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A Quantitative Meta-analysis of Neuroimaging Studies of Pragmatic Language Comprehension: In Search of a Universal Neural Substrate

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Abstract—Pragmatics may be defined as the ability to communicate by expressing and recognizing intentions. The objective of this meta-analysis was to identify neural substrates for comprehension of pragmatic content in general, as well as the differences between pragmatic forms, and to describe if there is differential recruitment of brain areas according to natural language. This meta-analysis included 48 functional magnetic resonance imaging studies that reported pragmatic versus literal language contrasts. The pragmatic forms were speech acts, metaphors, idioms, and irony. Effect Size-Signed Differential Mapping software was used to calculate the mean for all contrasts as well as for each pragmatic form, and make comparisons among all forms. Due to variations in pragmatic content configuration such as natural language, stimulus modality, and writing systems, these variations were also analyzed with subgroups' analyses. The analyses found a highly reproducible bilateral fronto-temporal and medial prefrontal cortex network for pragmatic comprehension. Each pragmatic form showed a specific convergence pattern within this bilateral network. Natural language analyses showed that fronto-temporal regions were recruited by Germanic languages, while only left frontal areas were recruited by Romance languages, and right medial prefrontal cortex by Japanese. In conclusion, pragmatic language comprehension involves classical language areas in bilateral perisylvian regions, along with the medial prefrontal cortex, an area involved in social cognition. Together, these areas could represent the ''pragmatic language network". Nonetheless, when proposing a universal neural substrate for all forms of pragmatic language, the diversity among studies in terms of pragmatic form, and configuration, must be taken into consideration.

Key words: neuropragmatics, speech acts, metaphor, idiom, irony, fMRI.

INTRODUCTION

To understand language in social interactions, the study of language itself is not sufficient (Airenti, 2017). It is necessary to focus on how communication works considering the intentional action of the utterance (from speaker to listener) in a specific contextual frame (Escandell Vidal, 2006; Egorova et al., 2016). Pragmatics has been deemed a capacity of mind to communicate in a way that is fundamentally a matter of social cognition; that is, expressing and recognizing intentions (Scott-Phillips, 2017). According to this perspective, pragmatics is not only a further level of linguistic processing, it is the social-cognitive basis of a type of communication (i.e., communicative intention) that is context dependent, involves an inferential process, and is not reducible to codes (Escandell Vidal, 2006; Scott-Phillips, 2017).

Interpreting an utterance (a spoken message) requires linguistic processes, such as retrieving a stable word meaning from lexical memory, grammatical and phonological processes involving the left fronto-temporal network (Friederici, 2011), and processes supported by neural networks beyond those of the classic language network, for socio-cognitive inferences and executive control for integration of information. Socio-cognitive inferences, for decoding the speaker's communicative intention, require mentalizing, defined as the ability to attribute mental states to others, including intentions (Schurz et al., 2014). Language as a social communicative tool includes speech acts, metaphors, idioms, and irony as its most important pragmatic forms. These pragmatic forms have in common that the receptor or listener must not only evaluate the literal meaning of the words and the relations between speaker and listener but also

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Abbreviations: dmPFC, dorsomedial prefrontal cortex; fMRI, functional magnetic resonance imaging; IFG, inferior frontal gyrus; MCC, middle cingulate cortex; mPFC, medial prefrontal cortex; MTG, middle temporal gyrus; rmPFC, rostromedial prefrontal cortex; STG, superior temporal gyrus.

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rebuild the speaker's intentions based on the contextual information provided (Escandell Vidal, 2006).

The classical language areas include Broca's area in the inferior frontal gyrus (IFG), Wernicke's area in the superior temporal gyrus (STG), as well as parts of the middle temporal gyrus (MTG) and angular gyrus in the parietal lobe in the left hemisphere (Friederici, 2011). The right hemisphere has been suggested to play a central role in comprehending non-literal language (Rapp et al., 2012). Coarse semantic coding theory (Jung-Beeman, 2005) proposes that while the left hemisphere is specialized in fine analysis of close semantic relationships, the right hemisphere is specialized in coarse or distant semantic relationships. Thus, the right hemisphere would have a general processing advantage for tasks that require the integration of distant semantic concepts (e.g., understanding non-literal language, such as pragmatic forms), which must be evaluated according to the social context, including the intention and expectation of the speaker and listener. Empirical evidence has shown bilateral brain activations during pragmatic processing, suggesting that both hemispheres participate in non-literal language comprehension (Bambini et al., 2011; Bohrn et al., 2012; Rapp et al., 2012).

Neuroimaging studies have described brain activation patterns according to type of pragmatic form. Speech acts are actions performed using language (Egorova et al., 2016), sometimes with an indirect meaning (Shibata et al., 2011). The speech act theory was put forward by John Austin (1962) in the last half of the twentieth century in part as a reaction to the view that sentences had to be verifiable to be meaningful. The theory proposes that utterances of every kind can be considered as acts; something is done in saying something like accusing, apologizing, or ordering (Senft, 2014). Utterances have also been described as the primary units of communication in discourse, typically defined by the verbs employed in them (Reed and Pitcher, 2015). Previous studies have shown that speech act comprehension recruits bilateral brain areas previously implicated in building and maintaining a coherent representation of discourse and mentalizing (Shibata et al., 2011; van Ackeren et al., 2012; Bašnáková et al., 2014). These areas include the bilateral IFG and MTG (Shibata et al., 2011; van Ackeren et al., 2012; Bašnáková et al., 2014; Egorova et al., 2016; Feng et al., 2017); precentral gyrus (Egorova et al., 2016; van Ackeren et al., 2016; Licea-Haquet et al., 2016), precuneus (van Ackeren et al., 2012; Senft, 2014; Feng et al., 2017; Licea-Haquet et al., 2016), and medial prefrontal cortex (mPFC) (Bašnáková et al., 2014; Egorova et al., 2016).

Metaphor comprehension involves an abstract connection between two concepts in semantic memory, which is established by extracting and relating similar properties of those different concepts. Conceptual metaphors involve understanding one conceptual domain (target) from properties of a different domain (source) of experience resulting in a new semantic mapping (Lakoff, 1993; Benedek et al., 2014). Thus, comprehension of metaphors requires access to the semantic mappings that are stored in memory. Previous studies have demonstrated that comprehension of metaphors activates the bilateral fronto-temporal network, which includes the IFG, MTG, and angular gyrus, and some studies include the superior frontal gyrus (Yang et al., 2009; Bambini et al., 2011; Desai et al., 2011; Shibata et al., 2012) and the paracingulate gyrus (Zamora-Ursulo, 2018).

Idiomatic expressions are "frozen" or lexicalized structures of expressions with familiar fixed multi-word expressions (Zempleni et al., 2007). The meaning of idioms such as "to kick the bucket" cannot be derived from an analysis of the individual words (Lauro et al., 2008), but it can be interpreted as a unique lexical expression with a particular and stable meaning stored in memory as any lexical word. The brain areas that show activation during idiom comprehension participate in the classic left language network (i.e., IFG and MTG) and extend into the right hemisphere in homologous areas (Zempleni et al., 2007; Lauro et al., 2008; Boulenger et al., 2009).

Irony conveys a meaning opposite to its literal meaning (Wakusawa et al., 2007; Shibata et al., 2010); it expresses feelings in an indirect way (Shamay-Tsoory et al., 2005). Sarcasm is a subtype of irony that is used in a hurtful or critical way (McDonald and Pearce, 1996). Ironic utterance comprehension requires mentalizing and emotional (prosody) processing for integration of social cues (Bohrn et al., 2012) with the involvement of the left STG (Uchiyama et al., 2006; Shibata et al., 2010) and mPFC (Wang et al., 2006; Wakusawa et al., 2007; Spotorno et al., 2012; Uchiyama et al., 2012).

The problem with using those individual studies to draw definite conclusions about the neural basis of pragmatic language comprehension is their variation in terms of natural language and stimulus modality, what we will designate as the "pragmatic content configuration". These studies have been conducted in a diversity of natural languages: Italian (Lauro et al., 2008; Bambini et al., 2011; Bosco et al., 2017), French (Spotorno et al., 2012; Obert et al., 2014, 2016), and Spanish (Licea-Haquet et al., 2016; Zamora-Ursulo, 2018) from the family of Romance languages; English (Lee and Dapretto, 2006; Stringaris et al., 2006; Wang et al., 2006; Stringaris et al., 2007; Chen et al., 2008; Boulenger et al., 2009; Hillert and Buračas, 2009; Schmidt and Seger, 2009; Yang et al., 2009; Desai et al., 2011; Diaz et al., 2011; Diaz and Hogstrom, 2011; Lacey et al., 2012; Obert et al., 2014; Egorova et al., 2016; van Ackeren et al., 2016, Rapp et al., 2004, 2010; Kircher et al., 2007; Forgács et al., 2012; Citron and Goldberg, 2014; Citron et al., 2016; Pomp et al., 2018), and Dutch (Zempleni et al., 2007; van Ackeren et al., 2012; Bašnáková et al., 2014; Bašnáková et al., 2015; Samur et al., 2015) from Germanic languages; and others, such as Japanese (Uchiyama et al., 2006; Shibata et al., 2007; Wakusawa et al., 2007; Shibata et al., 2010, 2011, 2012; Uchiyama et al., 2012; Akimoto et al., 2014), Hebrew (Mashal et al., 2009; Mashal et al., 2013), Mandarin Chinese (Ahrens et al., 2007; Yang et al., 2016; Feng et al., 2017), and Hungarian (Schnell et al., 2016). The stimulus modality is also heterogeneous and includes text, audio, image, videos, and a combination of these. Studies have also used different software for image analysis that may lead to variations in the results (Bowring et al., 2018), and the number of participants in each study is relatively small, with a mean of 17, thus affecting the power of the statistical tests. Fortunately, meta-analytic tools can tease apart false-positive findings (Eklund et al., 2016) and integrate and contrast results to provide the converging pattern of the neural areas involved in pragmatic language comprehension.

Previous meta-analyses of figurative and non-literal language (Bohrn et al., 2012; Rapp et al., 2012) have focused on the laterality of non-literal language, and on metaphors and their variations as non-salient versus salient, and novel versus conventional. Their results have shown that a bilateral fronto-temporal network with bias to the left is involved in figurative and non-literal language processing. Although the factors that recruit the right hemisphere remain to be established, this network may play a role in processing novel metaphors (Bohrn et al., 2012; Rapp et al., 2012). The overall contribution of the right hemisphere was found to be moderate, less coinciding, and less reproducible across studies (Bohrn et al., 2012; Rapp et al., 2012). Metaphors and idioms recruited the left IFG, while irony and sarcasm involved the mPFC and right fronto-temporal regions (Bohrn et al., 2012).

In this study we included speech acts, making it a meta-analysis of pragmatic function rather than of non-literal or figurative language. More importantly, we evaluated the effect of pragmatic content configuration, that is the effect of different natural languages, and the stimulus modality. In relation to methodological variation among studies, we compared the studies that used statistical correction for repeated measures versus those that did not correct their results. We only included functional magnetic resonance imaging (fMRI) studies, used a more stringent threshold for statistical significance than previous meta-analyses, and calculated the consistency of the results using jackknife (Biswal et al., 2001; Wilke, 2012), a resampling technique for data analysis to determine the reliability of task-activated fMRI.

The main objective of the present meta-analysis was to identify the neural correlates of pragmatic language comprehension respect to literal language comprehension, and to evaluate if these include brain areas associated with social cognition in addition to canonical areas of language processing. Given the cognitive differences between pragmatic forms, an additional objective was to evaluate if each pragmatic form has a neural signature that distinguishes it from the rest, as suggested by individual studies. Finally, we tested if there is a shared neural substrate for comprehension of pragmatic language regardless of pragmatic content configuration, given that it is a higher level of linguistic processing; we expected that the activation patterns would be determined by the pragmatic form, and not by its configuration. To accomplish this, we calculated a subgroup analysis for natural languages (i.e., Germanic and Romance languages, Japanese, and Mandarin Chinese), another for stimulus modality (i.e., text and audio), and another for writing systems (of the studies that used text to present pragmatic information).

EXPERIMENTAL PROCEDURES

Following the recommendations for meta-analysis (Moher et al., 2009), the literature search was performed using PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidance. The articles were searched in Web of Science, PUBMED, ScienceDirect, and PsycINFO databases. We used different keywords for each pragmatic form of interest: for speech acts, we used ‘‘speech acts”, ‘‘indirect request”, ‘‘direct request”, ‘‘indirect reply”, and ‘‘indirect replies”; for metaphors, we used the keyword ‘‘metaphor”; for idioms, we used ‘‘idiomatic” and ‘‘idioms”; and for irony, we used ‘‘irony” and ‘‘sarcasm”. Then, we combined these keywords with keywords alluding to functional magnetic resonance: ‘‘fMRI”, ‘‘functional magnetic”, and ‘‘MRI” (e.g., ‘‘speech acts” AND fMRI). We searched thirty word combinations in each database.

The literature search included articles published up to May 2018, and the earliest paper meeting our inclusion criteria was published in 2004 (Rapp et al., 2004). Studies were included if they met the following requirements: the paper reported the results of the contrast between the pragmatic form of interest respect to literal language as baseline; the participants were healthy adults; the study used fMRI scanning throughout the whole brain; when a study reported more than one contrast, we selected the contrasts that met the inclusion criteria (four articles report two contrasts of interest). We also included data from an experiment on speech acts, and a metaphor study performed by researchers from our laboratory (Licea-Haquet et al., 2016; Zamora-Ursulo, 2018) (Tables A1 and A2). Studies were excluded if they were not written in English (e.g., Hungarian); if they did not evaluate pragmatic language comprehension (e.g., metaphor production); if they only used the region of interest (ROI) approach, or if they did not report the activation coordinates for the contrast of interest in standard Montreal Neurological Institute (MNI) or Talairach space coordinates (Table A3).

Meta-analytic methods

We used the Effect Size-Signed Differential Mapping (ES-SDM version 5.12, https://www.sdmproject.com; Radua et al., 2012) software for meta-analysis because it is an improved version based upon existing probability methods, as described by (Schurz et al., 2014). In contrast with the original SDM and with other meta-analytic tools, such as activation likelihood estimation (ALE; Turkeltaub et al., 2002), it considers effect size (*t*-values) and allows the combination of both peak coordinates and statistical parameter maps, and the use of well-established statistics accounting for within- and between-study variability (Radua et al., 2012).

