

Stimuli were presented every 4.5 s (stimuli display during 4 s.) in an *event related* design, with a jittered ISI of $\bar{x} = 500$ ms ± 300 previously proven to be accurate to tease apart the BOLD response elicited by each trial (Rossell et al. 2003; Spengler et al. 2009; Wolf et al. 2012). The order of test trials and jitter intervals were optimized using optseq software (http://surfer.nmr.mgh.harvard.edu/optseq/). Stimuli were presented using a laptop with E-prime 3.0 stimulus delivery software (Psychology Software Tools, Pittsburgh, PA, USA). Using a back-projection system during the fMRI session, participants viewed stimuli via a mirror attached to the head coil. Responses were obtained using a magnet compatible system. The scanner was started 6 s before the behavioral task began to allow for steady state magnetization to be achieved; the resulting initial 4 scans were discarded. A single run was acquired for this paradigm. (Fig. 1).

Image Processing

Data was processed following the steps of a previous work (Alba-Ferrara et al. 2012). Image preprocessing and statistical analyses were performed using the SPM12 software package (Wellcome Department of Cognitive Neurology). The functional images were subjected to geometric distortion correction and motion correction. The structural images were co-registered to the mean unwarped and motion corrected functional image for each subject and segmented into gray and white matter images. Functional and structural gray matter images were normalized to Montreal Neurological Institute (MNI) space, and volumes were smoothed with a Gaussian kernel of 8 mm (FWHM). Individual statistics were computed using a general linear model approach as implemented in SPM, (Friston et al. 1994) a 128 s high-pass filter was used to remove non-physiological slow signal shifts. A random effects analysis was conducted for group averaging and population inference. One image per contrast was computed for each subject from a design matrix that included estimated individual movement parameters as regressors in addition to literal or IE sentences task conditions as explanatory variables. To explore regions specifically activated by IE and literal sentences, t-contrast analysis (SPM12) was performed.

