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Idiomatic expressions evoke stronger emotional responses in the brain than literal sentences

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ABSTRACT

Recent neuroscientific research shows that metaphors engage readers at the emotional level more strongly than literal expressions. What still remains unclear is what makes metaphors more engaging, and whether this generalises to all figurative expressions, no matter how conventionalised they are. This fMRI study aimed to investigate whether idiomatic expressions - the least creative part of figurative language - indeed trigger a higher affective resonance than literal expressions, and to explore possible interactions between activation in emotion-relevant neural structures and regions associated with figurative language processing. Participants silently read for comprehension a set of emotionally positive, negative and neutral idioms embedded in short sentences, and similarly valenced literal sentences. As in studies on metaphors, we found enhanced activation of the left inferior frontal gyrus and left amygdala in response to idioms, indexing stronger recruitment of executive control functions and enhanced emotional engagement, respectively. This suggests that the comprehension of even highly conventionalised and familiar figurative expressions, namely idioms, recruits regions involved in emotional processing. Furthermore, increased activation of the IFG interacted positively with activation in the amygdala, suggesting that the stronger cognitive engagement driven by idioms may in turn be coupled with stronger involvement at the emotional level.

1. Introduction

1.1. Emotion and language

In the last decade, a large body of neuroscientific literature has shown that the affective content of verbal material affects reading and more generally language comprehension (for reviews, see Citron, 2012; Jacobs et al., 2015). In particular, affectively-laden words are given processing priority in that they are processed faster and more efficiently, elicit larger electrophysiological responses at very early processing stages, and activate affect-related brain regions more strongly than neutral words. These regions include amygdala, insula, anterior cingulate cortex and orbitofrontal cortex, among others (e.g., Citron et al., 2014a; Herbert et al., 2009; Kissler et al., 2007; Kuchinke et al., 2005; Scott, O'Donnell, Leuthold and Sereno, 2009). Similar findings have been reported for affectively-laden sentences and texts (e.g., Altmann et al., 2012; Ferstl et al., 2005; Hsu et al., 2015a,b; Lai et al., 2015). These studies typically manipulated emotional valence, the extent to which a stimulus is pleasant/positive or unpleasant/negative, and emotional arousal, the degree of physiological activation elicited by a stimulus, e.g., how exciting/agitating or idle a stimulus is (Lang et al., 1997; Russell, 2003; Wilson-Mendenhall et al., 2013).

The relationships between language and affect have been primarily investigated at a literal level. This represents an important limitation since figurative language is extensively used in everyday communicative exchanges (Cameron, 2008; Jackendoff, 1995; Pollio et al.,

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1977), is very pervasive in literary texts and poems (Jacobs, 2015; Lüdtke et al., 2014), and represents a crucial medium for social communication (Maas et al., 2014).

1.2. The role of figurative language in conveying affect

Figurative language seems to be particularly suited to convey affect. Pioneering work on metaphors has already shown that these are used more productively in the description of one's own feelings about a personal event compared to the description of the event itself, and that such productivity is enhanced for more intense feelings (Fainsilber and Ortony, 1987; Ortony and Fainsilber, 1987). More recently, metaphors have been shown to help qualify the emotional meaning of social interactions (Maas et al., 2014): processing metaphors creates a sense of greater interpersonal closeness or intimacy compared to matched literal sentences (Bowes & Katz, 2015; Cameron, 2008; Horton, 2007), and enhances our ability to detect the mental states and emotions of others (Bowes & Katz, 2015).

Most importantly, recent neuroimaging research has shown that reading metaphorical expressions leads to significantly stronger activation of brain structures associated with the processing of highly arousing emotional stimuli compared to matched literal counterparts. For instance, sentences containing taste metaphors (e.g., *She looked at him sweetly*) activated the amygdala more strongly than their literal renderings (*She looked at him kindly*) (Citron and Goldberg, 2014). Since the amygdala is associated with the detection of evolutionary or contextually salient (emotional) stimuli (Cunningham and Brosch, 2012; Garavan et al., 2001; Hamann and Mao, 2002; Herbert et al., 2009; Seeley et al., 2007), the authors suggested that metaphorical formulations may be more emotionally engaging than literal ones (Citron and Goldberg, 2014). This result has subsequently been replicated using metaphors not related to taste embedded in natural stories (Citron et al., 2016a), simple sentences, and in proficient speakers of a second language (Citron et al., 2019a). These studies also reported significantly enhanced activations of other components of the emotion neural network, including insula, anterior cingulate cortex, orbitofrontal cortex, hippocampus and parahippocampal cortex, and caudate nuclei (Citron and Goldberg, 2014; Citron et al., 2016a; Citron et al., 2019a). Consistently, enhanced left amygdala activation was observed for metaphorical compared to literal compound words (Forgács et al., 2012), and for figurative compared to literal materials (mostly metaphors) in a meta-analysis of neuroimaging studies on figurative language (Bohrn et al., 2012a). Finally, metaphorical translations of English metaphors into Spanish elicited enhanced heart rate responses (a measure of physiological arousal) compared to literal translations (Rojo et al., 2014). Other brain regions associated with affective processing have shown significantly enhanced activation in response to figurative expressions also in studies that were not designed to explore the effects of emotional content, for instance the anterior cingulate and insular cortices (ACC, AIC; Bambini et al., 2011), the left hippocampus and parahippocampal cortex (Citron and Goldberg, 2014; Forgács et al., 2012; Schmidt and Seger, 2009), and the right orbitofrontal cortex (OFC; Citron and Goldberg, 2014), but less consistently than it was found for amygdala.