Briefly, we used the statistics converter from the ES-SDM web page (https://www.sdmproject.com/utilities/?

show = Statistics) to project peak coordinates into MNI space and effect size information into *t*-values. Then, as part of the preprocessing stage, we executed in ES-SDM one randomization for permutation of voxels in the fMRI or PET modality, a smoothing with an anisotropic un-normalized Gaussian Kernel with FWHM of 20 mm to create an ES-SDM map within a mask of gray matter for each original contrast useful for estimating the null distribution of the subsequent analyses. Statistical significance for all analyses was based on Monte Carlo randomizations as described before (Bohrn et al., 2012; Parhat et al., 2014; Radua and Mataix-Cols, 2009). For all meta-analytic maps, thresholds for voxel level were computed with a probability of 0.005, and for cluster level with size (k) > 10, and z value > 2.3.

Pragmatic versus literal language

To find the meta-analytic map, defined as the mean of the voxel values in areas involved in comprehension of pragmatic language with respect to literal language, we performed a mean analysis with all 54 contrasts. The consistency in the results was tested with a jackknife analysis, which consists in repeating a test as many times as there are studies, at each instance discarding a single study, then returning it to the data pool while removing another, and so on. Because of the observed methodological heterogeneity in the included studies, inter-study heterogeneity was calculated to identify the most heterogeneous brain regions (Bohrn et al., 2012; Schurz et al., 2014). In addition, we divided the studies into corrected and uncorrected, according to the method used for multiple comparisons, and then we evaluated if there were differences between them by subgroup analysis.

Subgroup analysis for pragmatic forms

To achieve our second objective, we selected subgroups for analysis according to pragmatic form as follows: (1) speech acts, 67 activation foci from 166 participants; (2) metaphor, 185 activation foci from 441 participants; (3) idiom, 30 activation foci from 261 participants; and (4) irony, which included sarcasm as a form of irony (McDonald and Pearce, 1996), 62 activation foci from 341 participants. A subgroup analysis for each pragmatic form (i.e., speech acts, metaphor, idiom, and irony) was done to evaluate brain activations during pragmatic language processing. A jackknife analysis was performed to test the consistency of the results, as well as a heterogeneity analysis to know which brain areas were heterogeneous across studies. Then, comparisons between pairs of pragmatic forms were carried out with a linear model analysis (e.g., speech acts > metaphor). Finally, we compared each pragmatic form against all the other pragmatic forms (e.g., speech acts > all others pragmatic forms) with linear model analysis.

Subgroup analysis for natural language

For the next objective, concerning variability in pragmatic content configuration, we selected studies according to natural language as follows: (1) Germanic languages, 188 activation foci from 407 participants; (2) Romance languages, 42 activation foci from 301 participants; (3) Japanese, 55 activation foci from 320 participants; and (4) Mandarin Chinese, 41 activation foci from 255 participants. Given that only two studies presented stimuli in Semitic language, Hebrew (Mashal et al., 2009), and two studies in Uralic language, Hungarian, we could not include them in this analysis of natural languages (Varga et al., 2013; Herold et al., 2018). A subgroup analysis for each natural language was done to evaluate brain activations during pragmatic language processing. A jackknife analysis was performed to test the consistency of the results, as well as a heterogeneity analysis to know which brain areas were heterogeneous across studies. Then, comparisons between pairs of natural language were carried out with the linear model analysis.

Subgroup analysis for stimulus modality and writing system

The studies that were included in this meta-analysis used text and audio as modalities for presenting pragmatic content. Text was the most frequent type of pragmatic content configuration, with 258 foci from 724 participants, while the use of audio to present pragmatic content included 86 foci from 231 participants. We conducted an analysis of means for each stimulus modality with a jackknife and heterogeneity analysis. Comparisons between type of modality (text vs audio) were performed with linear model analyses. In those studies using text, participants had to read to understand the pragmatic message (Table A2). To know if the writing system that represents speech sounds could have some effect on neural responses related to pragmatic language comprehension, we classified the studies that presented the stimulus in text by writing system: (1) transparent (Dutch, German, Spanish, Italian) with 98 activation foci from 247 participants; (2) opaque (English, French, Hebrew) with 71 activation foci from 346 participants; and (3) logographic (Mandarin Chinese and Japanese) with 89 activation foci from 346 participants (Table A1). Then, we conducted a subgroup analysis for transparent, opaque, and logographic writing systems. In addition to a mean analysis for each subgroup, jackknife and heterogeneity analyses were performed. Then, we compared between pairs of these writing system subgroups, and between each writing system and all the others, using a linear model analysis.

Cortical inflated reconstruction was performed with FreeSurfer Suite (http://surfer.nmr.mgh.harvard.edu/) (Dale et al., 1999). The names of the brain regions reported here were taken from the Harvard-Oxford Atlas of cortical and subcortical structural areas (https://fsl.fmrib.ox.ac.uk/fsl/fslwiki/fslview/atlas-descriptions.html#ha). The corresponding coordinates from the MNI152 template for pars opercularis, triangularis and orbitalis were taken from Petrides et al. (2015), and for the medial frontal wall were taken from Ullsperger et al. (2014).

RESULTS

A total of 827 citations were obtained by searching in Web of Science, PUBMED, ScienceDirect, and PsycINFO databases. We also included two experiments from our laboratory: one on speech acts and another on metaphors (Licea-Haquet et al., 2016; Zamora-Ursulo, 2018). We discarded 585 duplicate citations. Out of the remaining 244 studies, 183 did not meet the inclusion criteria (e.g., they did not include healthy controls or did not use fMRI, among others). A total of 61 articles met the inclusion criteria; of these, 11 articles with 12 contrasts of interest were excluded (e.g., they did not include coordinates, or whole-brain analysis). Finally, this meta-analysis identified 50 studies involving 54 contrasts of interest (Tables A1 and A2).

Considering all 54 contrasts of pragmatic form > literal language, 955 participants (442 males, 513 females) were included, ranging in age from 18 to 55 years. From those 54 contrasts, 66.66% were corrected and 33.33% were uncorrected for multiple comparisons. The distribution of studies for pragmatic form was the following: speech acts, 14.81%; metaphor, 51.85%; idiom, 11.11%; irony, 22.22%. These studies covered a broad range of natural languages: Germanic languages, 53.71%; Romance languages, 14.81%; Japanese, 16.66%; Mandarin Chinese, 7.41%; Hungarian 3.69%; and Hebrew, 3.69%. Two stimulus modalities were used in the experimental paradigms: text, 72.22% (three of these experiments used a combination of text and images); and audio, 27.77% (three of these experiments used a combination of audio and images). Studies that used text (39 studies) to present pragmatic stimuli were classified according to their writing system: transparent, 35.89%; opaque, 33.33%; and logographic, 30.76%.

Pragmatic versus literal language

We performed a meta-analysis on the reported maps for the 54 contrasts quantified by means of effect-size index (*t*-value). For these pragmatic > literal language contrasts, we found a bilateral fronto-temporal network that included the mPFC. This network incorporated three clusters: the left IFG (BA 44) extending to the temporal lobe (i.e., MTG and STG), supramarginal gyrus and lateral occipital cortex in the left hemisphere; the left anterior middle cingulate cortex (aMCC, BA 32) extending to perigenual anterior cingulate cortex; and the right IFG (BA 47) extending to temporal regions such as the middle and superior temporal gyri, temporal pole, planum polare and Heschl's gyrus in the right hemisphere (BA 31, Fig. 1). Jackknife sensitivity analysis showed that left frontal clusters of the meta-analysis were perfectly reproducible and remained significant for 54/54 combinations of contrasts using the leave-one-out method, while the middle cingulate cortex (MCC) showed high reproducibility (53/54), and the right brain regions (47/54) showed a moderate reproducibility. Heterogeneity analysis found significant variability across studies for the peak activations in regions of the left frontal lobe (aMCC and IFG), whereas right brain regions showed no significant variability across studies (Table A4).

Subgroup analysis for multiple comparison corrections

Diversity in methodological and statistical approaches was common across the studies included in this meta-analysis. Specifically, 33.33% of the contrasts in this meta-analysis were uncorrected for multiple comparisons. To identify differences between the results of corrected and uncorrected studies, we performed a mean analysis of corrected and uncorrected contrasts, followed by a comparison between them and a two-subgroup analysis. The average of corrected studies showed four clusters of activation, whereas uncorrected studies showed only three clusters (Table A5). Although multiple comparison methods can result in false positives (i.e., type I error) (Eklund et al., 2016), we did not detect any difference when contrasting corrected versus uncorrected results. Therefore, we included both corrected and uncorrected contrasts for the remaining analyses.

Subgroup analysis for pragmatic form

To test if each pragmatic form has a neural signature that distinguishes it from the rest, pragmatic > literal language contrasts were separated into subgroups according to the type of pragmatic language: speech acts, metaphor, idiom, and irony. This analysis included first a mean analysis for each pragmatic form, then a comparison between pairs of pragmatic forms.

Speech acts ($n = 8$)

A subgroup analysis for speech acts evidenced significant convergence in the IFG (BA 44–47) on both hemispheres (Fig. 2). Jackknife analysis found high and moderate consistency for right and left clusters, 7/8 and 5/8 combinations, respectively, while the heterogeneity analysis indicated that the observed variability across studies was larger than that resulting from sampling error alone in the left region (i.e., IFG) (Table A6).

In the contrasts between pairs, the speech acts > metaphor contrast showed significant differences in the right MTG (BA 22; MNI coordinates 58, −28, −6; $z = 2.00$, $p < 0.05$), and IFG (BA 47; MNI coordinates 38, 24, −8; $z = 3.00$, $p < 0.05$), and the speech acts > irony contrast detected differences in the right IFG (BA 47; MNI coordinates 40, 26, −10; $z = 3.00$, $p < 0.05$). The speech acts > idiom contrast showed no significant differences.

Metaphor ($n = 28$)

The mean activations for studies that analyzed metaphor as a pragmatic form showed greatest convergence in the left hemisphere in three clusters: the left IFG (BA 44) extending to temporal regions, the supramarginal gyrus and the anterior lateral occipital cortex; the left aMCC (BA 24) extending to the dorsomedial prefrontal cortex (dmPFC); and the left posterior lateral occipital cortex

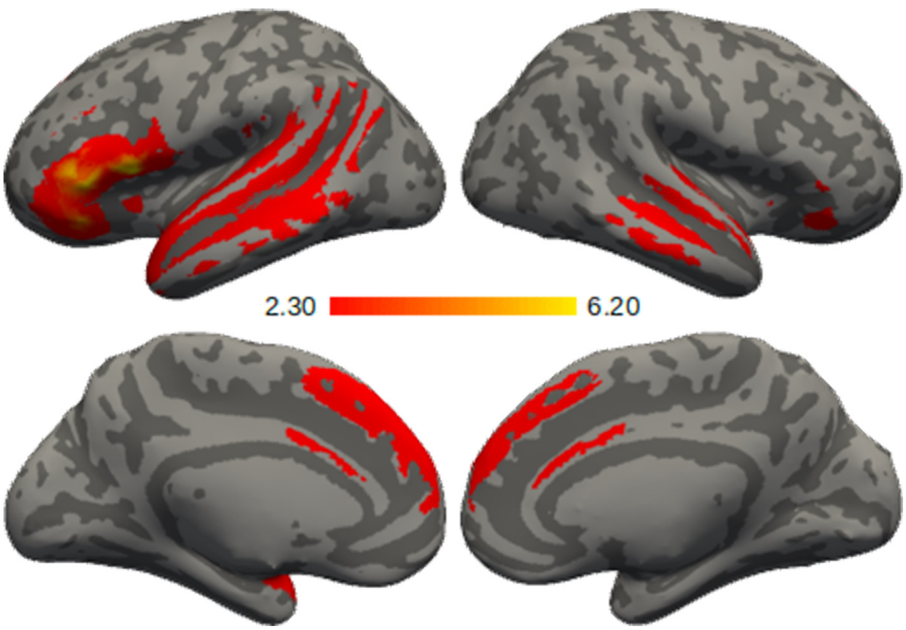

Fig. 1. Signed Differential Mapping (ES-SDM) analysis of the 54 pragmatic > literal language contrasts. Images to the left represent the lateral (top) and medial (bottom) views of the left hemisphere. Images to the right represent the lateral (top) and medial (bottom) views of the right hemisphere. Three significant clusters were found centered in the left inferior frontal gyrus, pars opercularis (BA 44); anterior middle cingulate cortex (BA 32); and right inferior frontal gyrus, pars orbitalis (BA 47). Maps were thresholded at $z < 2.3$, $k > 10$, $p < 0.005$ corrected for multiple comparisons. Region, cluster center, and individual foci are listed in Table A4. Cortical inflated reconstruction was performed with FreeSurfer Suite (http://surfer.nmr.mgh.harvard.edu/) (70). Coordinates are listed in Table A4.

(BA 19, Fig. 2). Jackknife sensitivity analysis revealed perfect replicability for the frontal regions, the left IFG and MCC (28/28 combinations), and good replicability for the lateral occipital cortex (24/28 combinations). Heterogeneity analysis found significant variability across studies for the left IFG, and no significant variability for other regions (Table A6).

A comparison analysis between metaphors and each of the other pragmatic forms revealed no significant differences.

Idiom ($n = 6$)

Subgroup analysis of contrasts for idioms found significant mean convergence in the left IFG (BA 45, Fig. 2), with low replicability according to the jackknife analysis (3/6 combinations). Heterogeneity analysis did not find significant variability across studies for this finding (Table A6).

A comparison analysis between idioms and each of the other pragmatic forms revealed no significant differences.

Irony ($n = 12$)

The subgroup analysis of contrasts for irony showed significant mean activation in the left hemisphere including dmPFC and rostromedial prefrontal cortex (rmPFC, BA 9, Fig. 2); IFG (BA 44), and STG (BA 22). These results obtained a high replicability in the mPFC, according to the jackknife analysis (11/12 combinations), and a moderate consistency in the IFG and STG, 7/12 and 6/12, respectively. Heterogeneity analysis found significant variability across studies for dmPFC and IFG, but not for STG (Table A6).