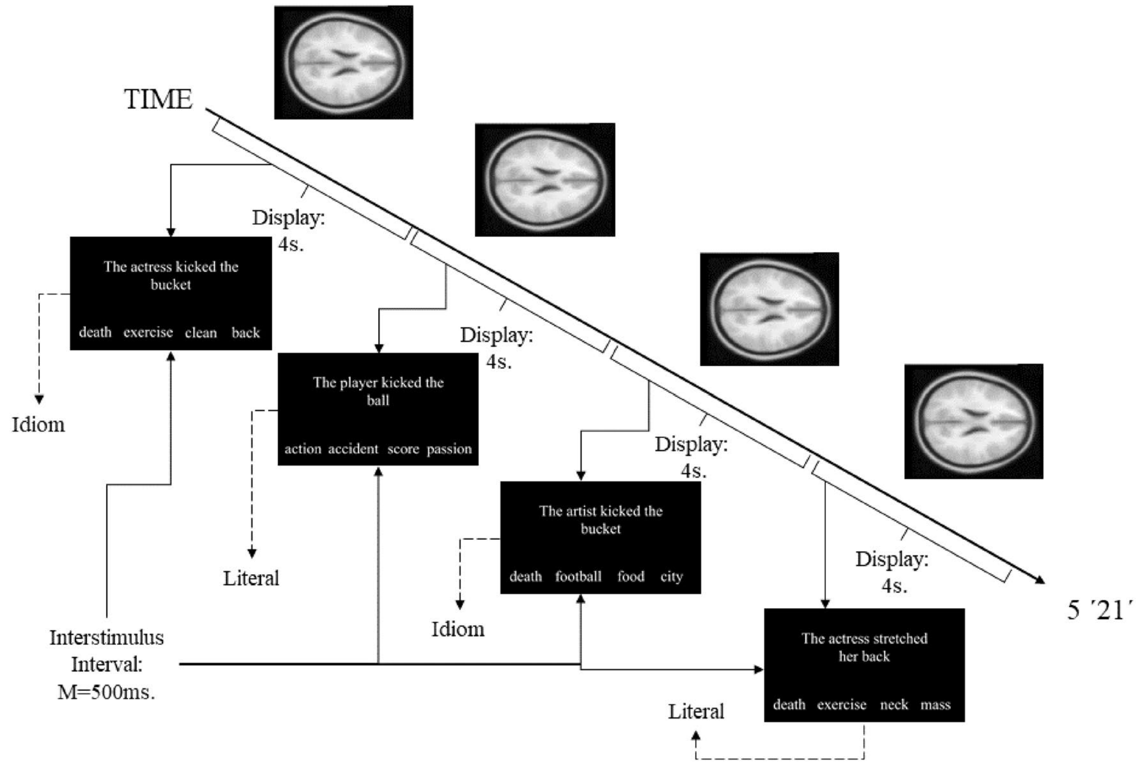

Fig. 1 Stimuli were presented every 4.5 s (stimuli display during 4 s.) in an event related design, with a jittered ISI of $\bar{x} = 500$ ms ± 300. The whole run lasted 5:21, and the whole session had a duration of around 25 min. 214 volumes corresponding to the task plus 4 dummies were acquired. The dummies (not shown in the figure) were acquired in the first 6 s of the run

Contrast

A randomized effect analysis was performed using SPM12, computing a BOLD contrast image for each subject. Subsequently we compared IE trials vs literal language trials by t tests. Correction for multiple comparisons to $p < 0.05$ was achieved via Monte Carlo simulations using a cluster extent threshold procedure first described by Slotnick et al. (Slotnick and Schacter 2004). As reported in the cited study, the cluster extent threshold procedure relies on the fact that given spurious activity or noise (voxel-wise type-I error), the probability of observing increasingly large (spatially contiguous) clusters of activity systematically decreases. Each simulation consisted of 1000 independent iterations with a $64 \times 64 \times 30$ matrix, and each voxel activity was modelled by assigning a normally distributed random number ($M = 0$, variance $= 1$). The spatial extent of each cluster was calculated. The simulation determined a cluster threshold of 18 voxels. Gyral locations and Brodmann area designations of regions of significant activation were identified by an experienced neuroanatomist.

To assess lateralization of activations we employed the LI-toolbox at the group level (Wilke and Lidzba 2007). To avoid the threshold dependency of simple lateralization indices, a bootstrapping approach was employed yielding a robust estimation of the true data distribution. With this approach, multiple bootstrapped resamples from the original dataset are analyzed at different thresholds, yielding a single, weighted mean laterality index (LI) which is based on the whole of the underlying dataset (Wilke and Schmithorst 2006). We considered the 5000 most activated voxels in both hemispheres of the brain, disregarding tissue 5 mm to the left and right of the inter-hemispheric fissure, excluding the cerebellum, and discarding clusters of less than 50 voxels. LIs were computed using the LI-toolbox masks for different regions of interests (ROI): the global gray matter, the frontal, temporal, and parietal lobes separately. LI was calculated based on the following formula:

$$\left(\sum \text{activation}_{LH}\right)/\text{mwf} - \sum \text{activation}_{RH} / \left(\sum \text{activation}_{LH}\right)/\text{mwf} + \sum \text{activation}_{RH}$$

being "∑ activation" the sum of activated voxels and "mwf", the mask weighting factor (Wilke and Lidzba 2007; Bartha-Doering et al. 2018).

The LI ranges from − 1 to 1, and a negative LI implies relatively more right hemispheric activation during the task, whereas a positive LI implies more left hemispheric activation. If LH and RH activations are identical, LI will be equal to zero.

Results

Behavioral Performance

The results of the general neuropsychological evaluation are shown in Table 2. We converted each participant digit span score and compared it with normative data from WAIS III (Spanish version) adjusted for age, and we found all individuals scored within the normal range. Behavioral responses during the fMRI session from three participants were not recorded due to technical difficulties with the response box. One sample t test demonstrated that the recorded participants had a performance significantly higher than the chance level (> 50% accuracy). The mean (± SD) percentage of correct answers were $\bar{x} = 76$ (± 11), [t (17) = 8.99; p < 0.001].

A paired sample t test showed that there were no significant differences between the accuracy of the responses for literal sentences and IE [t (17) = 1.175; p = n/s].

A paired sample t test showed that there were no significant differences in RT for IE ($\bar{x} = 2408$ ms, SD = 409) and literal language ($\bar{x} = 2548$ ms, SD = 363) [t (17) = − 1.76; p = n/s].