1.3. Open questions and aims

The empirical evidence in support of enhanced affective response to figurative expressions is strongly biased toward metaphors, which represent the most complex and often most creative members of the large family of expressions forming figurative language. The conventionality of figurative expressions has often been conceived as a graded property between two end poles, one pole represented by the most conventionalised expressions (for instance, idioms) and the other by the most creative ones (for instance, poetic metaphors). But even the meaning of highly conventional metaphorical expressions can be characterised by some interpretative ambiguity: for example, *She is a sweet girl* may mean that she is kind, gentle, caring or happy. Meaning ambiguity tends to be higher in novel metaphors whose meaning needs to be created on the fly, e.g., *Her husband is an elephant; Juliette is the sun*. Instead, the meaning of "frozen" or "dead" metaphors, is so conventionalised that they are no longer perceived as metaphors, e.g., *That was a superficial reaction; He left everything behind*. The highest degree of conventionalisation is the hallmark of idioms (e.g., *She kicked the bucket*) where the relationship between literal and figurative meaning is often entirely opaque. Hence, a reasonable question is whether high affective resonance is a property of figurative language *per se* or only concerns the trope par excellence, metaphor. It could be the case that the more conventionalised a figurative expression is (as is the case for idioms) the less the affective engagement, compared to literal expressions.

But what makes figurative language more affectively engaging than matched literal sentences? We do not know it yet. One possibility is that the higher cognitive demands associated with the processing of figurative language, indexed by additional prefrontal activation (Bohrn et al., 2012a; Reyes-Aguilar et al., 2018; Uchiyama et al., 2012; Yang, 2014), trigger a more attentive and affectively-laden mode of processing. This could be the case for metaphors that activate multiple lexico-semantic representations, require the blending of often distant semantic domains as well as the ability to selectively identify, within the source domain, what is relevant to the target. But this could be true for idioms as well since recent studies reported a stronger and more widespread activation of the language network for idioms, in particular in the inferior frontal and middle temporal gyri (e.g., Boulenger et al., 2009; Mashal et al., 2008; Romero Lauro et al., 2008; Zempleni et al., 2007). Idiom processing seems to be at the same time faster but more resource-demanding than the processing of comparable literal sentences. This increased workload on the language system may reflect the need to process at least part of the literal meanings of the idiom's constituent words, retrieve the idiomatic meaning from long-term semantic memory, select between potentially competing interpretations, and integrate the idiom meaning in context while suppressing idiom-irrelevant word meanings.

Another possibility is that, no matter the cognitive demands associated with processing, figurative meanings of conventional metaphorical expressions are more salient than literal meanings (Giora, 1999) and therefore trigger a higher attentional and affective engagement. This would be in line with the literature on emotive word processing, showing that highly emotionally arousing words are distinguished from neutral ones very early on (for a review, see Citron, 2012).

To address these questions, the present fMRI study focuses on the processing of idiomatic expressions varying in emotional content from very negative, through emotionally neutral, to very positive, and compares them with literal expressions with a similar range of emotional content. Beyond testing whether idiomatic expressions elicit stronger emotional responses in the brain than literal ones, this study explores possible interactions between activation in the amygdala and in other areas that respond to idiom processing through functional connectivity analyses, to address the question of what makes figurative expressions affectively engaging.

1.4. Idiom processing

Idioms belong to the vast family of multi-word expressions stored in semantic long-term memory (for overviews, see Cacciari, 2014; Siyanova-Chanturia, 2013). Multi-word expressions are as frequent as words (Jackendoff, 1995) and represent an inescapable challenge to language processing models. In contrast to most metaphors, idiomatic meanings are highly conventionalised and cannot be inferred from their constituent words since the relationship between lexical items (*He was over the moon)* and phrasal meaning (*He was extremely happy*) is often arbitrary and learned. Evidence for a role of idioms in conveying affect comes from studies on discourse analysis which have shown that idioms are preferred over literal sentences when speakers express something in indirect ways, seek affiliation with their interlocutors while formulating complaints, or signal a change of topic (Drew and Holt, 1988, 1998).

In recent years, neuroimaging, transcranial magnetic stimulation (TMS), and lesion studies have consistently shown that processing idiomatic sentences, compared to literal ones, involves a bilateral, fronto-temporal neural network including the inferior frontal gyri (IFG) and the middle temporal gyri (MTG), with a left-hemispheric dominance (Bohrn et al., 2012a; Mashal et al., 2008; Romero Lauro et al., 2008; Zempleni et al., 2007). In addition, the (left) dorso-medial prefrontal cortex (dmPFC) and the right temporal pole (TP) are more strongly active in processing idiomatic than matched literal sentences (Romero Lauro et al., 2008). Hence, processing idioms requires more processing resources than literal sentences. Specifically, activation of the IFG is associated with response selection and inhibition, problem solving, and working memory, more generally known as executive functions (Bunge et al., 2001; McNab et al., 2008; Osaka et al., 2004), but also with the integration of verbal material and word knowledge into meaningful sentences (Menenti et al., 2009; Rapp et al., 2011); the MTG is the seat of semantic and conceptual representations (Bookheimer, 2002; Ferstl et al., 2008); the dmPFC is functionally associated with inference processing, theory of mind, and processing of internal mental states (Frith and Frith, 2012; Jenkins and Mitchell, 2010; Siebörger et al., 2007); whereas the TP is associated with increasing activation demand while reading texts (Yarkoni et al., 2008) and mentalising while reading fiction (Altmann et al., 2012).

1.5. The present study

The present fMRI study investigated whether idiomatic expressions, that represent the least creative part of figurative language, indeed produce an affective response in the brain similar to that induced by metaphors, namely significantly enhanced activation of the left amygdala (Citron and Goldberg, 2014). This study also explored possible interactions between the neural activation in emotion-relevant neural structures (amygdala) and in the brain regions associated with figurative language processing (e.g., the IFG) (Cacciari and Papagno, 2012), through functional connectivity analyses. If there is stronger functional coupling between IFG and amygdala in the idiom condition than in the literal sentence condition, this would support the idea of enhanced cognitive engagement necessary for processing idioms, which in turn evokes stronger affective engagement. If, however, a weaker functional coupling between IFG and amygdala is found in the idiom condition than in the literal condition, this would be more consistent with the idea of affective engagement due to idioms' salience rather than to processing demands. Additionally, we also explored correlations between affective and psycholinguistic properties of the stimuli employed and discussed such relationships in light of extant literature.

2. Method

This study was approved by the Ethics Committee of the Freie Universität Berlin, was conducted in accordance with The Code of Ethics of the World Medical Association (Declaration of Helsinki), and with the guidelines of the American Psychological Association.