A comparison analysis between irony and each of the other pragmatic forms revealed no significant differences.

Subgroup analysis for natural language

We categorized each contrast according to the language in which the studies were conducted: Germanic languages (Dutch, English, and German), Romance languages (Spanish, French, and Italian), Japanese, and Mandarin Chinese. Studies in a Semitic languages (Hebrew) and in a Uralic languages (Hungarian) were not included in this subgroup analysis.

We calculated the mean of contrasts according to the natural language without considering the pragmatic form that was studied: Germanic languages included 29 contrasts (speech acts: 1, metaphor: 18, idiom: 14, and irony: 2); Romance languages, 8 contrasts (speech acts: 1, metaphor: 3, idiom: 1, and irony: 3); Japanese, 9 contrasts (speech acts: 1, metaphor: 3, and irony: 5); and Mandarin Chinese, 4 contrasts (speech acts: 1, metaphors: 2, and idiom: 1).

Germanic languages ($n = 29$)

The mean for pragmatic > literal language contrast for Germanic languages showed significant activation in the left IFG (BA 44, Fig. 3, Table A7) extending to temporal regions and the inferior lateral occipital cortex. Jackknife sensitivity analysis showed a perfect reproducibility in this region (29/29 combinations). The heterogeneity analysis revealed significant variability across studies for this finding (Table A7).

In the contrasts by pairs, Germanic versus other natural languages showed no significant differences.

Romance languages ($n = 8$)

The contrast of pragmatic > literal language for Romance languages showed significant activation in the left IFG (BA 44). Jackknife sensitivity analysis showed a perfect reproducibility for the left IFG (8/8). The heterogeneity analysis revealed significant between-study variability for both regions (Fig. 3, Table A7).

In the contrasts by pairs, Romance versus other natural languages showed no significant differences.

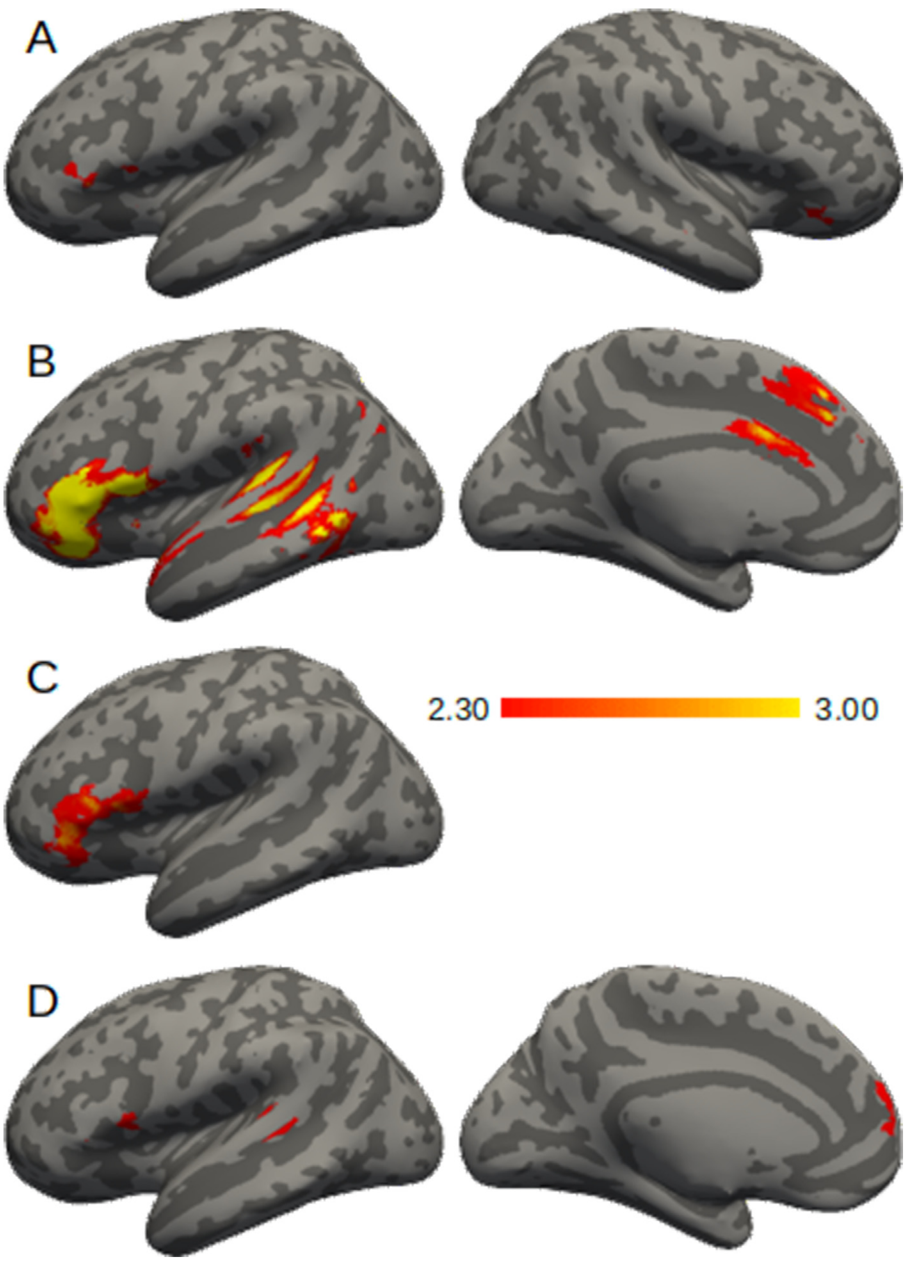

Fig. 2. Signed Differential Mapping (ES-SDM) subgroup analysis by pragmatic form. Mean activations per pragmatic form are shown. For speech acts, the lateral views of the left and right hemispheres are shown from left to right (A). Two significant clusters were found centered in the left and right inferior frontal gyrus, pars orbitalis (BA 47) and opercularis (BA 44), respectively. For metaphor the lateral (left) and medial (right) views of the left hemisphere are presented (B). Three significant clusters were found centered in left inferior frontal gyrus, pars opercularis (BA 44); the anterior middle cingulate cortex (BA 32); and left lateral occipital cortex (BA 19). For idioms, the lateral view of the left hemisphere is shown (C). One significant cluster was found centered in the left inferior frontal gyrus, pars triangularis (BA 45). For irony, the lateral (left) and medial (right) views of the left hemisphere are presented (D). Three significant clusters were found centered in the rostromedial prefrontal cortex (BA 10); left inferior frontal gyrus, pars opercularis (BA 44); and left superior temporal gyrus (BA 22). Not all views are presented for all pragmatic forms. Maps were thresholded at $z < 2.3$, $k > 10$, $p < 0.005$ corrected for multiple comparisons. Region, cluster center, individual foci, and their coordinates are listed in Table A6. Cortical inflated reconstruction was performed with FreeSurfer Suite (http://surfer.nmr.mgh.harvard.edu/) (70).

Japanese language (n = 9)

The contrast of pragmatic > literal language in Japanese presented greater convergence in the right dmPFC (BA 9) extending to the anterior cingulate cortex and rmPFC (Fig. 3), with a perfect replicability according to jackknife analysis (8/8 combinations). The heterogeneity analysis found significant between-study variability for this finding (Table A7).

In the contrasts by pairs, Japanese > Germanic languages contrasts showed significant differences in the right dmPFC (BA 9, MNI coordinates 2, 54, 22; z = 3.00, p < 0.05). In the Japanese > Romance and Japanese > Mandarin Chinese contrasts, no significant differences were found.

Mandarin Chinese language (n = 4)

The contrast of pragmatic > literal language for Mandarin Chinese showed no significant convergence in any region. However, in the contrasts by pairs, Mandarin Chinese > Germanic and Mandarin Chinese > Romance languages contrasts showed differences in the right inferior temporal gyrus (BA 20; MNI coordinates 62, −36, −16; 60, −38, −18; z = 3, p < 0.05), and Mandarin Chinese > Japanese presented differences in the right MTG (BA 21; 62, −36,-14; z = 3.00, p < 0.05).

Subgroup analysis for stimulus modality and writing system

Different stimulus modalities, as part of the pragmatic content configuration, were used in the studies included in this meta-analysis. Most studies used text and audio, sometimes in combination with images. We classified the contrasts according to stimulus modality: text (n = 39) and audio (n = 15). The mean of the contrasts for text showed convergence in the left IFG (BA 44) extending to temporal regions and the supramarginal gyrus; aMCC (BA 32); and right temporal pole (BA 38, Fig. 4, Table A8), while the average of experiments with audio showed convergence in the left IFG (BA 45), right MTG (BA 21), and STG (BA 22, Fig. 4, Table A8). The audio > text contrast showed differences in the right

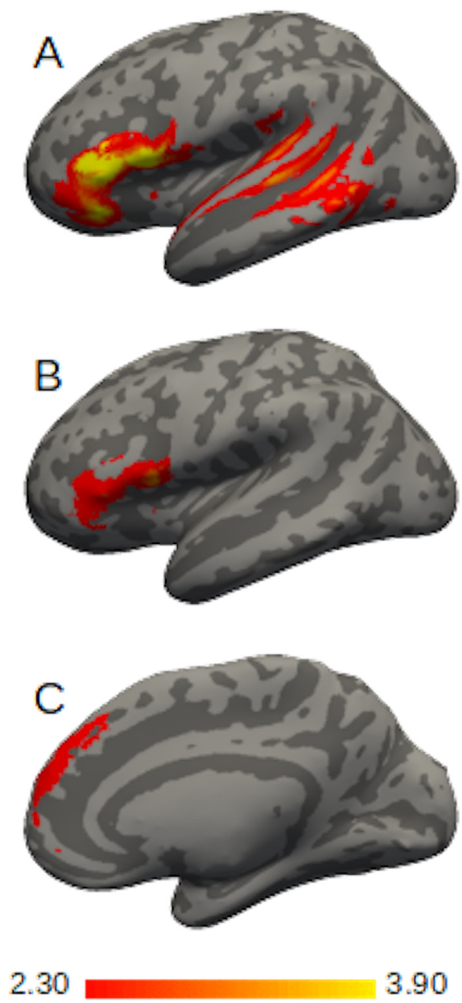

Fig. 3. Signed Differential Mapping (ES-SDM) subgroup analysis by natural languages. Mean activations per natural language are shown. For Germanic (A) and Romance (B) languages, the lateral view of the left hemisphere is shown. Only one significant cluster was found centered in the inferior frontal gyrus, pars opercularis (BA 44). For Japanese (C), the medial view of the right hemisphere is shown (bottom). One significant cluster was found centered in the dorso-medial prefrontal cortex (BA 9). Not all views are presented for all natural languages. Maps were thresholded at $z < 2.3$, $k > 10$, $p < 0.005$ corrected for multiple comparisons. Region, cluster center, individual foci, and their coordinates are listed in Table A7. Cortical inflated reconstruction was performed with FreeSurfer Suite (http://surfer.nmr.mgh.harvard.edu/) (70).

MTG (BA 21, MNI coordinates 54, −30, −4, $z = 2.00$, $p < 0.05$). In the opposite contrast (text > audio), no differences were detected.

Subgroup analysis for writing system

Then, we segregated the studies that used text to present the pragmatic content by type of writing system: transparent (Dutch, German, Spanish, Italian; $n = 14$), opaque (English, French, Hebrew; $n = 13$), and logographic (Japanese and Mandarin Chinese; $n = 12$). The studies that were conducted using audio were not included in this subgroup analysis.

Transparent writing system ($n = 14$)

The mean of pragmatic > literal language for transparent languages found two clusters with significant convergence: left IFG (BA 45) and planum temporale (BA 42) extending to MTG (Fig. 5, Table A9). No significant differences were detected for the transparent writing system compared to others (i.e., opaque and logographic).

Opaque writing system ($n = 13$)

The mean of pragmatic > literal language for opaque languages showed two clusters: left IFG (BA 44) extending to the temporal pole, and left MTG (BA 37) with extension to the planum temporale (Fig. 5, Table A9). Contrasts by pairs (opaque > transparent; opaque > logographic) did not show any differences.

Logographic writing system ($n = 12$)

The mean of pragmatic > literal language for logographic languages including Mandarin Chinese and Japanese found significant convergence in the dmPFC (BA 9, Fig. 5, Table A9). In contrast by pairs, the logographic > transparent contrast showed differences in the dmPFC (BA 9; MNI coordinates 6, 58, 18; $z = 2.00$, $p < 0.05$) including the anterior cingulate cortex (MNI coordinates −4, 54, 4; $z = 2.00$, $p < 0.05$), while the logographic > opaque contrast did not show any differences.

DISCUSSION

The main objective of the present meta-analysis was to identify the neural correlates of pragmatic function. For this purpose we selected contrasts of individual studies that tested pragmatic language comprehension compared to literal language comprehension, and we evaluated if they included brain areas associated with mentalizing processes as part of social cognition, in addition to canonical areas of language processing. An additional objective was to evaluate if each pragmatic form has a neural signature that distinguishes it from the rest. Finally, given the heterogeneity of studies in terms of pragmatic content configuration, such as natural language and modality of stimulus, we were interested in whether there was a differential recruitment of brain networks that could be related to these variations.