Correlations between the total score of digit span test and accuracy [r (17) = − 0.48, p = 0.080] or reaction times [r (16) = − 0.07, p = 0.794] in the experimental task were not significant.

Table 2 General neuropsychological evaluation results

	Mean	SD	Normative data
Word accentuation test	26/30	2.30	NA
Digit span total	11.52	3	Mean: 10 SD: 5.6 Cut-off = 7
Beck Depression Inventory	2.61	2.97	Cut-off = 13
State-Trait Anxiety Inventory -T	12.43	5.50	Cut-off = 40 (total score)
State-Trait Anxiety Inventory -S	16.75	7.52	
Edimburgh test	90	16.08	

Neural Activations

The results reported were obtained with a Pcorr. < 0.05, are listed in Table 3 and illustrated in Fig. 2. A network of increased cortical activity was found for IE compared with literal sentences. Significant clusters of activation were observed in the following regions: the frontal cortex bilaterally (including the pars triangularis of the inferior frontal gyrus in both hemispheres and the pars orbitalis of the left inferior frontal gyrus), the right middle frontal gyrus and the left superior frontal gyrus. Activity extended bilaterally to

Table 3 Conjunction analysis of the anatomical regions showing significant changes in BOLD response comparing IE vs. literal sentences, and vice versa, with the cytoarchitectural designation according to Brodmann (BA), the size of each area expressed as number of voxels (kE)

Region label	Hemisphere	BA	kE	TZ	Peak (MNI coordinates)		
					x	y	Z
IE vs literal							
Fusiform	L	37	303	3.49	− 34	-46	− 20
MFG Gyrus	R	9	57	3.41	10	48	28
Parahippocampal	R	36	397	3.29	18	-42	-11
Prefrontal	L	10	220	3.21	− 14	42	-6
Prefrontal	R	9	136	2.81	22	38	26
IFG Triangularis	L	45	126	2.70	− 28	22	12
Literal vs IE							
Supramarginal	L	40	446	3.39	− 51	− 17	10
Posterior.Cingulate G	L	30	96	2.87	− 25	− 53	6
Insula	R	13	733	2.84	38	− 17	14

The maximum T-score (TZ) of the contrasts and the stereotactic coordinates according to the Montreal Neurological Institute (MNI) space (x, y, z). In order to emphasize laterality effects, the hemispheric asymmetries are presented in a separate column

Hemisphere R right, L left, *IFG* inferior frontal gyrus *MTG* middle temporal gyrus, *SPL/Pcu* superior parietal lobe/precuneus, *MFG* middle frontal gyrus, *SFG* superior frontal gyrus, *Ang* angular gyrus, *Supramarg* supramarginal gyrus