2.1. Participants

Twenty-six German native speakers from the Berlin area (13 women, 19–36 years, mean age = 27, SD = 5) participated in the study. They were paid 20€. Participants had normal or corrected-to-normal vision, no neurological diseases or learning disabilities. They gave informed consent prior to the experiment. After pre-processing, the data of 3 participants were excluded from further analyses because one suffered from claustrophobia in the scanner and the remaining two had very noisy data (head movements larger than 3 mm). The remaining 23 participants (12 women) had the same demographics as above. No participants were excluded based on their performance in the yes/no comprehension questions, which was good overall (*mean response accuracy* 91%, *SD* 8%).

2.2. Materials

The full stimulus dataset is openly accessible through the Open Science Framework at: https://mfr.osf.io/render?url=https%3A%2F%2Fosf.io%2Fgd8e6%2Fdownload. Ninety idiomatic sentences, ranging in their affective content from very negative through emotionally neutral to very positive, were selected from a database of German idioms normed for emotional valence, emotional arousal, familiarity, concreteness, figurativeness, semantic transparency, confidence about the knowledge of the idiomatic meaning, and actual knowledge (Citron et al., 2016b). In addition, 129 German literal sentences were created and normed for emotional valence, arousal, familiarity and concreteness by 11-to-12 participants (23 in total, 16 women, 7 men, *mean age* = 32, *SD* = 11 years), who did not take part in the current experiment. Ninety literal sentences were selected, ranging in their degree of affective content similarly to the idiomatic sentences. These were unrelated to the idiomatic sentences but had similar values in affective and psycholinguistic variables (see Table 1 for examples). We selected

Table 1
Examples of idiomatic and literal sentences used.

Valence	Language	Idiomatic sentences	Literal sentences
Negative	Original German	Er führt Böses im Schilde.	Sie ärgert sich über ihren Vorgesetzten.
	Literal translation in English	He carries evilness in the shield.	She is angry at her supervisor.
	Idiomatic meaning	He has evil intentions.	-
Negative	Original German	Sie holt sich den Tod.	Sie ist überarbeitet.
	Literal translation in English	She catches death.	She is over-worked.
	Idiomatic meaning	She does something imprudent.	-
Neutral	Original German	Sie hält ihre Zunge im Zaum.	Er kontrolliert gerade den Ablauf.
	Literal translation in English	She holds her tongue in the bridle.	He is currently checking the process.
	Idiomatic meaning	She is cautious of what she says.	-
Neutral	Original German	Sie lassen Gras über die Sache wachsen.	Er denkt jetzt daran.
	Literal translation in English	They let the grass grow over something.	He thinks about it now.
	Idiomatic meaning	They forget about an incident that happened.	-
Positive	Original German	Er ist bis über beide Ohren verliebt.	Sie lacht über den Scherz.
	Literal translation in English	He is in love over both ears.	She laughs about the joke.
	Idiomatic meaning	He is crazily in love.	-
Positive	Original German	Er hat einen guten Draht zu ihm.	Sie verwirklicht nun ihren Wunsch.
	Literal translation in English	He has a good wire to him.	She realises her wish now.
	Idiomatic meaning	He gets along very well with him.	-

Table 2
Descriptive statistics of affective and psycholinguistic properties of idiomatic and literal sentences.

Variables	Idiomatic sentences		Literal sentences	
	Mean (SD)	Min - Max	Mean (SD)	Min - Max
Emotional valence	-0.01 (1.60)	-2.78 - 2.78	0.02 (1.53)	-2.67 - 2.67
Absolute valence	1.34 (0.86)	0.00 - 2.78	1.27 (0.83)	0.00 - 2.67
Emotional arousal	3.91 (0.91)	1.88 - 6.00	4.32 (0.98)	2.40 - 6.45
Familiarity	5.12 (0.77)	3.00 - 6.64	4.78 (0.68)	2.91 - 5.91
Concreteness	2.98 (0.83)	1.33 - 5.18	3.28 (1.10)	1.67 - 5.75
Syntactic complexity	1.00 (1.00)	0.00 - 3.00	2.00 (1.00)	0.00 - 3.00
Length in letters	28.00 (7.00)	14.00 - 49.00	29.00 (9.00)	15.00 - 61.00
Figurativeness	3.87 (0.25)	3.27 - 5.05	-	-
Semantic transparency	4.40 (1.05)	2.00 - 6.44	-	-
Knowledge of idiom meaning	6.55 (0.72)	3.63 - 7.00	-	-

idioms without a semantically plausible literal interpretation (unambiguous idioms) to avoid ambiguity of interpretation. Syntactic complexity of all items was determined by counting the number of subordinate clauses, relative clauses, passive forms, compound nouns, appearing persons, adverbs and adverbial phrases, conjunctive forms, analytically-formed tenses or infinitive constructions, marked or deviating sentence structures. Descriptive statistics are reported in Table 2.

Idiomatic meanings were very well known, with a mean rating of 6.55 out of 7, and ranged in their degree of figurativeness, with a mean of 3.87 out of 7 (7 = highly figurative), and semantic transparency, with a mean of 4.40 out of 7 (7 = semantically opaque).

Idiomatic and literal sentences were matched for emotional valence ($t(178) = 0.12$, *ns*), absolute valence (i.e., the degree of emotional content irrespective of whether its valence is positive or negative) $t(178) = 0.59$, *ns*), length in letters ($t(167.17) = 1.48$, *ns*), and syntactic complexity $t(178) = 1.27$, *ns*). Idiomatic sentences had slightly but significantly lower levels of arousal ($t(178) = 2.90$, $p < .01$) and were slightly more familiar ($t(178) = 3.20$, $p < .01$) than literal sentences, while literal sentences were slightly more concrete ($t(165.27) = -2.03$, $p = .044$).

Ninety hash mark string sequences were used as a visual baseline, matched with all sentences in length in letters/hash marks ($t(268) = 0.53$, *ns*) and number of words/hash mark strings ($t(268) = 0.90$, *ns*). Finally, 6 filler sentences were presented in groups of 2 at the beginning of each of 3 runs. A total of 24 yes/no comprehension questions[1] were also presented to control for accurate comprehension and to make sure participants kept engaging with the materials throughout the whole experiment.