Meta-analyses have been widely accepted in social and health sciences as a useful research methodology to integrate and summarize the results of a collection of single studies on a given topic. In this meta-analysis, we included 48 articles and 54 contrasts that tested comprehension of pragmatic language, along with two fMRI studies from our laboratory, one dealing with speech acts (Licea-Haquet et al., 2016) and another dealing with metaphors (Zamora-Ursulo, 2018). Despite variability in methodological approaches between studies (e.g., different stimulus materials and control conditions, pragmatic forms, natural languages), we found a highly reproducible bilateral fronto-temporal network that included the mPFC including anterior cingulate cortex,

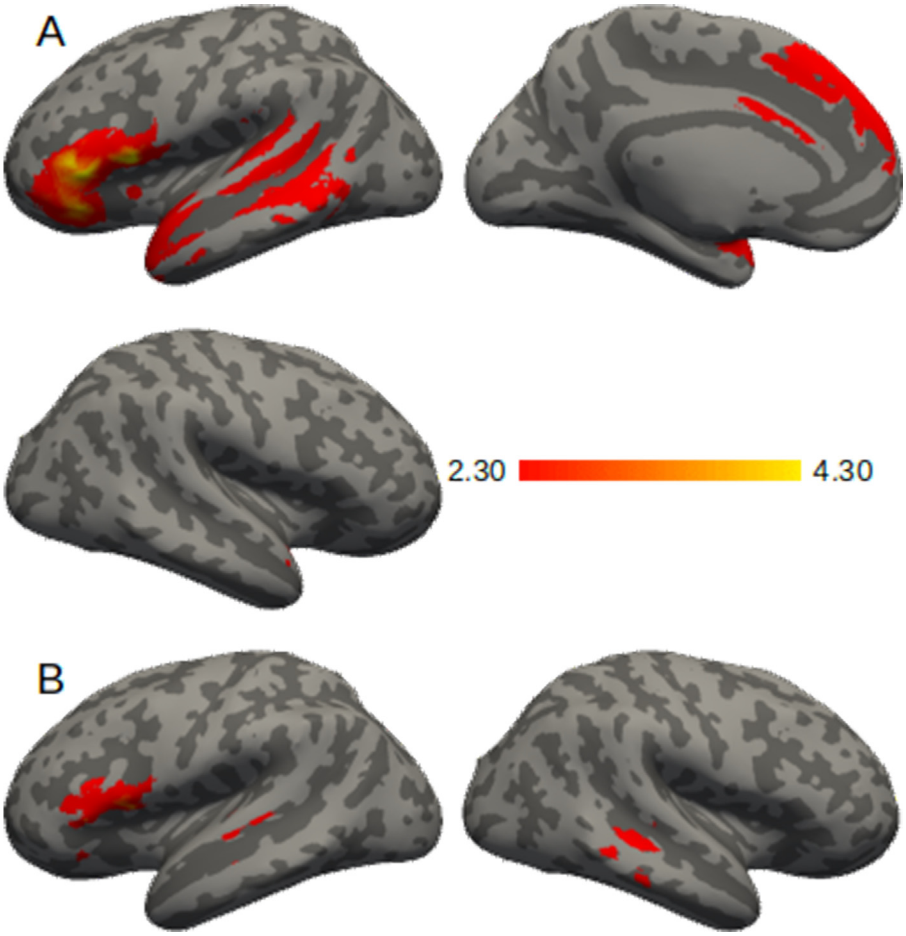

Fig. 4. Signed Differential Mapping (ES-SDM) subgroup analysis for stimulus modality. Mean activations per stimulus modality (i.e. text and audio, are shown). For text (A), the lateral and medial views of the left hemisphere (top) and the lateral view of the right hemisphere (middle) are shown. Three significant clusters were found centered in the left inferior frontal gyrus, pars opercularis (BA 44); anterior middle cingulate cortex (BA 32); and right temporal pole (BA 38). For audio (B), the lateral views of the left and right hemispheres are shown (bottom, from left to right). Three significant clusters were found centered in the left inferior frontal gyrus, pars triangularis (BA 45); and left superior temporal gyrus (BA 22). Not all views are presented for all modalities. Maps were thresholded at $z < 2.3$, $k > 10$, $p < 0.005$ corrected for multiple comparisons. Region, cluster center and coordinated are listed in Table A8. Cortical inflated reconstruction was performed with FreeSurfer Suite (http://surfer.nmr.mgh.harvard.edu/) (70).

regions that are part of the social cognition network that appears to support comprehension of pragmatic language. Significant inter-study heterogeneity was found only for left frontal regions (i.e. cingulate cortex, and inferior frontal gyrus) which could be associated with methodological differences (e.g., tasks, stimulus modality, pragmatic form) among studies. Thus, differences in the task characteristics may require a differential strategic-executive manipulation and selection of information resulting in heterogeneous involvement of frontal regions for pragmatic language comprehension.

In addition to the heterogeneity analysis, we performed a jackknife sensitivity analysis to evaluate the robustness and replicability of each individual analysis. Our results indicated that findings in frontal regions were perfectly replicable in analyses for all pragmatic forms (54 contrasts) and for subgroups of pragmatic forms. These results suggest that pragmatic language comprehension consistently engages heterogeneous executive mechanisms for complex integration of lexical, semantic, and contextual aspects of speech to select the best interpretation.

Pragmatic versus literal language

In support of previous meta-analyses of non-literal language (Bohrn et al., 2012; Rapp et al., 2012), pragmatic language comprehension with respect to literal language comprehension was found to recruit brain areas of the perisylvian fronto-temporal network in the left hemisphere (BA 44, 45, 47, 21, and 22), with homologous areas in the right hemisphere and mPFC. These findings are in agreement with the proposal that the communication of intentions involves the left language processing network as well as an extended network that includes the right hemisphere and brain regions associated with attribution of mental states or mentalizing, such as the mPFC (Bambini et al., 2011; Schurz et al., 2014).

The involvement of the bilateral IFG (BA 44, and 47) in pragmatic language comprehension could be understood in terms of its role in the detection of semantic violations, re-analysis of meanings (Bašnáková et al., 2014), and selection of the best interpretation of the message according to the context (Egorova et al., 2016). The results showed that the bilateral IFG is recruited during encoding of pragmatic meaning, underscoring its importance in selecting competing meanings (Yang et al., 2016) and building alternative models to choose the best one (Egorova et al., 2016); these processes are crucial for adequate pragmatic comprehension. While frontal regions are committed to selecting the best meaning, the temporal and parietal regions, such as the supramarginal gyrus, have been associated with activation and integration of the semantic knowledge relevant to a situation (e.g. specific social rules, listener's expectations, and speaker's intentions (Jung-Beeman, 2005; Frith and Frith, 2006; Chow et al., 2014)). According to the coarse semantic coding theory, the right hemisphere is more sensitive to distant semantic relations for selection of meaning, thus facilitating the comprehension of non-literal language (Jung-Beeman, 2005). In agreement with this hypothesis, right frontal and temporal brain regions could be recruited during pragmatic language comprehension to facilitate the interpretation of non-literal pragmatic content.

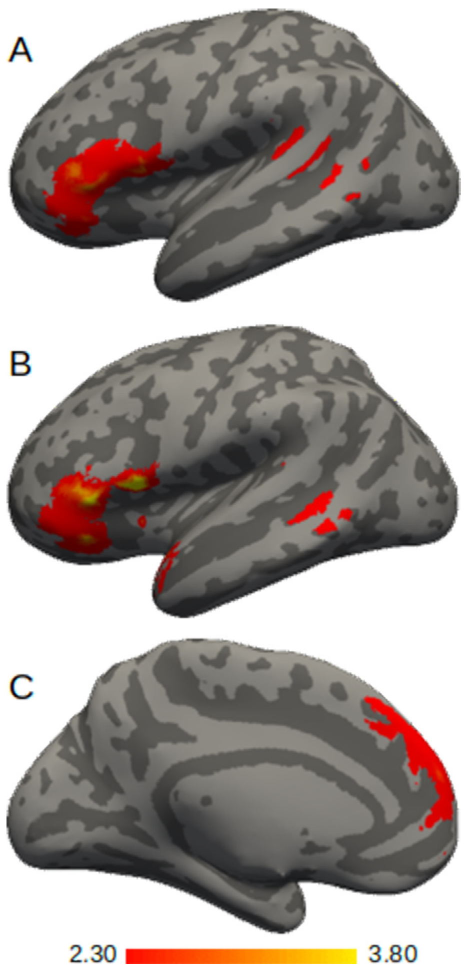

Fig. 5. Signed Differential Mapping (ES-SDM) subgroup analysis for text modality according to writing system. Mean activations per writing system are shown only on the left hemisphere. For the transparent writing system (A), two significant clusters were found centered in the inferior frontal gyrus, pars triangularis (BA 45); and planum temporale (BA 42). For the opaque writing system (B), two significant clusters were found centered in the inferior frontal gyrus, pars opercularis (BA 44); and middle temporal gyrus, posterior (BA 37). For the logographic writing systems (C), one significant cluster was found centered in the dorsomedial prefrontal cortex (BA 9). Maps were thresholded at $z < 2.3$, $k > 10$, $p < 0.005$ corrected for multiple comparisons. Region, cluster center, individual foci and their coordinates are listed in Table A9. Cortical inflated reconstruction was performed with FreeSurfer Suite (http://surfer.nmr.mgh.harvard.edu/) (70).

The regions of the mPFC engaged in pragmatic language comprehension included the middle and anterior cingulate cortex. These regions, with extension to the dorsomedial prefrontal cortex, have been implicated in mentalizing (Schurz et al., 2014; Yang et al., 2015) for inferring the communicative intention as part of pragmatic function. This area together with the precuneus, the temporo-parietal junction, and the anterior temporal lobe has been proposed as the neural system for mentalizing (Schurz et al., 2014; Yang et al., 2015) that forms part of a broader network of neural systems underlying social information processing (Yang et al., 2015). In addition, the frontal aslant tract, a newly described fascicle that connects Broca's region (BA 44/45) to the mPFC, has been proposed to participate in higher aspects of mentalizing. The frontal aslant tract appears to have evolved early, since it is also present in non-human primates, and may provide the basis for intentional communicative acts including gestures, vocalizations, and verbal expressions. It "may constitute the neural underpinning of the expression and recognition of communicative intentions" (Catani and Bambini, 2014).

In short, the results of the pragmatic versus literal language contrasts showed that pragmatic language comprehension involves areas related to social cognition, such as the mPFC, and bilateral fronto-temporal brain areas for the selection, activation and integration of meaning. According to coarse semantic coding theory, recruitment of these areas in the right hemisphere suggests that pragmatic language comprehension imposes additional cognitive processing for maintenance of broader meaning activation and recognition of distant relations (Jung-Beeman, 2005). Thus, frontal regions would be involved in the integration of high-level semantic information stored in temporal and parietal areas, and the mPFC would support the recognition of communicative intentions. In the following sections, we will discuss the functional roles of these brain areas as core or extended network components for processing pragmatic language in its different forms, to evaluate if each pragmatic form has a neural signature that distinguishes it from the rest.

Speech acts

Previous studies have suggested that comprehension of speech acts as a communicative function of an utterance involves lexico-semantic, action, and mentalizing circuits (Senft, 2014). However, the results of this meta-analysis showed that speech act comprehension recruited frontal brain areas, the left IFG and its homolog area in the right hemisphere. Indeed, the right IFG showed stronger convergence for speech acts compared to metaphor and irony, and the MTG only with respect to metaphors. It has been proposed that these areas in the right hemisphere perform semantic selection and integration of unusual, non-literal, novel, and diffuse or distant semantic fields (Jung-Beeman, 2005).

Metaphors

Metaphor comprehension, which associates two concepts of different domains in semantic memory, involved areas in the left hemisphere including the fronto-parietal-temporal network, the mPFC, and the lateral occipital cortex. The functional role of these areas in metaphor comprehension may include the activation and integration of knowledge for comprehension by parietal and temporal regions; attribution of intentions associated with the mPFC; and processing of shape features by the lateral occipital cortex as part of a large semantic cortical network (Beauchamp, 2005; Benedek et al., 2014; Yang et al., 2015; Handjaras et al., 2016). When compared with other pragmatic forms, no significant differences were found, even though there were more contrasts of metaphors than of other pragmatic forms. It may be that metaphor comprehension does not require additional cognitive resources because of its extended and familiar use and its fundamental role in abstract reasoning (Lakoff, 1993). It must be noted that in this meta-analysis, we did not test the influence of familiarity or salience of metaphors, which has been explored in previous studies (Rapp et al., 2012), instead we explored the role of pragmatic content configuration, that is natural language, writing system, and modality.

Idioms

Comprehension of this pragmatic form, considered as "frozen" semantic structures, recruited only left inferior frontal regions without involvement of mentalizing regions. The IFG may be required for increased attention to the salient or familiar idioms as an automatic semantic process (Yang et al., 2016), for selection of the best meaning of the utterance according to the context and stored meaning in memory, and inhibition of the literal meaning (i.e. word by word). Idioms did not show differences with respect to other pragmatic forms. Thus, the left inferior frontal gyrus, as part of a pragmatic language network, may be responsible for a process (likely the selection of meaning), that may be shared by all pragmatic forms.

Irony

Irony is a linguistic expression that normally signifies the opposite, typically for humorous or emotional effect. Comprehending irony requires a listener's ability to make inferences regarding a speaker's thoughts, intentions, and attitudes in terms of humoristic context. Consistently, our findings based on the mean of irony studies revealed increased activation in the dmPFC and rmPFC, IFG and STG for irony comprehension. No differences were detected in irony relative to other pragmatic forms. It must be taken into consideration that, in contrast to other pragmatic forms, irony frequently has a negative valence which involves emotional processing, as well as the recognition of intentions. The dmPFC and rmPFC have been shown to be involved in social behavior, decision-making, and emotional processing. Taken together, these findings support the role of an emotional correlate for irony comprehension (Tranel et al., 2002).

From these results, we may conclude that the only pragmatic form to show a particular neural signature is speech acts. The neural substrate for speech acts involves the right IFG associated with semantic selection of unusual, non-literal, novel, and diffuse semantic fields (Jung-Beeman, 2005). Speech acts share with the other pragmatic forms other brain regions, typically those classically associated with language processing, such as the left IFG.

Pragmatic content configuration

Our last objective was to find evidence for a shared neural substrate for pragmatic language comprehension regardless of the natural language and modality of stimulus presentation, what we designated as the "pragmatic content configuration".

Research on pragmatic language has been conducted mainly in Germanic languages with metaphors as the most frequently studied pragmatic form (Table A1). The subgroup of studies in Germanic languages showed convergence in the left language network. This convergence did not survive with respect to other natural languages. Studies that were conducted in Romance languages showed convergence in frontal regions, especially the IFG, related to selection of meaning. However, the convergence in this frontal area did not survive when compared to other natural languages. In contrast, studies in Japanese that included irony as the most frequent pragmatic form recruited areas associated with mentalizing (i.e., mPFC), which could be related to irony comprehension and not to the configuration of the Japanese language. The convergence in the mPFC in Germanic languages, survived for the Japanese language. Finally, Mandarin Chinese did not show convergence in any brain region. However, when compared to other languages, studies in Mandarin Chinese converged in the right temporal regions. In summary, the analysis of comparisons between languages showed that medial prefrontal regions were recruited by the Japanese language and right temporal regions by Mandarin Chinese in the right hemisphere, with respect to other languages. However, these results should be taken with caution since the number of studies in the various natural languages is very different: specifically, only four contrasts were included for Mandarin Chinese. Indeed, in the mean analysis as a subgroup these contrasts did not reach the statistical threshold for convergence in any brain region.