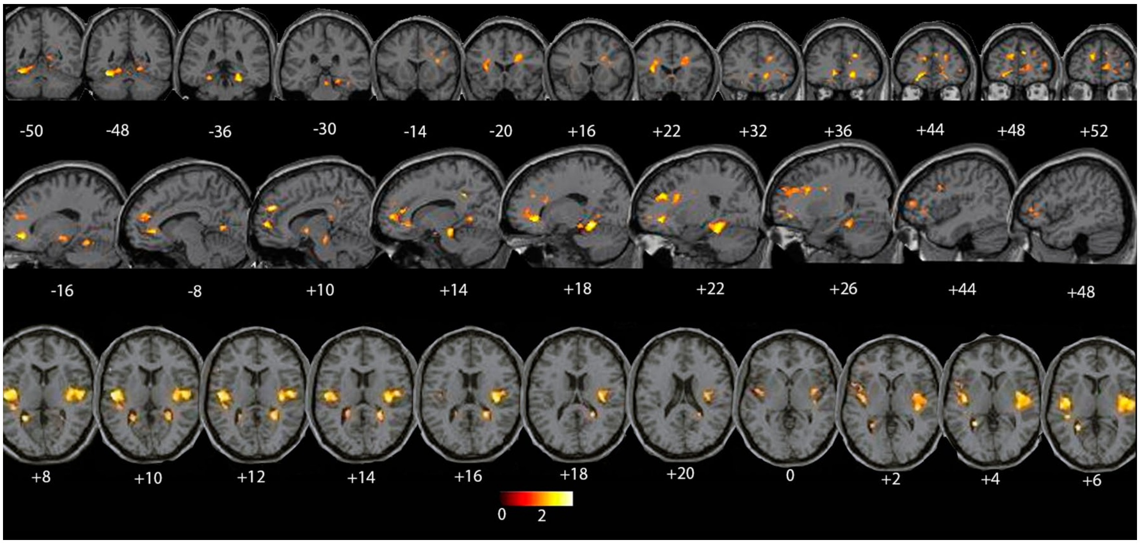

Fig. 2 Group fMRI activation maps for the contrast of IE versus literal processing. Activations are shown for $p < 0.05$, corrected for multiple comparisons. Significant effects are displayed as serial sections through a canonical brain on coronal, sagittal and axial slices (y, x, z coordinate levels in millimeters)

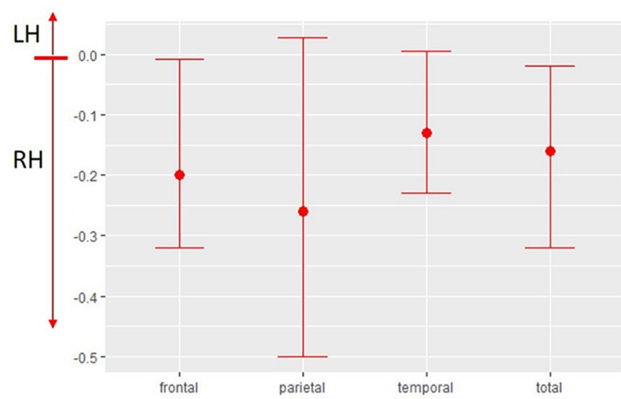

Fig. 3 Language laterality indices for different regions of interests at the group level. Red dots indicate mean values, vertical lines show minimum and maximum values. Note that all values are below zero, indicating lateralization to the right hemisphere (RH)

prefrontal areas (BA 9 and 10) and to the posterior part of the superior temporal gyrus, as well as to the right anterior insula, and supramarginal/angular and fusiform gyrus in the left hemisphere.

Given the laterality index formula used in the bootstrap analysis, bilateral and identical activations in both hemispheres will yield results equal to zero, a negative LI implies relatively more right hemispheric activation during the task, whereas a positive LI implies more left hemispheric activation.

LIs in group analyses of IE versus literal sentences showed RH-lateralized activations in the overall brain (mean − 0.16, SD 0.064). The same rightwards tendency was observed in each lobe separately: temporal lobe (mean − 0.13, SD 0.048) parietal lobe (mean − 0.26, SD 0.13), and frontal lobe (mean − 0.2, SD 0.091) (Fig. 3).

Discussion

Behavioral Level

Processing figurative language such as IE is thought to be more demanding than processing literal language. However, this would be compensated with their superior communicative effectiveness and linguistic economy. Similar to other neurolinguistic studies reported, we did not find significant differences in accuracy or response times between IE and literal sentences (Cacciari and Tabossi 1988; Giora et al. 2000; Cacciari et al. 2007).When context is adequate, IE are comprehended as quickly as literal sentences. This is consistent with the idea that IE were not first understood literally and then reprocessed, instead, they were probably processed concurrently, as the Configuration Hypothesis proposes (Cacciari and Tabossi 1988). Even without special contexts, figurative meanings may be generated as quickly as literal ones (Cacciari and Glucksberg 1994) but if the predictable IE fragment is at the beginning of the sentence, it facilitates meaning retrieval (Cacciari and Glucksberg 1994; Titone and Connine 1999). So, a pivotal moment determining the time course of IE comprehension occurs at the point in which the IE string is recognized as idiomatic. The IE used in this task were matched in predictability, to avoid this confounding factor.

The high percentage of correct answers suggests that the task was not extremely demanding from a cognitive point of view; and that the observed BOLD activity could not be attributed to cognitive effort.

Functional Neuroanatomy

The results showed that processing idiomatic expressions in Spanish requires simultaneous activation of a wide neural network, extending especially over fronto-temporal cortices in both hemispheres. These findings are in line with other reports about the functional anatomy of pragmatic language, even those with a different linguistic family, such as Japanese (Shibata et al. 2007), Korean (Yi et al. 2017), Chinese (Yang et al. 2016) or Hebrew (Faust and Mashal 2007; Mashal et al. 2008a), among others (Zempleni et al. 2007; Hillert and Buračas 2009; Papagno and Romero Lauro 2010; Bohrn et al. 2012; Kana et al. 2012).