2.2.1. Statistical analyses of stimulus properties

To explore the relationships between affective and psycholinguistic properties of our sentences and assess their consistency with previously published databases, the following analyses were conducted. For idiomatic sentences only, literal sentences only, and all sentences together, multiple regression analyses predicting emotional arousal ratings from emotional valence ratings (linear and quadratic, or $valence^2$) were computed by entering all other variables in a first step to ensure any additional source of variance was explained and to test the unique contribution of valence to arousal. In the first step, the following variables were included for all three sets of stimuli: familiarity, concreteness, syntactic complexity and length in letters; whereas for idioms only the additional variables figurativeness, semantic transparency and knowledge of the idiomatic meaning were included. In addition, for each set of stimuli, partial linear correlations between variables were computed by using the remaining variables as covariate and partial out their variance.

2.3. Procedure

The experiment was conducted at the Dahlem Institute for the Neuroimaging of Emotion (D.I.N.E.), at the Freie Universität Berlin, and programmed with Presentation (Neurobehavioral System Inc.). Stimulus order and timings were optimised by using OPTSEQ2 (Dale, 1999) which created randomised sequences of experimental conditions and null events of varying durations. Four different randomised orders of stimuli were created with varying inter-stimulus intervals (ISIs). Each sequence was subsequently divided into 3 runs.

Participants read instructions describing the whole experiment, signed the informed consent form and were led into the scanner room. First, the magnitude and phase images of the magnetic field in the scanner were measured (gradient echo field map, 1 min). Then the experimenter repeated the task instructions orally, asking participants to silently read sentences for comprehension, to attend to the hash mark strings and to respond to occasional yes/no questions by pressing one of two buttons with their right index and middle fingers. During functional scanning, the stimuli were visually presented in 3 runs with each run lasting approximately 8 min. At the beginning of each run, 2 filler sentences were presented, followed by 30 idiomatic sentences, 30 literal sentences, 10 hash mark string sequences and 8 questions, in intermixed order. After the task, a structural image was acquired (5 min). After scanning, participants completed an online questionnaire with all idioms used: they were first asked to rate how confident they were about their knowledge of each idiom (on a 7-point Likert scale) and then to type in its meaning.

Each stimulus was presented for 2 s at the centre of a computer screen, in white font on a black background. Only the questions were presented for 4 s. During the jittered ISIs (1000–6000 ms), a fixation cross was centrally presented in order to keep participants' gaze and attention focused. The experiment lasted approximately 1.5 h, including preparation, scanning and debriefing; 267 functional volumes were acquired per run.

2.4. MRI data acquisition and pre-processing

The neuroimaging and behavioural data are openly accessible through OpenNeuro at: https://openneuro.org/datasets/ds001934. Magnetic resonance images were acquired by means of a 3-T Tim-Trio scanner (Siemens, Erlangen) equipped with a 12-channel receive RF head coil. Magnitude and phase images (gradient echo field map) were acquired first: 37 slices per image; 3-mm thick with a 60° flip angle;

[1] Examples of occasional yes/no comprehension questions after some of the target sentences used for the experiment. Literal sentence: "She is now silent."; followed by the question: "Is she wildly hopping around?" (from the German idiom "wild herumspringen"). Literal sentence: "He can no longer tolerate that."; followed by "Does he still like that?". Idiomatic sentence: "He does not leave any good hair at it." (German idiom "kein gutes Haar daran lassen"), meaning "He has nothing good to say about it."; followed by the question "Is his remark negative?".

voxel size: 3x3x3 mm; FOV 192 mm isotropic voxels without gap; matrix per slice: 64 × 64 mm; TR 488 ms; 2 TE: 4.92; 7.38 ms; acquisition time 1'05". For functional images, a standard EPI sequence was used: 37 slices, 3-mm thick with a 70° flip angle; voxel size: 3x3x3 mm; FOV 192 mm isotropic voxels without gap; matrix per slice: 64x64 mm; TR 2000 ms; TE 30 ms; acquisition time 8'36". Lastly, full-brain, T1-weighted structural scans were acquired (MPRAGE sequence): 176 slices, 9° flip angle, voxel size: 1x1x1 mm, FOV 256 mm without gap; matrix per slice: 256 × 256 mm; TR 1900 ms, TE 2.52 ms, acquisition time 4'26".

Pre-processing of the functional images and statistical analyses were performed using SPM12 (Wellcome Trust Centre, http://www.fil.ion.ucl.ac.uk/spm), employing field map estimation, slice timing correction, realign and unwarp for magnetic field inhomogeneity, and co-registration of structural T1 to the realigned mean functional image. Structural images were segmented into grey matter, white matter, cerebrospinal fluid (CSF), bone, soft tissue and air/background. Based on the segmented grey and white matter images, a group anatomical template was created with the DARTEL toolbox (Ashburner, 2007). The functional images were then iteratively normalised to standard space (Montreal Neurologic Institute, MNI), and spatially smoothed with a 6-mm Gaussian kernel to adjust for between-participant anatomical differences.

2.5. *Statistical analyses of fMRI data*

A General Linear Model (GLM) was created in an event-related design. Hemodynamic responses were time-locked to the stimulus onset for the whole duration of each stimulus presentation and convolved with the canonical hemodynamic response function of SPM12. Seven linguistic regressors were used to model the different stimuli and conditions: a first linguistic regressor defined the onsets of each sentence (both idiomatic and literal) and was followed by two parametric regressors containing arousal and familiarity ratings, and a dummy parametric regressor defining idiomatic (coded as 1) versus literal sentences (coded as -1). This model aimed to partial out the variance due to imbalance in arousal and familiarity between idiomatic and literal sentences and then compare the BOLD signal response between the two conditions.[2] Additionally, three linguistic regressors contained hash mark strings, questions, and fillers. Functional images containing idioms for which participants did not know the correct meaning were omitted from the analysis (modelled as fillers). On average, we had to exclude 1.74 (SD = 1.63) idioms per participant or 1.93% of idioms in the whole experiment. Finally, 6 regressors of non-interest for head movements were included in the model: 3 for linear movements across the sagittal (x), horizontal (y) and vertical/coronal (z) axes, 3 for non-linear (warping) movement including pitch, roll and yaw. Beta images of the parametric regressor capturing variance for the contrast of Idiomatic sentences > Literal sentences (after arousal and familiarity ratings have been accounted for) for each participant were used for the group analysis in both directions. For statistical significance at the whole brain level, a cluster-forming threshold of $p < .005$ uncorrected was chosen, along with a cluster-level threshold, corrected for false-discovery rate (FDR), of $p < .05$ (Lieberman and Cunningham, 2009).