In addition to the difference in the number of studies per natural language, there is an uneven distribution of the various pragmatic forms that are studied in each language. As indicated before, metaphor is predominantly represented in Germanic languages, while irony is predominant in Japanese, and irony and idioms predominate in Romance languages. Given this heterogeneity, it is difficult to ascertain that the results of the subgroup analysis for natural language reflect only the effect of this variable. However, if one compares the results of the subgroup analyses for natural language and for pragmatic form it may be possible to distinguish between the two. In the case of Germanic languages, there are similarities with the brain regions of convergence for metaphor; in the case of Romance languages there are similarities with idioms, and not with irony, although there is the same number of studies for both pragmatic forms, and in the case of Japanese, irony recruits the left hemisphere, while the Japanese language recruits the right hemisphere. When comparisons were made between pairs of natural languages, Japanese and Germanic languages showed a significant difference in the right dorsomedial prefrontal cortex, while metaphor showed no differences when compared to irony. These results suggest that natural language may play a role in pragmatic language comprehension but more empirical studies are needed to ascertain this. In addition, it must be stressed that among languages we found more similarities than differences, in support of a putative universal neural correlate for pragmatic function which includes bilateral fronto-temporal regions and the mPFC engaging differentially depending on pragmatic form and stimulus configuration (including natural language).

The most common modalities for presenting pragmatic content are text and audio. In some cases a combination of text and image or audio and image, such as videos, is used. The studies that used text to present the pragmatic content showed a convergence in the left language network (i.e., fronto-temporal regions, mPFC, and right temporal pole). On the other hand, studies with auditory stimuli recruited left fronto-temporal regions and the right posterior middle temporal regions; the latter survived in the comparison between auditory and text modalities. Finally, the studies using text as a modality were classified according to the writing system of the various languages. The orthographic depth hypothesis (Katz et al., 1992) suggests that alphabetic orthographies could be classified according to the transparency of their letter-to-phoneme correspondence, where transparent writing systems (e.g., Dutch, German, Spanish, Italian) should be easier to read using word recognition processes that involve a constant and regular relation between letters and phonemes in the spoken word (sound–symbol), unlike opaque writing systems, such as English, French, Hebrew, which have an ambiguous-irregular letter–phoneme alignment (Katz et al., 1992). Languages such as Mandarin Chinese and Japanese use logographic scripts that do not follow the rules of grapheme–phoneme correspondence, but use symbols to represent meaning directly (Ellis et al., 2004). However, it must be noted that the Japanese writing system consists of two different types of letters, kana (phonogram) and kanji (morphogram) (Iwata, 2004). Japanese studies included in this meta-analysis did not report which type of writing system was used; hence, we categorized all of these studies as kanji because it is the most common form of writing system in Japanese.

In the case of transparent writing systems, pragmatic language comprehension recruited left fronto-temporal brain areas from the core language network (i.e., IFG and planum temporale, which are related to selection of meaning and auditory processing, respectively, Friederici, 2011). The possible involvement of auditory processing in the transparent writing system during pragmatic comprehension could be associated with the correspondence between letter and phoneme. Similarly, opaque writing systems recruited the left fronto-temporal language network. On the other hand, writing systems that use logographic scripts that do not follow the rules of grapheme–phoneme correspondence, such as Mandarin Chinese and Japanese, did not recruit neural areas from the language network. Findings of logographic writing systems involved activation in the dmPFC related to mentalizing, possibly because these languages use symbols to represent meaning directly (Ellis et al., 2004), and in pragmatic language, the meaning itself is the communicative intention. Indeed, significant differences in the dmPFC were detected only when comparing between logographic and transparent writing systems. Thus, this aspect of the pragmatic content configuration by itself does not change the proposed neural substrate for pragmatic language comprehension.

These results confirm that pragmatic language comprehension involves a bilateral fronto-temporal and medial prefrontal network, which we have named "pragmatic language network". Literal language processing and pragmatic language processing share many structures, but in support of coarse semantic coding theory, pragmatic language comprehension requires cognitive resources from fronto-temporal regions of the right hemisphere for activation and integration of semantic information and selection of the more appropriate meaning of an utterance; and the mPFC for coding of communicative intentions (i.e. mentalizing). Those resources are recruited differentially by different pragmatic forms: speech acts recruited both hemispheres for selection of word meaning (i.e. inferior frontal gyrus); metaphors involved areas in the left language network and mPFC related to mentalizing; idioms only recruited areas in the left hemisphere involved in the selection of meaning. Irony understanding requires the left language network and areas that participate in mentalizing. In sum, this "pragmatic language network" that reflects the interaction between the bilateral perisylvian regions and areas related to social cognition is needed for decoding pragmatic language, independently of natural language, modality of stimulus, and writing system. This pattern of activation supports the theoretical proposal that human language as a communicative tool involves semantic activation (parietal regions), integration (temporal regions), and selection (frontal regions); and intention recognition (mPFC). Accordingly, pragmatics refers to the capacity "to communicate in a way that is fundamentally a matter of social cognition" (Scott-Phillips, 2017).

This meta-analysis also underscores the importance of considering "pragmatic content configuration" including the natural language and stimulus modality. In this study, we found that the family of Germanic languages recruited only brain language areas, Romance languages only recruited left frontal regions, while Japanese recruited part of the mentalizing network, although those differences could be more related to pragmatic form than natural language. The role of natural language, however, cannot be completely rejected since significant differences were found in temporal areas in Mandarin Chinese with respect to other languages, and in the mPFC in Japanese relative to Germanic languages. This is probably not surprising, since according to Evans and Levinson (2009) "... diversity can be found at almost every level of linguistic organization." Regarding stimulus modality, both text and audio recruited the left-brain regions of the language network and mPFC, whereas right temporal regions were recruited for auditory versus text stimuli. All writing systems recruited elements of the left-brain regions of the language network and the mPFC, which was distinctive for the logographic writing system. Finally, the proposal of a universal neural substrate for all forms of pragmatic language needs to be tempered by the heterogeneity in the number of studies by pragmatic form and by natural language. Quantitative meta-analyses such as this one, represent a powerful tool to integrate information obtained from culturally and socially diverse studies to understand complex cognitive processes such as pragmatic language comprehension.

Among the limitations of this meta-analysis, the main one is the number of studies included. Subgroup analyses included as few as 4 and as many as 39 contrasts, thus limiting the inferences that can be made. Metaphor studies dominate the body of literature, irony studies rank a distant second, and speech acts a distant third. This heterogeneity in the number of studies per pragmatic form could produce a bias in the results toward cognitive strategies and neural correlates of the most studied pragmatic form (metaphor). Studies using Germanic languages dominate the literature, thus hindering the evaluation of whether there is indeed a universal neural substrate for comprehension of pragmatic language in all its forms. Therefore, it is difficult to separate the effect of the natural language from that of the pragmatic form. Similarly, the results of the contrast between stimulus modality and writing systems should be considered preliminary due to the unequal number of studies per stimulus modality and writing system. Finally, we did not differentiate between subtypes of pragmatic forms (e.g., different types of speech acts or metaphors) or factors such as imaginability, esthetic considerations, or familiarity; instead we explored the role of pragmatic content configuration (i.e., natural language, writing system, and modality).

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DECLARATION OF INTEREST

Conflict of interest: none.

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APPENDIX

Table A1. List and description of contrasts included in the meta-analysis organized by pragmatic form

Pragmatic form	First author, year	*n* (M, F)	Mean age (range)	Type of natural language	Writing system	Stimulus modality	*p*	Correction	Activation foci	Software
Speech acts	Shibata et al. (2011)	11, 4	25.2 (NI)	Japanese	Logographic	Text	< 0.001	Uncorrected	10	SPM5
Speech acts	van Ackeren et al. (2012)	0, 13	21.39 (18–24)	Germanic	NA	Image and audio	< 0.0001	Uncorrected	14	SPM8
Speech acts	Bašnáková et al. (2014)	5, 23	21.2 (2.67 SD)	Germanic	NA	Audio	< 0.001	FWE	12	SPM5
Speech acts	Bašnáková et al. (2015)	4, 16	20.8 (2.6 SD)	Germanic	NA	Audio	< 0.001	FWE	5	SPM8
Speech acts	van Ackeren et al. (2016)	0, 22	NI (18–35)	Germanic	NA	Audio	< 0.05	Cluster-corrected	5	SPM8
Speech acts	Egorova et al. (2016)	8, 10	27 (18–41)	Germanic	NA	Video and audio	< 0.05	FDR	11	SPM
Speech acts	Feng et al. (2017)	11, 12	22.4 (1.97 SD)	Mandarin Chinese	NA	Audio	< 0.05	AlphaSim	7	SPM8
Speech acts	Licea-Haquet et al. (2016)	14, 13	22.83 (19–28)	Romance	Transparent	Text	< 0.05	Multiple non independent comparisons	3	FSL 5
Metaphor	Rapp et al. (2004)	9, 6	NI (NI)	Germanic	Transparent	Text	< 0.001	Uncorrected	3	SPM99
Metaphor	Lee and Dapretto (2006)	6, 6	27.7 (23–35)	Germanic	NA	Audio	< 0.05	Multiple comparisons at the cluster level	3	SPM99
Metaphor	Stringaris et al. (2006)	12, 0	32.5 (8.6)	Germanic	Transparent	Text		SSQratio	4	Software developed at the Institute of Psychiatry, King's College London, using a non-parametric approach
Metaphor	Ahrens et al. (2007)	8, 0	21 (20–22)	Mandarin Chinese	Logographic	Text	< 0.001	Uncorrected	1	
Metaphor	Ahrens et al. (2007)	8, 0	21 (20–22)	Mandarin Chinese	Logographic	Text	< 0.001	Uncorrected	31	
Metaphor	Kircher et al. (2007)	11, 1	28.9 (8.2 SD)	Germanic	Transparent	Text	< 0.05	Uncorrected	1	SPM99
Metaphor	Shibata et al. (2007)	8, 5	23.8 (21–29)	Japanese	Logographic	Text	< 0.001	Uncorrected	5	SPM2
Metaphor	Stringaris et al. (2007)	11, 0	33.3 (NI)	Germanic	Opaque	Text		SSQratio	9	Software developed at the Institute of Psychiatry, King's College London, using a non-parametric approach
Metaphor	Chen et al. (2008)	10, 4	21.5 (NI)	Germanic	Opaque	Text	< 0.01	Uncorrected	6	VoxBo
Metaphor	Mashal et al. (2009)	9, 6	25 (22–28)	Hebrew	Opaque	Text	< 0.001	Uncorrected	1	BrainVoyager
Metaphor	Schmidt and Seger (2009)	5, 5	25 (19–42)	Germanic	Opaque	Text	< 0.001	Uncorrected	6	BrainVoyager
Metaphor	*Yang et al. (2009)	8, 10	26 (19–44)	Germanic	Opaque	Text	< 0.05	FDR	7	SPM5
Metaphor	*Yang et al. (2009)	8, 10	26 (19–44)	Germanic	Opaque	Text	< 0.05	FDR	10	SPM5
Metaphor	Bambini et al. (2011)	5, 4	25 (1 SD)	Romance	Transparent	Text	< 0.005	Multiple comparisons at the cluster level	10	AFNI

(*continued on next page*)

Table A1 (*continued*)

Pragmatic form	First author, year	*n* (M, F)	Mean age (range)	Type of natural language	Writing system	Stimulus modality	*p*	Correction	Activation foci	Software
Metaphor	Desai et al. (2011)	11, 11	24 (18–33)	Germanic	Opaque	Text	< 0.01	Monte Carlo	7	AFNI
Metaphor	Diaz et al. (2011)	8, 8	23.8 (18–30)	Germanic	Opaque	Text	< 0.01	Multiple comparisons at the cluster level	7	FSL 4.1.4
Metaphor	Diaz and Hogstrom (2011)	8, 9	24.8 (21–31)	Germanic	Opaque	Text	< 0.01	GRF	6	FSL 4.1.4
Metaphor	Forgács et al. (2012)	0, 20	24.2 (19–30)	Germanic	Transparent	Text	< 0.05	FWE	4	Brain Voyager
Metaphor	Lacey et al. (2012)	2, 5	20.8 (NI)	Germanic	NA	Audio	< 0.05	Monte Carlo	4	Brain Voyager
Metaphor	Shibata et al. (2012)	4, 10	25.9 (21–47)	Japanese	Logographic	Text	< 0.001	Uncorrected	5	SPM5
Metaphor	*Uchiyama et al. (2012)	10, 10	25.6 (21–30)	Japanese	Logographic	Text	< 0.05	Multiple comparisons at the cluster level	11	SPM5
Metaphor	Mashal et al. (2013)	7, 7	27.07 (3.88 SD)	Hebrew	Opaque	Text	< 0.001	Uncorrected	2	Brain Voyager
Metaphor	Citron and Goldberg (2014)	7, 19	27 (4.9 SD)	Germanic	Transparent	Text	< 0.05	FWE	7	SPM8
Metaphor	Obert et al. (2014)	9, 10	21.95 (19–27)	Romance	NA	Audio	< 0.001	Uncorrected	3	SPM8
Metaphor	Samur et al. (2015)	4, 16	21.89 (18–27)	Germanic	Transparent	Text	< 0.05	GRF	3	SPM8
Metaphor	Citron et al. (2016)	10, 15	26.2 (21–35)	Germanic	Transparent	Text	< 0.005	Uncorrected	24	SPM8
Metaphor	Pomp et al. (2018)	12, 6	25.83 (19–39)	Germanic	Transparent	Text	< 0.05	FWE	2	SPM8
Metaphor	Zamora-Ursulo (2018 in preparation)	13, 15	22.9 (20–26)	Romance	Transparent	Text	< 0.05	Multiple non independent comparisons	3	FSL6.0
Idiom	Zempleni et al. (2007)	8, 7	30.8 (7.7 SD)	Germanic	Transparent	Text	0.001	Uncorrected	5	SPM99
Idiom	Romero et al. (2008)	9, 13	25 (19–40)	Romance	Transparent	Text and picture	< 0.05	FWE	10	SPM2
Idiom	Boulenger et al. (2009)	10, 8	24.3 (6.3 SD)	Germanic	Opaque	Text	0.001	Uncorrected	2	SPM5
Idiom	*Hillert and Buračas (2009)	3, 7	23 (21–31)	Germanic	Transparent	Text	< 0.01	Cluster-corrected	5	FSL 5.4
Idiom	*Hillert and Buračas (2009)	3, 7	23 (21–31)	Germanic	Transparent	Text	< 0.01	Cluster-corrected	6	FSL 5.4
Idiom	Yang et al. (2016)	10, 10	21.7 (20–25)	Mandarin Chinese	Logographic	Text	< 0.05	Monte Carlo	2	AFNI
Irony	Uchiyama et al. (2006)	10, 10	21.9 (19–29)	Japanese	Logographic	Text	< 0.05	Multiple comparisons at the voxel level	10	SPM2
Irony	Wang et al. (2006	6, 6	26.9 (22–33)	Germanic	NA	Cartoon and audio	< 0.05	Multiple comparisons at the cluster level	4	SPM99
Irony	Wakusawa et al. (2007)	21, 17	22.3 (18–38)	Japanese	Logographic	Image and text	< 0.05	Multiple comparisons at the cluster level	2	SPM2
Irony	Rapp et al. (2010)	0, 15	28.1 (21–53)	Germanic	Transparent	Text	< 0.0005	Uncorrected	6	SPM5
Irony	Shibata et al. (2010)	10, 3	23.8 (20–29)	Japanese	Logographic	Text	< 0.0001	Uncorrected	4	SPM5
Irony	Spotorno et al. (2012)	8, 12	22 (NI)	Romance	Opaque	Text	< 0.05	FDR	8	SPM8