In line with the current literature (Bobrow and Bell 1973; Swinney and Cutler 1979; Cacciari and Glucksberg 1994; Tabossi and Zardon 1995; Papagno et al. 2006, 2002; Jung-Beeman 2005; Caillies and Butcher 2007; Giora 2007; Small 2008; Papagno and Romero Lauro 2010; Bohrn et al. 2012; Rapp et al. 2012; Cacciari and Tabossi 2014; Yi et al. 2017; Kulkova and Fischer 2019) there has been an extensive bilateral activation of the *IFG*, slightly rightwarded according to our results. This gyrus, besides being the main speech production node, is also involved in the comprehension of IE in all languages. According to its cytoarchitectural structure, the IFG can be divided into three sections: the most inferior part coincides with Brodmann's area (BA) 47, and its dorsal boundary is BA45 (which also extends into part of the middle frontal gyrus); the most superior area is BA44, adjoining the motor cortex, which includes BA6 and BA4, and also BA9. BA44 and BA45 in the LH are considered to be part of Broca's area. Although both areas participate in verbal fluency due to its contribution to phonological and semantic operations, they do so in a different manner. Left BA45 is principally involved in semantic processes, while BA44 is probably involved in the high-level aspects of programming speech production per se (Amunts et al. 2004). Semantic functions rely on the most anterior portions of the IFG (BA45 and 47), while phonological tasks and syntax are located more posteriorly (BA44) (Stowe et al. 2005; D'Ouakil 2012; Uddén and Bahlmann 2012; Katzev et al. 2013; Zaccarella et al. 2017). It has also been claimed that the left IFG supports temporary storage of verbal information during short-term verbal memory tasks and during sentence processing, maintaining structural as well as lexical information. The right frontal lobe is involved in some semantic aspects of sentence comprehension and may also be recruited to create secondary interpretations of the sentence or to review the initial interpretation, perhaps relating it to information retrieved from episodic memory (Stowe et al. 2005).The IFG is also related to the executive functions necessary to understand IE, such as working memory, problem solving and response selection (Citron et al. 2019).

There was also an activation of the *MFG*, which, according to several neuroimaging studies, would play a role in the comprehension of Theory of Mind (ToM) stories and the detection, maintenance, or creation of coherent natural language representations (Gallagher et al. 2000; Bird et al. 2004; Jung-Beeman 2005; Citron et al. 2019). ToM is the ability that allows us to attribute mental states to ourselves and to other people. It enables us to decode what others believe, think, feel, or want, facilitating to predict and understand others' behaviors. In order to decode IE as figurative, contextual information such as the speaker´s communicative intention is needed, which is closely related to TOM. Therefore, it is expected that in tasks involving decoding figurative meanings, areas related to ToM will be activated, as it has been reported in other pragmatic aspects of language. (Mar 2011; Schurz et al. 2014; Feng et al. 2017; Boccadoro et al. 2019).

The results showed an additional activation of the *SFG*, already reported by other language studies involving ToM and probabilistic reasoning tasks, reflecting its role in decision making, and, in this case, choosing between the four possible meanings of the sentence (Gallagher et al. 2000). Semantic and conceptual representations take place at the MTG (Bookheimer 2002; Citron et al. 2019).The MTG and the STG are part of a language network connecting parietal and frontal structures, and thus are conceived to play a general role in language comprehension (Turken and Dronkers 2011).

Regarding the *prefrontal* activation, the supplementary motor area (SMA) is subdivided into a posterior region, SMA proper, related to motor planning, and an anterior region, pre-SMA) involved in cognitive functions such as attention, ambiguity resolution and contextualization, among others. The pre SMA and dorsal anterior cingulated cortices integrate the cingulo-opercular network, which has a broad role in cognition and learning (Geranmayeh et al. 2014; Federenko 2015). Language performance, then, not only depends on brain regions specifically involved in linguistic functions, but also on widely distributed and often overlapping brain networks that make broader contributions to cognition (Geranmayeh et al. 2014; Federenko 2015). Fogliata et al. applied rTMS to explore the temporal dynamics of left prefrontal and temporal cortex in idiom processing. As was shown in previous TMS and neuropsychological studies, the frontal and temporal cortices are involved in idiom comprehension, but inhibition of the prefrontal cortex affects performance even at later stages, suggesting involvement in literal meaning inhibition (Fogliata et al. 2007; Papagno and Romero Lauro 2010).