2.5.1. *Functional connectivity analysis*

We anticipate that, among other brain regions, we found significantly enhanced activation of the left amygdala in response to Idiomatic sentences > Literal sentences at the whole brain level. In order to test whether this brain response was functionally coupled with activations in other significant clusters, we conducted a generalised Psychophysiological Interaction analysis (gPPI; Friston et al., 1997; McLaren et al., 2012). We defined two seed regions: one in the left amygdala based on the Talairach Deamon (TD) Brodmann areas atlas, adapted to MNI coordinates, as implemented in the WFU PickAtlas toolbox (Maldjian et al., 2003); and one spherical region of 10-mm radius in the left IFG (MNI -45 30 16) based on the results of the contrast Idiomatic sentences > Literal sentences. The vector of neural response in each condition was estimated by deconvoluting the first eigenvariate of the BOLD signal extracted from the seed regions. The interaction vector of each condition was calculated as the product of the estimated neural response vector and the condition vector. We then performed a first level general linear model analysis[3] separately for each seed region. Due to difficulty to run a gPPI analysis with parametric modulators, we did not partial out the variance of arousal and familiarity ratings in these models. Each first-level gPPI model included five interaction vectors, five condition vectors (idiomatic sentences, literal sentences, hashmark strings, questions and fillers), and the estimated neural response vector of each seed region as regressors. The contrast images between the interaction term of the Idiomatic sentence condition and that of the Literal sentence condition from each participant were taken for the second level, one-sample t-test. For each gPPI analysis we looked at results at the whole-brain level and also applied a-priori small volume corrections (SVC): for the gPPI with left IFG seed, we applied SVC with the amygdala mask based on Brodmann areas, while for the gPPI with amygdala as seed, we applied SVC with the left IFG mask, based on the seed created for the main analyses. For significance levels within the small volume, an initial threshold of $p < .001$ uncorrected was chosen, then the voxel-level threshold of $p < .05$ corrected for family-wise error (FWE; Bennett et al., 2009) within the mask.

2.5.2. *Post-hoc parametric analyses of emotional valence. Computation of percentage signal change (PSC) in amygdala and IFG as a function of emotional valence and of idiomatic versus literal conditions*

Our experimental design did not allow investigation of the effects of idiomaticity and emotional valence in a factorial design (2x3 ANOVA) as the number of stimuli per condition is 30, which does not provide enough statistical power (also considering the exclusion of a few idiom trials based on participants' actual knowledge of them).[4] However,

[2] We did not include concreteness ratings as an additional parametric regressor as we were convinced that the difference in concreteness (lower for idioms, only just significant at p = .044) was solely due to how this variable was measured: the rating task asked participants to evaluate the *idiomatic meaning* of idioms. This may have led them to consider only the more abstract, figurative meaning of the strings. In fact, idioms' SD is lower than literal sentences' SD and significantly unequal (see statistics in the Materials sub-section and Table 2). However, we know from a wealth of psycholinguistic research that, when people read idioms for comprehension, the literal meaning of their constituting words is partly retrieved. In addition, our literal stimuli included more abstract words than our idioms, which goes in the opposite direction than the difference in ratings found. To support our claim, we collected concreteness ratings on the idiomatic sentences once again but we did not explicitly ask participants to focus on the idiomatic meaning. Out of 20 participants (5 men, 15 women, age range 25–51 years, M 35; SD 7.5), only 5 rated most idioms as very abstract ($M < 1.93$ on a scale from 1, very abstract, to 7, very concrete). The other 15 participants used the whole range of the scale, although the ratings leaned more toward the abstract pole (Idiomatic sentences: M 3.31 SD 1.03 *Min-Max* 1.73-6.50). These ratings were not significantly different in concreteness than the ratings we had originally obtained on literal sentences from a similar participant sample (Literal sentences: M 3.28 SD 1.10 *Min-Max* 1.67-5.75, $t(178) = 0.21$, *ns*).

[3] Because of difficulty to run a gPPI analysis with parametric modulators, we conducted this analysis on a simplified model compared to the one reported above: the simplified model did not partial out the effect of arousal and familiarity ratings. Nevertheless, we anticipate that the results of this model are very similar to the controlled model. They are reported in Appendix A.

[4] Nevertheless, following a reviewer's suggestions, we conducted a 2x3 ANOVA with factors Idiomaticity (idiomatic, literal sentences) and Emotional valence (neutral, negative, positive). We observed no significant clusters of activation for either main effects or the interaction. We also extracted the

following helpful suggestions from a reviewer, we conducted GLM parametric analyses of emotional valence for all sentences and for idiomatic and literal sentences separately: 1) the first model included a linguistic regressor specifying the onsets of all sentences, followed by a parametric linear regressor containing emotional valence ratings, and an additional parametric quadratic regressor to explore quadratic effects, i.e., brain activations in response to increasing positive or negative valence; additionally, 3 linguistic regressors containing hash mark strings, questions, and fillers, and 6 regressors of non-interest for head movements were included; 2) the second model included a first regressor defining the onsets of idiomatic sentences, followed by the two linear and quadratic parametric regressors for emotional valence, then a second regressor defining the onsets of the literal sentences, followed by the linear and quadratic regressors for valence, and then the same 3 additional linguistic and 6 head-movement regressors as above. To further confirm the emotion involvement effect associated with idiomaticity based on left amygdala and IFG activation, we also computed and reported PSC analyses using MarsBar (Brett et al., 2002) using left amygdala and IFG as regions of interest (ROIs), as a function of emotional valence in both models described above and as a function of idiomatic versus literal sentences using the two models described in sections 2.5 and 2.5.1.