Table A1 (*continued*)

Pragmatic form	First author, year	*n* (M, F)	Mean age (range)	Type of natural language	Writing system	Stimulus modality	*p*	Correction	Activation foci	Software
Irony	*Uchiyama et al. (2012)	10, 10	25.6 (21–30)	Japanese	Logographic	Text	< 0.05	Multiple comparisons at the cluster level	6	SPM5
Irony	Varga et al. (2013)	10, 14	33.96 (23–55)	Hungarian	NA	Audio	< 0.05	cluster significance threshold	11	FSL 4.1.3
Irony	Akimoto et al. (2014)	18, 17	20.2 (18–23)	Japanese	Logographic	Text and picture	< 0.05	cluster size	2	SPM5
Irony	Obert et al. (2016)	11, 10	22.1 (20–27)	Romance	NA	Audio	< 0.05	FWE	3	SPM8
Irony	Bosco et al. (2017)	14, 9	22.7 (19–27)	Romance	Transparent	Text	< 0.05	FWE	2	SPM8
Irony	Herold et al. (2018)	5, 7	37 (26–55)	Hungarian	NA	Audio	< 0.05	cluster significance threshold	4	FSL 5.0.9

*Included more than one contrast, M = Male, F = Female, SD = Standard deviation, NI = No information, FWE = family wise error, FDR = free discovery rate, SSQratio = sum of squares of deviation due to residuals, GRF = Gaussian random fields.

Table A2. Description of task included in the meta-analysis organized by pragmatic form

Pragmatic form	First author, year	Type of fMRI design	Experimental task	Control task
Speech acts	Shibata et al. (2011)	ER	Participants completed an indirect replay reading task. Each scenario consisted of a short dialog involving two people: an initial remark spoken by the first person to a second person and a reply by the second person to the initial remark. The participants indicated whether the stimulus had a positive connotation, a negative connotation, or was meaningless; e.g., ‘‘Taro has given a 10 min presentation in his class. Taro asked his friend Jiro, ‘‘What did you think of my presentation?’’ ‘‘It’s hard to give a good presentation.’’	Participants completed a literal reading task. Each scenario consisted of a short dialog involving two people: an initial remark spoken by the first person to a second person and a reply by the second person to the initial remark. The participant indicated whether the stimulus had a positive connotation, a negative connotation, or was meaningless; e.g., ‘‘Yoko is taking a painting class and has finished her painting. Yoko asked her friend Ai, ‘‘What do you think of my oil painting?’’ ‘‘Your painting is very good.’’
Speech acts	van Ackeren et al. (2012)	ER	Participants listened to indirect requests, while seeing an image; 15% of the experimental trials were accompanied by a catch question (‘‘Do you think that the person made a request?’’), to which participants would respond by pressing a button to indicate either ‘‘yes’’ or ‘‘no’’; e.g., ‘‘It is very hot here (image of a closed window)’’	Participants listened to control utterances while seeing a control image (plausible statement but not a request); e.g. ‘‘It is very hot here (image of the desert)’’

(*continued on next page*)

Table A2 (*continued*)

Pragmatic form	First author, year	Type of fMRI design	Experimental task	Control task
Speech acts	Bašňáková et al. (2014)	Block	Participants heard stories and dialogs, and then answered if a statement was true/false by pressing a button; e.g., "John and Robert are following a course in Philosophy. It is almost the end of the semester. The lecturer has announced that they can either write a paper or give a presentation about a philosopher of their choice. Both John and Robert are ambitious students and want to get good grades. They know that they want to talk about postmodern philosophers, but they are not yet sure about the format. They are discussing their possibilities. J: I think that I will rather write a paper. R: I agree, you are a very good writer. J: Will you choose a presentation? R: It's hard to give a good presentation."	Participants heard stories and dialogs, and then answered if a statement was true/false by pressing a button; e.g., "John needs to earn some extra course points. One of the possibilities is to attend a student conference. He has never been to a conference before, and he has to decide whether he wants to present a poster or give a 15-min oral presentation. He is talking to his friend Robert, who has more experience with conferences. John knows that Robert will be realistic about how much work it takes to prepare for a conference. J: How is it to prepare a poster? R: A nice poster is not so easy to prepare. J: And how about a presentation? R: It's hard to give a good presentation."
Speech acts	Bašňáková et al. (2015)	ER	Participants listened to indirect questions and indirect replies. Then, a question was displayed, followed by a button-press; e.g., Have you followed any certified courses on leadership?	Participants listened direct questions and direct replies; e.g., What inspired you to go into people management?
Speech acts	van Ackeren et al. (2016)	ER	Participants were instructed to listen to the conversation carefully and think about whether B's response implied a request for A to act. To ensure that participants were engaged in the task, catch trials were introduced in 10% of trials. In catch trials, participants were asked to indicate whether B wants A to perform an action. Participants responded using their right hand via a non-magnetic button box inside the scanner. Indirect reply, e.g., Have you started preparing for the exam? Indirect question; e.g., Shall I move the TV closer to the sofa?	Participants were instructed to listen to the conversation carefully and think about whether B's response implied a request for A to act. To ensure that participants were engaged in the task, catch trials were introduced in 10% of trials. In catch trials, participants were asked to indicate whether B wants A to perform an action. Participants responded using their right hand via a non-magnetic button box inside the scanner. Direct reply; e.g., How far away is China?
Speech acts	Egorova et al. (2016)	ER	Participants watched videos of two people interacting (a "Partner" and a "Speaker") sitting at a table with 12 objects in front of them, and one of them would ask the other for these objects (requesting)	Participants watched videos of two people interacting (a "Partner" and a "Speaker") sitting at a table with 12 objects in front of them, and one of them would ask the other to name the objects on the table (naming)
Speech acts	Feng et al. (2017)	ER	Participants listened to a cover story that briefly introduced communication circumstance of indirect replay. There were 3 types of indirect replay: relevant replay, irrelevant replay with contextual hint, and irrelevant replay without contextual hint. Participants were asked to say if the speaker wanted to say "yes" or "no", and make the judgment as accurately and as quickly as possible by pressing the appropriate button	Participants listened to a cover story that briefly introduced communication circumstance of direct replay. There were 3 types of indirect replay: relevant replay, irrelevant replay with contextual hint, and irrelevant replay without contextual hint. Participants were asked to say if the speaker wanted to say "yes" or "no", and make the judgment as accurately and as quickly as possible by pressing the appropriate button
Speech acts	Licea-Haquet et al. (2016)	ER	Participants read short statements that included a direct speech-act. After reading the statement they had to answer whether or not the probe word that appeared on the screen referred to the action performed in the statement; e.g., Do not forget your appointment with the dentist today	Participants read short statements that were descriptions of a state of affairs. After reading the statement they had to answer whether or not the probe word that appeared on the screen referred to the action performed in the statement. In half of the trials the probe word did not refer to the previous statement; e.g., Ím really sorry I ruined your shirt
Metaphor	Rapp et al. (2004)	ER	Participants read metaphorical sentences and then indicated whether the sentences had a positive or negative connotation by pressing a button; e.g., "The lovers words are harp sounds."	Participants read literal sentences and then indicated whether the sentences had a positive or negative connotation by pressing a button; e.g., "The lovers words are lies."
Metaphor	Lee and Dapretto (2006)	Block	Participants heard triads of adjectives; the first two adjectives were literally related but opposite in meaning (e.g., hot–cold) and the third adjective was metaphorically related to the middle word (e.g., hot–cold followed by unfriendly or friendly)	Participants heard triads of adjectives; the first two adjectives were literally related but opposite in meaning (e.g., hot–cold) and the third adjective was literally related to the middle word (e.g., hot–cold followed by chilly or warm)

Table A2 (*continued*)

Pragmatic form	First author, year	Type of fMRI design	Experimental task	Control task
Metaphor	Stringaris et al. (2006)	ER	Participants were asked to silently read each presented sentence and the word that followed it, and decide as fast and as accurately as possible whether the meaning of the word was related or not to the meaning of the sentence that preceded it by pressing one of two buttons. The sentences were metaphorical; e.g., Some answers are straight—meetings	Participants were asked to silently read each presented sentence and the word that followed it, and decide as fast and as accurately as possible whether the meaning of the word was related or not to the meaning of the sentence that preceded it by pressing one of two buttons. The sentences were literal; e.g., Some answers are straight—honesty
Metaphor	Ahrens et al. (2007)	Block	Participants read conventional metaphors and pressed a button when they finished; e.g., ''The framework of this theory is very loose.''	Participants read literal sentences and pressed a button when they finished; e.g., ''He studied in the library the whole day.''
Metaphor	Ahrens et al. (2007)	Block	Participants read anomalous metaphor sentences and pressed a button when they finished; e.g., ''Their (financial) capital has a lot of rhythm''.	Participants read literal sentences and pressed a button when they finished; e.g., ''He studied in the library the whole day.''
Metaphor	Kircher et al. (2007)	ER	Participants read metaphorical sentences and then responded by pressing one of two buttons with the right index finger to indicate whether the sentence had a positive or negative connotation; e.g., ''The lovers words are harp sounds.''	Participants read literal sentences and then responded by pressing one of two buttons with the right index finger to indicate whether the sentence had a positive or negative connotation; e.g., ''The lovers words are lies.''
Metaphor	Shibata et al. (2007)	ER	Participants read metaphorical sentences and had to press a button if they understood the meaning of the metaphorical sentence, or a different button if they did not; e.g., ''An education is stairs.''	Participants read literal sentences and had to press a button if they understood the meaning of the sentence, or a different button if they did not; e.g., ''The dolphin is an animal.''
Metaphor	Stringaris et al. (2007)	Block	Participants read metaphorical sentences and indicated whether they ''made sense or not'' by pressing one of two buttons; e.g., ''Some surgeons are butchers.''	Participants read literal sentences and indicated whether they ''made sense or not'' by pressing one of the two buttons; e.g., ''Some surgeons are fathers.''
Metaphor	Chen et al. (2008)	ER	Participants read metaphorical sentences and judged whether they were plausible or not; e.g., ''The man fell under her spell.''	Participants read literal sentences and judged whether they were plausible or not; e.g., '' The child fell under the slide.''
Metaphor	Mashal et al. (2009)	Block	Participants read metaphorical sentences and pressed a button to indicate whether they thought the sentence had a positive or a negative meaning; e.g., ''In my window syllables knocked repeatedly.''	Participants read literal sentences and pressed a button to indicate whether they thought the sentence had a positive or a negative meaning; e.g., ''In the park, trees swayed silently.''
Metaphor	Schmidt and Seger (2009)	Block	Participants read metaphorical sentences and pressed the response key after each sentence as soon as they had understood it; e.g., ''The shadow is a piece of night.''	Participants read literal sentences and pressed the response key after each sentence as soon as they had understood it; e.g., ''The computers at my house are new.''
Metaphor	*Yang et al. (2009)	Block	Participants read metaphorical sentences and decided whether this item had a positive, negative, or neutral meaning; e.g., ''She is a candy.''	Participants read literal sentences and decided whether this item had a positive, negative, or neutral meaning; e.g., ''She is a friend.''
Metaphor	*Yang et al. (2009)	Block	Participants read metaphorical sentences and were asked to form a mental image of the subject of each sentence using the description provided. They were instructed to press the right button if they could form a mental image and press the left button if they could not; e.g., ''Life is a novel.''	Participants read literal sentences and were asked to form a mental image of the subject of each sentence using the description provided. They were instructed to press the right button if they could form a mental image and press the left button if they could not; e.g., ''Life is a mystery.''
Metaphor	Bambini et al. (2011)	ER	Participants read a metaphorical passage and made a judgment concerning which of the two adjectives better matched the previous passage by pressing a button; e.g., ''That voice is very shrill. (It) is an alarm.''	Participants read a literal passage and made a judgment concerning which of the two adjectives better matched the previous passage by pressing a button; e.g., ''That siren is very shrill. (It) is an alarm.''
Metaphor	Desai et al. (2011)	ER	Participants read a metaphorical sentence; e.g., ''The jury grasped the concept'', and then made a covert meaningfulness decision.	Participants read a literal sentence and then made a covert meaningfulness decision; e.g., ''The daughter grasped the flowers''. Participants were also tested in a recognition task to encourage attentiveness.