Pre SMA is also implicated in movement planning and control (Nachev et al. 2007; Benjamin et al. 2017)**.** Several studies showed that non-literal expressions with action-related semantics are "embodied". There is an activation of sensory and motor brain areas during their processing (Hauk et al. 2009; Desai et al. 2011, 2013; Boulenger et al. 2012; Romero Lauro et al. 2013; Kulkova and Fischer 2019). Overall, these studies suggest that the involvement of sensory-motor areas in processing non-literal sentences decreases as the level of abstraction increases, so idiomatic meaning may be less embodied compared to literal meaning, but not totally disembodied (Caillies and Butcher 2007; Boulenger et al. 2012; Cacciari and Pesciarelli 2013).

The left middle and inferior temporal gyri (BA20 and 21) are also involved in some aspects of language processing, including lexical semantic retrieval. Previous research showed the same areas in the RH activated by increased retrieval need (Pilgrim et al. 2002; Stowe et al. 2005). Kuperberg et al. (2000) also found that right middle and superior temporal gyri are sensitive to semantic violations. Activation of the right middle temporal gyrus in response to figurative material has also been reported in PET studies on healthy subjects, suggesting that this area plays an important role in figurative language comprehension (Bottini et al. 2007). It was first suggested that posterior inferior temporal and fusiform gyri might be important for accessing semantic information from visual input, as in reading.

Right Hemisphere vs. Left Hemisphere or Both

Although the relative role of each hemisphere in pragmatic language is still a matter of debate, most authors (Gibbs Jr and Nagaoka 1985; Tompkins et al. 1992; Chobor and Schweiger 1998; Gagnon et al. 2003; Rapp et al. 2004, 2012; Jung-Beeman 2005; Mason and Just 2006; Mashal et al. 2008a; Papagno and Romero Lauro 2010; Bambini et al. 2011; Bohrn et al. 2012; Hagoort and Levinson 2014; Carotenuto et al. 2018) agree that it involves a bilaterally distributed neural network, as seen in the present study. In fact, when the language task consists of finding the appropriate meaning in a given context, there is bilateral activity (Jung-Beeman 2005; Hillert and Bura 2009; Proverbio et al. 2009; Papagno and Romero Lauro 2010; Carotenuto et al. 2018). Some authors consider that each hemisphere has different processing abilities: the LH performs finer coding of the semantic information and is in charge of the idiomatic interpretation of IE, while the RH does a coarser coding, needed for pragmatics and discourse processing and for the literal interpretation of idioms (Jung-Beeman 2005; Mashal et al. 2008a; Papagno and Romero Lauro 2010). Different patterns of RH activation during idioms comprehension could be related to the kind of stimuli used during the experiment. Some studies suggested that figurativeness, familiarity, difficulty, novelty and context are important factors in recruiting networks in the RH (Mashal et al. 2008b; Pobric et al. 2008; Bélanger et al. 2009; Papagno and Romero Lauro 2010).

There is an interhemispheric integration that would be critical for the processing of non-literal language, in which different meanings are derived from a phrase: the RH makes context-appropriate inferences and reinterprets a phrase when the LH has chosen an irrelevant meaning (Beeman 1993) Huber-Okrainec et al. (2005) reported that in corpus callosum agenesis, idiom comprehension is impaired. Adults with corpus callosum agenesis also perform poorly in pragmatic tasks, suggesting that the interhemispheric transference of information cannot be fully compensated (Brown et al. 2005). So, there would be no shift from LH to RH activation, instead, the activation extends to both hemispheres without suppressing the LH contribution. We found bilateral activation in our study, which is in line with the idea of interhemispheric integration for pragmatic language processing.

Due to the fact that the present study evaluated the neural correlates of a language task, the expected activations of the LH were found, but when comparing IE with literal language, a lateralization towards the RH was observed. These findings are in agreement with a fMRI meta-analysis in which figurative language processing was studied (Rapp et al. 2012). The cited study reported a predominantly left lateralized network, with 32% of the additional coordinates from non-literal stimuli located in the RH.