3. Results

3.1. Relationships between affective and psycholinguistic variables

For idiomatic sentences, 30% of the variance in emotional arousal ratings was significantly predicted by figurativeness, $R^2 = .30$, $R = .55$, F *change*(1,88) = 38.33, $p < .0001$, an additional 3% by concreteness, $R^2 = .34$, $R = .58$, F *change*(1,87) = 4.24, $p < .05$, and an additional 11% by the quadratic function of emotional valence, i.e., valence squared, $R^2 = .46$, $R = .67$, F *change*(1,86) = 17.06, $p < .0001$, with the following regression equation (with beta coefficients): emotional arousal = 0.48 x figurativeness - 0.10 x concreteness + 0.37 x valence squared. In line with these results, highly significant large positive partial correlations between arousal and figurativeness and between concreteness and figurativeness were found. Significant moderate positive partial correlations were also found between familiarity and knowledge of idiom meaning, semantic transparency and figurativeness, and between syntactic complexity and length in letters (see Table 3).

For literal sentences, 68% of the variance in emotional arousal ratings was significantly predicted by quadratic valence, $R^2 = .68$, $R = .82$, F *change*(1,88) = 183.79, $p < .0001$, with the following regression equation: emotional arousal = 0.82 x valence squared. Furthermore, syntactic complexity showed moderate positive partial correlations with emotional arousal, concreteness and length in letters (see Table 3).

Finally, for all sentences together, 3% of the variance in emotional arousal ratings was significantly predicted by syntactic complexity, $R^2 = .03$, $R = .16$, F *change*(1,178) = 4.87, $p < .05$, and an additional 42% by quadratic valence, $R^2 = .44$, $R = .67$, F *change* (1,177) = 133.05, $p < .0001$, with the following regression equation: emotional arousal = 0.12 x syntactic complexity + 0.65 x valence squared. In addition, small partial correlations were found between familiarity and emotional valence (positive); concreteness (negative); length in letters (negative); syntactic complexity showed small positive partial correlations with emotional arousal and concreteness, and a moderate positive partial correlation with length in letters (see Table 3).

(*footnote continued*)
percentage signal change (PSC) within left amygdala and IFG ROIs using Marsbar and reported the results, along with bar graphs showing mean PSC values and beta values for all conditions, in Appendix B.

3.2. Idiomatic versus literal sentences: neuroimaging data

At the whole-brain level, the contrast Idiomatic > Literal sentences, after having accounted for the variance in arousal and familiarity ratings, showed one cluster of significantly enhanced activation in the left IFG, and enhanced activation of the left amygdala (see Table 4 and Fig. 1). In addition, we observed enhanced activation of visual areas including the left fusiform gyrus, inferior occipital and temporal gyri, and middle occipital gyri. The opposite contrast Literal > Idiomatic sentences showed clusters of significant activation in the right middle frontal gyrus and medial parieto-occipital cortices including the middle cingulate cortex, the cunei, and the calcarine fissure.

In the gPPI analyses, using the left IFG as seed, we found no significant clusters of activation at the whole-brain level, but a significant peak of activation when we applied SVC on the left amygdala (MNI -28 -1 -23). This means that there was no functional connectivity from the left IFG to any other brain structure but the amygdala, and the latter only when we applied SVC. Using the left amygdala as seed, we found no significant clusters of activation at the whole-brain level, and no significant peak when we applied SVC on the left IFG. This means that no functional connectivity from the amygdala to any brain structure emerged, even when applying SVC.

3.3. Parametric effects of emotional valence: neuroimaging data

The quadratic function of emotional valence in all sentences, as well as in the idiomatic and literal sentence subsets separately considered, seemed to drive most effects at the whole brain level. In particular, increasingly positive and negative sentences showed significantly enhanced activation of the posterior part of the right rolandic operculum, including the superior temporal gyrus and sulcus, and extending into the right posterior insula (see Appendix C). This effect was driven by the idiomatic sentence subset, which showed significant activations in the very same areas bilaterally, with right-hemispheric dominance (larger cluster; see Fig. 2). No clusters of significant activations were found for increasing quadratic valence in the literal sentence subset. On the other hand, decreasing quadratic valence, i.e., increasingly neutral sentences, activated large portions of the right IFG (pars triangularis and opercularis), bilateral visual areas including the calcarine fissure (primary visual cortex) and the middle occipital gyri, extending to the posterior part of the right (and left, although less to a lesser extent) middle temporal gyri, and finally the right angular gyrus. These activations were mostly driven by the literal sentence subset, which showed a very similar pattern of activations characterised by bilateral temporo-occipital cortices. However, left (not right) prefrontal activations were found, involving the anterior insular cortex more strongly, and also activation of the left superior temporal gyrus. The idiom subset only showed a significant cluster in the left middle frontal gyrus.

With regards to linear effects of emotional valence, increasingly negative valence in all sentences significantly activated the right caudate nucleus; activation of its left homologue was also visible but did not survive the significance threshold. For literal sentences, increasing negative valence instead activated the visual cortices bilaterally, but no clusters of significant activations were observed for idiomatic sentences. In addition, increasingly positive valence only showed significant clusters of activation in the idiom subset (not in the literal sentences, and not in all sentences together), which included left IFG, MFG, left IPL and angular gyrus, and left MOG.

3.4. Percentage signal change (PSC) in left amygdala and IFG as a function of emotional valence and of idiomatic versus literal conditions

PSC was extracted from the first level images of all participants in four models: 1) the parametric models of emotional valence for all sentences together; 2) the second model with idiomatic and literal sentences separated; 3) the idiomatic versus literal sentence condition

Table 3
Partial correlations between affective and psycholinguistic properties, for idiomatic and literal sentences separately, and for all sentences.