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Table A2 (*continued*)

Pragmatic form	First author, year	Type of fMRI design	Experimental task	Control task
Metaphor	Diaz et al. (2011)	ER	Participants read metaphorical sentences (familiar metaphors and novel metaphors) and rated their valence; e.g. ''The rumor was a disease.''	Participants read literal sentences (familiar literal and novel literal) and rated their valence; e.g. ''That bird is a robin.''
Metaphor	Diaz and Hogstrom (2011)	ER	Participants read two sentences. The first sentence was literal and the second was metaphoric (congruent or incongruent). Then participants judged each pair as related, unrelated, or non-word sentences; e.g., ''They casually traveled across the Mediterranean'' and ''A sailboat is a floating leaf.''	Participants read two sentences. The first sentences was literal and the second was also literal (congruent or incongruent). Then participants judged each pair as related, unrelated, or non-word sentences; e.g., ''The curious kids searched for wildfire'' and ''The pond creature was a water bug.''
Metaphor	Forgács et al. (2012)	ER	Participants read metaphorical sentences and indicated by pressing a button as fast and as accurately as possible whether the word appearing on the screen seemed familiar of unfamiliar to therm; e.g., plastic-oath	Participants read literal sentences and indicated by pressing a button press as fast and as accurately as possible whether the word appearing on the screen seemed familiar of unfamiliar to them; e.g., alarm-signal
Metaphor	Lacey et al. (2012)	ER	Participants listened to the conventional texture metaphor sentences and pressed a response button as soon as they understood the sentences; e.g., ''She had a rough day.''	Participants listened to a literal sentence and pressed a response button as soon as they understood the sentence; e.g., ''She had a bad day.''
Metaphor	Shibata et al. (2012)	ER	Participants read a metaphorical sentence, and pressed one button if they understood the meaning of the sentence or a different button if they did not; e.g., '' A memory is a warehouse.''	Participants read a literal sentence and pressed one button if they understood the meaning of the sentence or a different button if they did not; e.g., ''A dolphin is an animal.''
Metaphor	[*]Uchiyama et al. (2012)	ER	Participants read contexts describing situations and metaphorical sentences, then the participants were given four choices to classify the sentence as metaphor, sarcasm, literal incoherent, or literal coherent; e.g., ''The senior colleague tried hard to explain the history of the martial art to a foreigner who knew nothing about it. The senior said to his junior: It was bone-breaking.''	Participants read contexts describing situations and a literal sentences, then the participants were given four choices to classify the sentence. e.g., "The younger brother had an accident and his leg was in plaster. He said the following to his friend, who visited him and asked what happened: It was bone-breaking"
Metaphor	Mashal et al. (2013)	Block	Participants read pairs of words of metaphoric expressions; e.g., hatred net.	Participants read pairs of words of literal expressions; e.g., birth weight.
Metaphor	Citron and Goldberg (2014)	ER	Participants were instructed to silently read metaphorical sentences for comprehension and to respond to occasional ''yes/no'' questions by pressing one of two buttons with their right index and middle fingers; e.g., ''She received a sweet compliment.''	Participants were instructed to silently read literal sentences for comprehension and to respond to occasional ''yes/no'' questions by pressing one of two buttons with their right index and middle fingers; e.g., ''She received a nice compliment.''
Metaphor	Obert et al. (2014)	ER	Participants listened to predicative metaphorical sentences and decided whether they were literal or metaphorical; e.g., ''From the top of the dais, Jeremy catapulted his words.''	Participants listened to literal sentences and decided whether they were literal or metaphorical; e.g., ''From the top of the dais, Jeremy catapulted the stones.''
Metaphor	Samur et al. (2015)	ER	Participants read stories with metaphorical content, then responded to general questions about the content of the stories (yes/no); e.g., ''Robert was lost in thought. He had to make a decision about his job. He did not think about it too much.''	Participants read stories with literal content, then responded to general questions about the content of the stories (yes/no); e.g., ''Robert was lost in thought. He had his textbook lying open for three hours. He did not want to look at it''.
Metaphor	Citron et al. (2016)	ER	Participants read metaphorical stories, then answered a yes/no comprehension questions; e.g., ''China's economy was slowly growing again. Incomes went up, prices rose, and exports were at a record high. The Chinese stock exchange had arrived at the top again, while inflation was sinking.''	Participants read literal stories, then answered a yes/no comprehension questions; e.g., ''The economy in China slowly began to earn profits again. Incomes doubled, prices increased, and exports were record-breaking. The Chinese stock prices had arrived again at a good level, while the inflation rate was smaller.''

Table A2 (*continued*)

Pragmatic form	First author, year	Type of fMRI design	Experimental task	Control task
Metaphor	Pomp et al. (2018)	ER	Participants were instructed to silently read metaphorical olfactory sentences and to answer comprehension questions by pressing one of two response buttons with their right index and middle fingers; e.g., "He cannot smell him at all."	Participants were instructed to silently read literal sentences and to answer comprehension questions by pressing one of two response buttons with their right index and middle fingers; e.g., "He cannot stand him at all.
Metaphor	Zamora-Ursulo (2018 in preparation)	ER	Participants read metaphorical sentences, then responded categorical questions (yes/no); e.g. "Heart of stone."	Participants read literal sentences, then responded categorical questions (yes/no); e.g., "Stone sculpture."
Idiom	Zempleni et al. (2007)	ER	Participants read idiomatic sentences (opaque and transparent), then they were asked to press a button if they saw an italicized character; e.g., "During the laundry/became the skirt/out of the pleat."	Participants read literal sentences, then they were asked to press a button if they saw an italicized symbol; e.g., "During the interview the minister became less formal."
Idiom	Romero et al. (2008)	ER	Participants read idiomatic sentences, then a picture appeared below each sentence. Participants were instructed to judge whether the picture represented the meaning of the sentence or not	Participants read idiomatic sentences, then a picture appeared below each sentence. Participants were instructed to judge whether the picture represented the meaning of the sentence or not
Idiom	Boulenger et al. (2009)	ER	Idiomatic sentences were presented word by word, and then participants had to answer questions testing their comprehension; e.g. "Pablo kicked the habit."	Literal sentences were presented word by word, and the participants then answered questions testing their comprehension; e.g. "Pablo kicked the ball."
Idiom	*Hillert and Buračas (2009)	ER	Participants heard explicit idiomatic sentences and were instructed to perform a sentence decision task when the cross-hair was displayed. If they considered the sentence they heard to be meaningful, they were instructed to press the right key as quickly as possible; if they believed the sentence to be not meaningful, they were told to press the left key as soon as possible; e.g., "He was shooting the breeze."	Participants heard literal sentences and were instructed to perform a sentence decision task when the cross-hair was displayed. If they considered the sentence they heard to be meaningful, they were instructed to press the right key as quickly as possible; if they believed the sentence to be not meaningful, they were told to press the left key as soon as possible; e.g., "He met her in the new mall."
Idiom	*Hillert and Buračas (2009)	ER	Participants heard ambiguous idiomatic sentences, and were instructed to perform a sentence decision task when the cross-hair was displayed. If they considered the sentence they heard to be meaningful, they were instructed to press the right key as quickly as possible; if they believed the sentence to be not meaningful, they were told to press the left key as soon as possible; e.g., "The woman held the torch."	Participants heard literal sentences and were instructed to perform a sentence decision task when the cross-hair was displayed. If they considered the sentence they heard to be meaningful, they were instructed to press the right key as quickly as possible; if they believed the sentence to be not meaningful, they were told to press the left key as soon as possible; e.g., "He met her in the new mall."
Idiom	Yang et al. (2016)	Block	Participants read idiomatic phrases (opaque and transparent), and then they pressed a button if they saw a italicized character (experimental blocks) or an italicized symbol (in baseline blocks) and pressed another button if they did not see an italicized character or symbol; e.g., "Pretend to be deaf and dumb."	Participants read non-idiomatic literal phrases, and then pressed a button if they saw an italicized character (experimental blocks) or an italicized symbol (in baseline blocks), and pressed another button if they did not see an italicized character or symbol; e.g., "Jump off a cliff."
Irony	Uchiyama et al. (2006)	ER	Participants completed a sarcastic-scenario task. Each scenario consisted of two parts. The first part explained the situation of the protagonist, while the second part showed the comment of another protagonist. The comment did not directly match the situation and implied the opposite feeling; e.g., "When Takuya's mother came home, his clothes were strewn all over his room. When she saw this, she said to him: how do you always keep your room so tidy?"	Participants completed a sarcastic-scenario task. Each scenario consisted of two parts. The first part explained the situation of the protagonist, while the second part showed the comment of another protagonist. The comment corresponded to the situation and hence reflected the protagonist's true feeling; e.g., "When Takuya's mother came home, his clothes were strewn all over his room. When she saw this, she said to him: why do you always leave your room so messy?"

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Table A2 (*continued*)

Pragmatic form	First author, year	Type of fMRI design	Experimental task	Control task
Irony	Wang et al. (2006)	Block	Participants viewed cartoon drawings of children in a conversational setting while listening to a short story that ended with a potentially ironic remark, then they decided whether the speaker really meant what he or she said and pressed a button for yes, or another button for no; e.g., ‘‘When Mary accidentally knocked it down, Tom said: Way to go!”	Participants viewed cartoon drawings of children in a conversational setting while listening to a short story that ended with a sincere ending, then they decided whether the speaker really meant what he or she said, and pressed a button for yes, or other button for no; e.g., ‘‘Ashley and Zack are riding their bikes. When it starts to get dark out, Ashley says: Let's go home.”
Irony	Wakusawa et al. (2007)	ER	Participants were shown pictures depicting daily communicative situations during judgment tasks involving situational appropriateness and literal correctness. An utterance by one actor to the other was shown in a balloon; utterances could be ironic or metaphoric. Participants were asked to press one button if the utterance was situationally appropriate to the image, and other button if it was not	Participants were shown pictures depicting daily communicative situations during judgment tasks involving situational appropriateness and literal correctness. An utterance by one actor to the other was shown in a balloon; utterances could be literally correct but situationally inappropriate. Participants were asked to press one button if the utterance was situationally appropriate to the image, and other button if it was not
Irony	Rapp et al. (2010)	ER	During fMRI scans, the subjects silently read short text vignettes that ended in an ironic statement, and pressed a button any time the picture of a football appeared on the screen (attention task); e.g., ‘‘Petra hates fish. Her mother has cooked salmon for her. Petra says: Oh brilliant, my favorite meal!”	During fMRI scans, the subjects silently read short text vignettes that ended in a literal statement, and pressed a button any time the picture of a football appeared on the screen (attention task); e.g., ‘‘Katja loves spaghetti. Her mother has cooked a lot of spaghetti for her. Katja says: Oh brilliant, my favorite meal!” For non-target sentences, the priming text was presented acoustically with a female voice.
Irony	Shibata et al. (2010)	ER	Participants read the first four sentences that explained the situation of the protagonists. The fifth sentence suggested an ironic meaning. The participants had to press a button for ‘‘yes” or ‘‘no” depending on whether or not the final sentence expressed an ironic meaning; e.g., Ichiro and Yoko made a promise to have dinner at the restaurant. Seeing the guidebook, Yoko said, ‘‘This restaurant is fashionable and really nice!” When they went to the restaurant, the atmosphere was bad and they left most of their food. Ichiro said to Yoko, ‘‘This restaurant is fashionable and really nice!”	Participants read the first four sentences that explained the situation of the protagonists. The fifth sentences suggested a literal meaning. The participants had to press a button for ‘‘yes” or ‘‘no” depending on whether or not the final sentence expressed an ironic meaning; e.g., Jiro and Hanako made a promise to have dinner in the cafe. Seeing the guidebook, Hanako said, ‘‘This cafe is fashionable and really nice!” When they went to the cafe, the atmosphere was bad and they left most of their food. Jiro said to Hanako, ‘‘This cafe is disappointing!”
Irony	Spotorno et al. (2012)	ER	Participants read stories with a final ironic sentence, then answered a yes/no question; e.g., ‘‘Cynthia and Lea sing together in the same opera. On the night of the premier they meet at the theater. The show begins exactly on time. During their performance, both ladies sing out of key. After the show, Cynthia says to Lea: Tonight we gave a superb performance.”	Participants read stories with a final literal sentence, then answered a yes/no question; e.g., ‘‘Cynthia and Lea sing together in the same opera. On the night of the premier they meet at the theater. The show begins exactly on time. Both ladies sing beautifully and receive a rapturous round of applause. After the show, Cynthia says to Lea: Tonight we gave a superb performance.”
Irony	*Uchiyama et al. (2012)	ER	Participants read a sentence describing a certain situation and a sarcastic sentence, then the participants were given four choices to classify the sentence; e.g.,‘‘The woman was not a good cook and was taking up to an hour just preparing the ingredients. Her mother-in-law, who was watching how she was doing, said to her: You're very skillful.”	Participants read a sentence describing a certain situation and a literal sentences, then the participants were given four choices to classify the sentence. e.g., ‘‘The woman was a good cook and was preparing dinner efficiently. Her mother-in-law, who was watching how she was doing, said to her: You're very skillful.”