Pragmatic abilities, including idiom comprehension, are impaired in a wide range of clinical populations as was previously mentioned, including LH and RH damaged subjects (Winner and Gardner 1993; Chobor and Schweiger 1998; Cacciari et al. 2006; Thoma and Daum 2006; Voets et al. 2006; Abusamra et al. 2009; Cardillo et al. 2018; Arcara et al. 2019), neurodegenerative diseases as Alzheimer, Amyotrophic Lateral Sclerosis (ALS) or fronto-temporal dementia (Papagno 2001; Amanzio et al. 2008; Gainotti 2012; Orange and Hillis 2012; Bambini et al. 2016), basal ganglia diseases (Arroyo-Anllo and Botez-Marquard 1998; Chenery et al. 2002; Monetta and Pell 2007; Eddy et al. 2010), neurodevelopmental disorders (Strandburg et al. 1993; Brown et al. 2005; Huber-Okrainec et al. 2005; Vulchanova et al. 2015; Chahboun et al. 2016), psychiatric conditions as schizophrenia (Titone et al. 2002; Thoma and Daum 2006; Kircher et al. 2007; Sela et al. 2015; Rapp et al.

2018; Rossetti et al. 2018), white matter diseases as multiple sclerosis or HIV dementia (Abusamra et al. 2012, 2014; Carotenuto et al. 2018), etc. Even considering the difficulties in interpreting these studies in diseased brains, in which the lesions are not circumscribed or there are other comorbidities, all the evidence seems to reinforce the idea that it is a broad and bilaterally distributed network that requires interhemispheric communication which includes fronto-temporo-parietal cortices and subcortical structures.

Bilateral activation for pragmatic language was reported to be even stronger in some subjects with less proficiency, such as second language users (Ding et al. 2003), elderly (Holler-Wallscheid et al. 2017), subjects diagnosed with autistic disorders (Coulson and Van Petten 2007; Vulchanova et al. 2015; Chahboun et al. 2016) and schizophrenia (Titone et al. 2002; Kircher et al. 2007; Saban-Bezalel and Mashal 2017; Rapp et al. 2018; Rossetti et al. 2018). The same effect was found in a group of patients with refractory epilepsy without clinically evident language deficits (Bendersky and colleagues, unpublished data). RH activation for language tasks after damage to primary language areas in the LH has been frequently reported. This adaptive reorganization is seen in homologous regions of the RH, such as the IFG, but also in other perisylvian areas in the RH, such as the STG, MFG, supramarginal and angular gyrus, and also in the right precuneus (Gold and Kertesz 2000; Thivard et al. 2005; Voets et al. 2006). This additional recruitment of areas in both hemispheres to perform the same task might be a compensatory strategy to master cognitive challenges, as was previously noticed by Alba-Ferrara et al. regarding complex emotional prosody comprehension (Alba-Ferrara et al. 2011).

Our results showed that processing IE in Spanish requires the activation of the same neural network as that used by other languages in the world.

Conclusions

The comprehension of idiomatic expressions in Spanish, as in other languages, requires the activation of a network that extends along fronto-temporal cortices in both hemispheres, similarly to the processing of other forms of figurative language. A better understanding of the functional anatomy of language networks might have implications for the interpretation of non-literal language deficits in clinical populations, such as Alzheimer, autism, schizophrenia, stroke, and even basal ganglia disease. Moreover, these networks for non-literal language processing must be considered when planning an eventual cortical resection for epilepsy surgery, or when designing rehabilitation programs for different clinical populations.

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Author Contributions MB and LAF designed the study, collected the data and contributed to data analysis together. LAF designed the fMRI protocol. CL and VA designed the linguistic paradigm. MB wrote the manuscript and made anatomical analysis. BEA performed the laterality index SK supervised data analysis and revised the manuscript. All authors approved the final manuscript.

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Availability of data and material Data are available upon request. Paradigms and supplementary data are appended as supplementary material.

Declarations

Conflict of interest The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Ethical Approval The study was approved by the institutional review board of the Hospital Roffo of Buenos Aires in agreement with the Declaration of Helsinki ethical standards.

Informed Consent **Consent to participate**: Participants gave informed consent to take part in the study. **Consent** for publication**:** All authors approved the publication of the manuscript.

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