Idiomatic sentences									
Variables	Em. Valence	Em. Arousal	Familiarity	Concreteness	Synt. complexity	Length in letters	Figurativeness	Sem. transparency	Knowledge of idiom
Emotional valence	1								
Emotional arousal	-.08	1							
Familiarity	.06	.06	1						
Concreteness	.04	-.19	-.18	1					
Syntactic complexity	-.11	.12	.09	.03	1				
Length in letters	.11	-.17	-.21	-.09	.35**	1			
Figurativeness	-.05	.50***	.20♦	.66***	-.05	.12	1		
Semantic transparency	.08	-.02	-.16	-.10	-.04	.08	.25*	1	
Knowledge of idiom meaning	.16	.03	.39***	-.17	-.01	.13	.16	.10	1
*** p < .001; ** p < .01; * p < .05; ♦ marginally significant at p = .06									
Literal sentences									
Variables	Em. Valence	Em. Arousal	Familiarity	Concreteness	Synt. complexity	Length in letters			
Emotional valence	1								
Emotional arousal	-.10	1							
Familiarity	-.20♦	-.08	1						
Concreteness	-14	-.06	-.16	1					
Syntactic complexity	-.07	.22*	.11	.31**	1				
Length in letters	.06	-.12	-.25*	-.07	.31**	1			
*** p < .001; ** p < .01; * p < .05; ♦ marginally significant at p = .06									
All sentences									
Variables	Em. Valence	Em. Arousal	Familiarity	Concreteness	Synt. complexity	Length in letters			
Emotional valence	1								
Emotional arousal	-.10	1							
Familiarity	.16*	.05	1						
Concreteness	.08	.09	-.15*	1					
Syntactic complexity	-.08	.16*	.08	.18*	1				
Length in letters	.10	-.08	-.22**	-.04	.32***	1			

*** p < .001; ** p < .01; * p < .05.

Table 4
Regions showing significant BOLD signal change for the contrast Idiomatic > Literal sentences with arousal and familiarity ratings as covariates; whole brain level with cluster-forming threshold of $p < .005$ uncorrected, and false-discovery rate (FDR) correction at the cluster level of $p < .05$.

Lobe	Hemi.	Region	Cluster size	T	x	y	z
		Idiomatic sentences > Literal sentences					
Frontal	L	Middle frontal gyrus, pars orbitalis	**2768**	6.18	**-33**	**33**	**-15**
		Inferior frontal gyrus, pars triangularis		5.81	**-45**	**30**	**16**
		Inferior frontal gyrus, pars triangularis		4.93	**-51**	**29**	**6**
Medial temporal	L	Amygdala	**814**	6.93	**-20**	**-6**	**-12**
		Amygdala		6.33	**-22**	**-3**	**-23**
		Fusiform gyrus		5.59	**-33**	**-10**	**-30**
Occipital	L	Fusiform gyrus	**1265**	6.93	**-42**	**-52**	**-21**
		Inferior temporal gyrus		6.18	**-40**	**-43**	**-18**
		Fusiform gyrus		4.30	**-32**	**-54**	**-17**
Occipital	L	Inferior occipital gyrus (BA 18)	**589**	5.43	**-30**	**-87**	**-2**
		Fusiform gyrus		4.18	**-38**	**-79**	**-14**
		Middle occipital gyrus		3.88	**-39**	**-90**	**-6**
Occipital	R	Inferior occipital gyrus	**1124**	5.65	**34**	**-88**	**-11**
		Inferior temporal gyrus		4.63	**42**	**-70**	**-5**
		Middle occipital gyrus		4.36	**45**	**-76**	**10**
		Literal sentences > Idiomatic sentences					
Frontal	R	Middle frontal gyrus	**380**	4.13	**36**	**38**	**34**
		Middle frontal gyrus		3.83	**39**	**18**	**39**
		Middle frontal gyrus (BA 9)		3.78	**42**	**27**	**40**
Parietal and occipital	R	Middle cingulate cortex	**1046**	5.28	**3**	**-24**	**42**
		Middle cingulate cortex		4.13	**2**	**-34**	**46**
		Cuneus		3.85	**16**	**-66**	**37**
Occipital	L	Calcarine fissure (BA 31)	**1392**	4.92	**-3**	**-69**	**21**
		Calcarine fissure (BA 31)		4.41	**-14**	**-72**	**19**
		Cuneus (BA 7)		4.22	**-2**	**-76**	**34**

Hemi. = hemisphere, L = left, R = right; cluster size is in voxels, T = peak t value; x, y, z = MNI stereotactic space coordinates.