Table A2 (*continued*)

Pragmatic form	First author, year	Type of fMRI design	Experimental task	Control task
Irony	Varga et al. (2013)	ER	Participants heard short scenarios about social situations containing ironic remarks. Then had to answer ''YES" if the comment was true or ''NO" if the comment was false; e.g. Context phase: Tom and Ben are having an argument. Ben does not listen to Tom's opinion at all. Tom says: Ironic statement phase: I am so glad you always listen to my opinion. Question–answer phase: „Does Tom think that Ben does not listen to his opinion?	Participants heard short scenarios about physical causality. Then had to answer ''YES" if the comment was true or ''NO" if the comment was false; e.g., Context phase: There are peaches and apricots on the fruit trees in the garden. Suddenly, it starts hailing so strongly that all the fruit falls on the ground. Statement phase: By the time it stops, there is hardly any fruit left on the trees. Question–answer phase: Is there a lot of fruit on the trees after the storm?
Irony	Akimoto et al. (2014)	ER	Participants read stories that consisted of three phases: an introduction, a result, and a target statement. The statement had an irony intention. Each sentence was accompanied by a picture. e.g., Subject 1: I'll try the advanced course. How about you? Subject 2: Of course, me too! Subject 1: I'm going to practice in the beginner course. You: You got scared looking down a big slope. You miserably went down with the help of your friend. Subject 1: You are a good skier!	Participants read stories consisted of three phases: an introduction, a result, and a target statement. The statement had an irony intention. Each sentence was accompanied by a picture. e.g., Subject 1: I'll try the advanced course. How about you? Subject 2: Of course, me too! Subject 1: I'm going to practice in the beginner course. You: You and your friend skied down a big slope without stopping. You really enjoyed skiing. Subject 1: You are a good skier!
Irony	Obert et al. (2016)	ER	Participants were invited to listen to two-sentence stories, which were presented in a semirandom order. Then participants were invited to judge the nature of the item and indicate their choice by pressing the corresponding button (i.e., ironic or literal); e.g., This is the best promotion I've ever had in this company. ''Tomorrow, I'm leaving for good."	Participants were invited to listen two-sentence stories, which were presented in a semi-random order. Then participants were invited to judge the nature of the item and indicate their choice by pressing the corresponding button (i.e., ironic or literal); e.g. It's the worst post I've ever held in this company. ''Tomorrow, I'm leaving for good."
Irony	Bosco et al. (2017)	ER	Participants read stories with ironical context, then the target sentence was displayed on the screen. The participants had to identify the speaker's communicative intention expressed by means of the (same) utterance. Four alternative choices (literal, deceitful, ironic, and meaningless) were provided, and the subjects responded by pressing a button on the response box	Participants read stories with literal context, then the target sentence was displayed on the screen. Then the participants had to identify the speaker's communicative intention expressed by means of the (same) utterance. Four alternative choices (literal, deceitful, ironic, and meaningless) were provided, and the subjects responded by pressing a button on the response box
Irony	Herold et al. (2018)	ER	Participants heard 15 short scenarios about social situations containing ironic remarks. Then they had to answer ''YES" if the comment was true or ''NO" if the comment was false. e.g. Context phase: Joe went home from school and told his father that he had failed his math test. Ironic statement phase: His father said, ''Oh boy, you just made my day!" Question-answer phase: Did Joe's father think that Joe made his day? (Varga et al., 2013, pp. 240)	Participants heard 15 short scenarios about physical causality. Then they had to answer ''YES" if the comment was true or ''NO" if the comment was false; e.g., Context phase: It has been raining all day. There is so much water flowing down the water-spout that it floods the whole yard. Statement phase: The huge amount of water renders the entire yard heavily muddy. Question-answer phase: Does the yard stay dry after the day-long rain? (Varga et al., 2013, pp. 240)

ER = event related.

Table A3. List of studies that were excluded from the meta-analysis

Study	n		Pragmatic form	Natural language	Modality of stimulus	Reason for exclusion
	M	F				
Solomon (2017)	0	31	Metaphor	English	Text	Without whole-brain analysis
Lacey (2017)	6	6	Metaphor	English	Text	Without whole-brain analysis
Mashal (2014)	8	7	Metaphor	Hebrew	Text	Without whole-brain analysis
Benedek (2014)	10	18	Metaphor	German	Text	Measured production of metaphors
Desai (2013)	12	15	Metaphor	English	Text	Without coordinates for the contrast metaphor > literal
Subramaniam (2013)	7	7	Metaphor	English	Text	Without whole-brain analysis
Straube (2011)	17	0	Metaphor	German	Video	Measured metaphoric gestures
Eviatar (2006)	8	7	Metaphor and Irony	English	Text	Without whole-brain analysis
Desai (2013)	12	15	Idiom	English	Text	Without coordinates for the contrast idiom > literal
Mashal (2008)	14		Idiom	Hebrew	Text	Without coordinates for the contrast idiom > literal
Varga (2015)	14		Irony	Hungarian	ND	Article in Hungarian

*ND: No data.

Table A4. Results of the meta-analysis for pragmatic versus literal language

Voxels	Hem.	Region	Cluster center – MNI Coordinate			*Z*	JK	Het	Individual foci – MNI Coordinate			Label
			x	*y*	*z*				*x*	*y*	*z*	
Pragmatic > literal language n = 54												
9074	Left	Inferior frontal gyrus, opercularis (BA 44)	−46	18	0	6.2	54	5.29				
						5.81			−50	26	2	Left inferior frontal gyrus, triangularis
						4.2			−60	−34	10	Left superior temporal gyrus, posterior
						4.16			−58	−44	10	Left supramarginal gyrus, posterior
						3.96			−60	−42	0	Left middle temporal gyrus, posterior
						2.83			−56	−6	−6	Left superior temporal gyrus, anterior
						2.83			−48	−64	34	Left lateral occipital cortex, superior
						2.54			−56	−4	−18	Left middle temporal gyrus, anterior
4396	Left	Middle cingulate cortex, anterior (BA 32)	−4	40	30	4.39	53	3.98				
						4.37			−4	42	26	Anterior cingulate cortex, perigenual
2039	Right	Inferior frontal gyrus, orbitalis (BA 47)	44	24	−14	2.94	47	n.s				
						2.84			58	−14	−10	Right middle temporal gyrus, posterior
						2.71			49	14	−14	Right temporal pole
						2.69			60	−18	0	Right superior temporal gyrus, posterior
						2.54			52	−12	8	Right Heschl's gyrus
						2.54			52	6	−8	Right planum polare

Hem = Hemisphere, BA = Brodmann's area, JK = Jackknife, Het = Heterogeneity, n.s = not significant.

Table A5. Results of subgroup analysis for corrected and uncorrected studies

Voxels	Hem.	Region	Cluster center – MNI Coordinate			Z	JK	Het	Individual foci – MNI Coordinate			Label
			x	y	z			Label	x	y	z	
Corrected n = 36												
7165	Left	Inferior frontal gyrus, opercularis (BA 44)	−46	18	0	5.24	28	4.79				
						5.23			−42	18	−2	Left insular cortex
						3.69			−58	−40	16	Left planum temporale
						3.59			−60	−44	10	Left superior temporal gyrus
						3.47			−60	−22	4	Left planum temporale
						3.31			−60	−48	0	Left middle temporal gyrus, posterior
						2.48			−44	−68	36	Left lateral occipital cortex, superior
2785	Left	Middle cingulate cortex, anterior (BA 24)	0	40	28	3.77	36	4.28				
						3.31			−2	34	42	Prefrontal cortex, dorsomedial
404	Right	Superior temporal gyrus, posterior (BA 22)	60	−34	2	2.63	32	n.s				
						2.62			62	−34	−2	Right middle temporal gyrus, posterior
						2.32			58	−18	4	Right planum temporale
75	Right	Inferior frontal gyrus, opercularis (BA 44)	44	22	−10	2.55	32	n.s				
						2.52			40	22	−14	Right frontal orbital cortex
Uncorrected n = 18												
2020	Left	Inferior frontal gyrus, triangularis (BA 45)	−50	30	6	3.67	18	3.79				
259	Left	Prefrontal cortex, dorsomedial (BA 8)	−2	28	40	2.61	16					
						2.41			2	18	34	Middle cingulate cortex, anterior
33	Right	Precentral gyrus (BA 4)	56	2	30	2.41	2					

Hem. Hemisphere, BA = Brodmann's area, JK = Jackknife, Het = Heterogeneity, n.s = not significant.

Table A6. Results of subgroup analysis by pragmatic form

Voxels	Hem.	Region	Cluster center – MNI Coordinate			Z	JK	Het	Individual foci – MNI Coordinate			Label
			x	y	z				x	y	z	
Speech-acts n = 8												
110	Right	Inferior frontal gyrus, orbitalis (BA 47)	42	24	−8	2.46	5	n.s				
257	Left	Inferior frontal gyrus, opercularis (BA 44)	−44	20	0	3.07	7	3.39				
Metaphor n = 28												
3192	Left	Inferior frontal gyrus, opercularis (BA 44)	−48	18	−2	4.22	28	4.09				
						3.47			−60	−52	−2	Left middle temporal gyrus, posterior
						3.45			−58	−36	16	Left planum temporale
						3.05			−58	−48	10	Left supramarginal gyrus
						2.81			−50	−64	−12	Left lateral occipital cortex, inferior
						2.46			−54	−2	−6	Left superior temporal gyrus, anterior

(*continued on next page*)

Table A6 (*continued*)

Voxels	Hem.	Region	Cluster center – MNI Coordinate			Z	JK	Het	Individual foci – MNI Coordinate			Label
			x	y	z				x	y	z	
1868	Left	Middle cingulate cortex, anterior (BA 24)	0	10	38	3.08	28	n.s				
						3.04			−4	34	44	Prefrontal cortex, dorsomedial
1868	Left	Lateral occipital cortex, superior (BA 19)	−40	−68	40	2.57	24	n.s				
Idiom n = 6												
1290	Left	Inferior frontal gyrus, triangularis (BA 45)	−56	24	12	2.87	3	n.s				
						2.87			−54	28	14	Left inferior frontal gyrus, triangularis
						2.7			−52	12	4	Left inferior frontal gyrus, opercularis
Irony n = 12												
857	Left	Prefrontal cortex, dorsomedial (BA 9)	2	54	20	2.74	11	4.54				
						2.72			−2	56	16	Prefrontal cortex, rostromedial
150	Left	Inferior frontal gyrus, opercularis (BA 44)	−50	16	4	2.49	7	3.44				
68	Left	Superior temporal gyrus, posterior (BA 22)	−60	−40	12	2.46	6	n.s				

Hem. Hemisphere, BA = Brodmann's area, JK = Jackknife, Het = Heterogeneity, n.s = not significant.

Table A7. Results of subgroup analysis by natural language family

Voxels	Hem.	Region	Cluster center – MNI Coordinate			Z	JK	Het	Individual foci – MNI Coordinate			Label
			x	y	z				x	y	z	
Germanic n = 29												
6326	Left	Inferior frontal gyrus, opercularis (BA 44)	−46	18	0	4.84	29	3.79				
						4.63			−50	28	6	Left inferior frontal gyrus, triangularis
						3.67			−56	−36	18	Left planum temporale
						3.63			−60	−28	4	Left superior temporal gyrus
						3.62			−60	−50	−2	Left middle temporal gyrus, posterior
						2.83			−50	−66	−8	Left lateral occipital cortex, inferior
Romance n = 8												
1487	Left	Inferior frontal gyrus, opercularis (BA 44)	−46	12	0	3.65	8	4.67				
						2.91			−44	36	2	Left inferior frontal gyrus, triangularis
Japanese n = 9												
2681	Right	Prefrontal cortex, dorsomedial (BA 9)	2	54	22	3.18	9	2.93				
						2.18			0	50	20	Middle cingulate cortex, anterior
						3.17			-4	56	18	Prefrontal cortex, rostromedial
						3.16			-2	52	14	Anterior cingulate cortex, perigenual
						2.78			6	50	38	Prefrontal cortex, dorsomedial

Hem. Hemisphere, BA = Brodmann's area, JK = Jackknife, Het = Heterogeneity.

Table A8. Results of subgroup analysis for studies with text as stimulus modality

Voxels	Hem.	Region	Cluster center – MNI Coordinate			Z	JK	Het	Individual foci – MNI Coordinate			Label
			x	y	z				x	y	z	
Text n = 39												
5201	Left	Inferior frontal gyrus, opercularis (BA 44)	−46	18	0	5.24	38	5.41				
						5.24			−48	22	−2	Left inferior frontal gyrus, triangularis
						3.62			−58	−36	14	Left planum temporale
						3.58			−60	−50	0	Left middle temporal gyrus, posterior
						3.56			−58	−42	14	Left supramarginal gyrus, posterior
3892	Left	Middle cingulate cortex, anterior (BA 32)	−4	42	26	3.84	38	3.84				
						3.72			−4	34	38	Prefrontal cortex, dorsomedial (BA 8)
						3.15			0	14	38	Middle cingulate cortex, posterior
19	Right	Temporal pole (BA 38)	46	12	−18	2.36	37	n.s				
Audio n = 15												
1104	Left	Inferior frontal gyrus, triangularis (BA 45)	−44	20	−2	3.43	15	3.09				
300	Right	Middle temporal gyrus, posterior (BA 21)	56	−36	−6	2.52	0	n.s				
						2.48			52	−34	−12	Right inferior temporal gyrus, posterior
						2.38			56	−24	−4	Right superior temporal gyrus
122	Left	Superior temporal gyrus (BA 22)	−60	−20	−2	2.59	12	2.44				
						2.49			−60	−32	6	Left superior temporal gyrus/planum temporale

Hem. Hemisphere, BA = Brodmann's area, JK = Jackknife, Het = Heterogeneity, n.s = not significant.

Table A9. Results of subgroup analysis by writing system

Voxels	Hem.	Region	Cluster center – MNI Coordinate			Z	JK	Het	Individual foci – MNI Coordinate			Label
			x	y	z				x	y	z	
Transparent n = 14												
2202	Left	Inferior frontal gyrus, triangularis (BA 45)	−48	24	−2	3.46	14	3.98				
						3.41			−48	14	2	Left inferior frontal gyrus, opercularis
350	Left	Planum temporale (BA 42)	−58	−40	18	2.69	14	n.s				
						2.59			−56	−54	4	Left middle temporal gyrus, posterior
Opaque n = 13												
2665	Left	Inferior frontal gyrus, opercularis (BA 44)	−48	16	0	4.56	13	3.98				
						4.54			−48	18	−4	Left inferior frontal gyrus, triangularis
						4.41			−46	6	−24	Left temporal pole
193	Left	Middle temporal gyrus, posterior (BA 37)	−60	−52	−2	2.73	13	2.43				
						2.36			−58	−38	16	Left planum temporale

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Table A9 (*continued*)

Voxels	Hem.	Region	Cluster center – MNI Coordinate			*Z*	JK	Het	Individual foci – MNI Coordinate			Label
			x	*y*	*z*				x	y	z	
Logographic n = 12												
2835	Right	Prefrontal cortex, dorsomedial (BA 9)	2	54	22	3.3	12	2.4				

Hem. Hemisphere, BA = Brodmann's area, JK = Jackknife, Het = Heterogeneity, n.s = not significant.

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