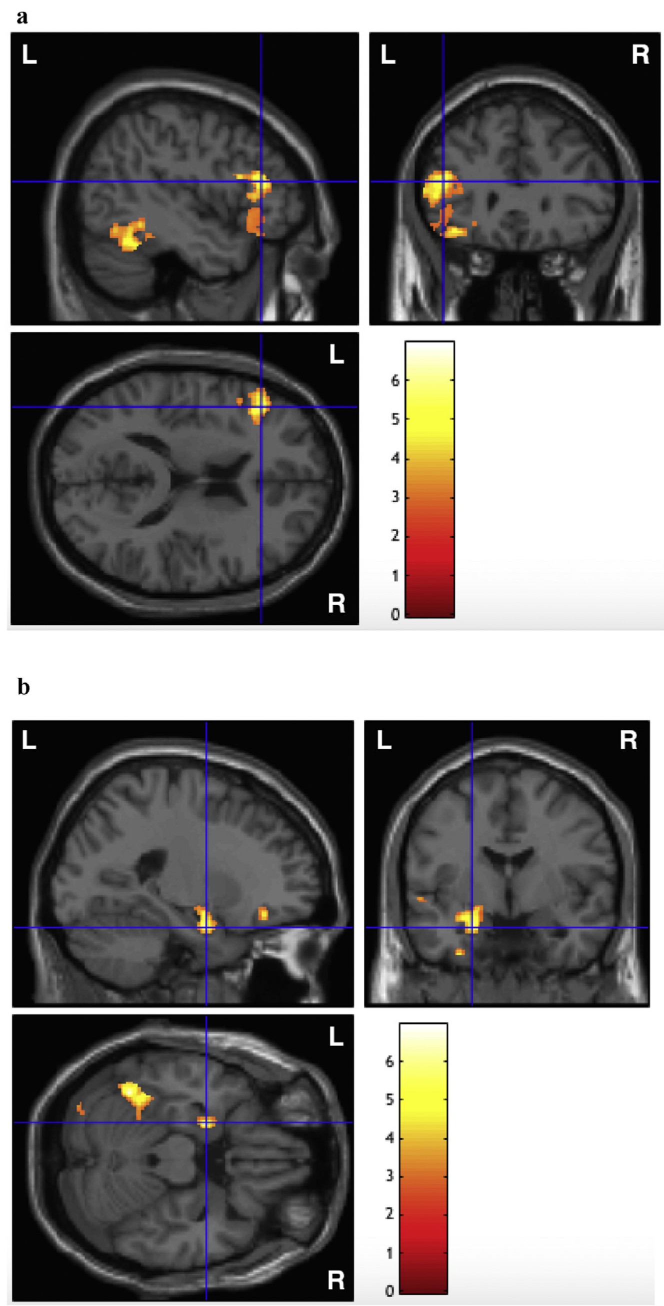

Fig. 1. Clusters of significantly enhanced activation in response to Idiomatic > Literal sentences **(a)** in the left inferior frontal gyrus (MNI -45 30 16) and **(b)** in the left amygdala (MNI -22 -3 -23).

model reported described in section 2.5, in which the effects of arousal and familiarity were partialled out; and 4) the simpler model used for the gPPI analysis (section 2.5.1) where no control over non-matched variables was included. The PSC was extracted from the left amygdala and left IFG (by using the same seed regions reported in the gPPI). PSC analyses allow testing of whether variation of activation in a specific ROI as a function of a specific regressor (e.g., quadratic valence, linear valence, idiomaticity) significantly differs from variation due to chance, without any inferences about the direction of these differences (e.g., increasing PSC for increasingly negative or increasingly positive valence). Therefore, in models 1 and 3, one-sample t-tests were computed. In models 2 and 4, it was instead possible to compare PSC between idiomatic and literal sentences in paired-samples t-tests.

Group-level one-sample t-tests were performed for PSC as a function

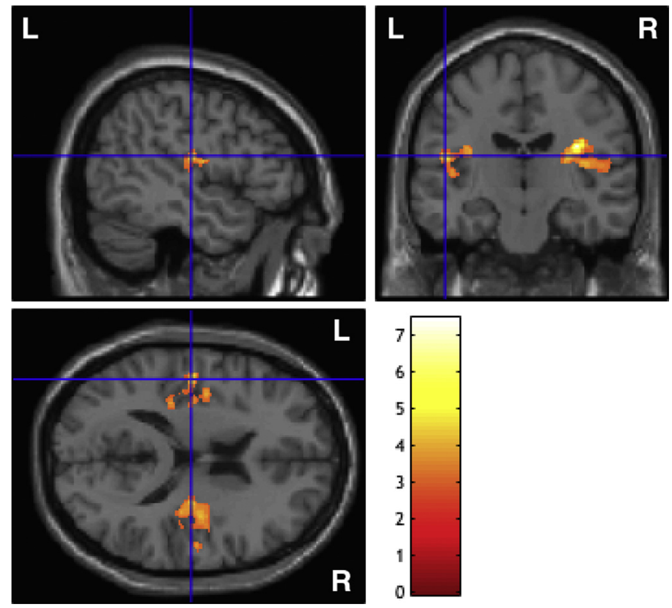

Fig. 2. Clusters of significantly enhanced activation in response increasingly positive and negative idiomatic sentences (i.e., increasing quadratic valence), including the left posterior superior temporal gyrus and sulcus (MNI -48 -16 16), posterior insula, and similar but more extended clusters within the right hemisphere.

of quadratic valence and showed significant effects of this regressor in both left amygdala and IFG, whereas no significant effects in either ROI were found in response to linear valence (see Table 5 and Fig. 3). Hence, quadratic valence seems to affect the activation in both ROIs. Paired-sample t-tests comparing the effects of these variables between idiomatic and literal sentences showed no significant difference in quadratic valence in the left amygdala, suggesting that the effect of quadratic valence on the amygdala does not differentiate between idioms and literal sentences; whereas a significant difference was found in the left IFG between the two conditions. Linear valence showed no significant difference between idiomatic and literal sentences in the left amygdala, in line with the lack of an effect in all sentences, whereas a significant difference between idiomatic and literal sentences as a function of linear valence was found in the left IFG, with idioms having higher values. This suggests that linear valence affects left IFG activation and is driven by idiomatic sentences.

One-sample t-tests were performed for PSC as a function of idiomatic versus literal sentences in the model in which arousal and valence were controlled, where the two conditions were coded by a unique dummy regressor; these tests showed significant effects of idiomaticity on both amygdala and IFG (see Table 5). Paired-sample t-tests between idiomatic and literal sentences in the simple model, where these conditions were coded by two distinct linguistic regressors, confirmed and qualified these effects by showing significantly higher PSCs for idiomatic than literal sentences in both ROIs; this confirms that idiomatic sentences are affecting activations in both structures.

4. Discussion

4.1. Relationships between affective and psycholinguistic properties

All our sentences, and idiomatic and literal subsets separately, showed a quadratic relationship between emotional valence and arousal, i.e., increasingly positive and negative stimuli are also higher in emotional arousal, therefore replicating the typical U-shaped relationship originally found in pictures (Lang et al., 1999), written words (e.g., Bradley and Lang, 1999; Võ et al., 2009), and idioms (Citron et al., 2016b). Given the careful selection and manipulation of our stimuli, no

Table 5
Descriptive and inferential statistics of percentage signal change (PSC) extracted from first level images of four different statistical models, and focused on the regions of interests left amygdala and IFG, as defined in the seed regions used for the gPPI analysis.

Region of interest:	**Left amygdala**		**Left IFG**	
Model	**Mean PSC (SD)**	**T-test**	**Mean PSC (SD)**	**T-test**
Emotional valence, parametric, with all sentences				
Quadratic valence	0.11 (0.10)	$t(22) = 5.42$, $p < .001$	0.15 (0.09)	$t(22) = 7.55$, $p < .001$
Linear valence	0.04 (0.11)	$t(22) = 1.65$, ns	0.002 (0.10)	$t(22) = 0.11$, ns
Emotional valence, parametric, separate for idiomatic vs. literal sentences				
Quadratic valence - idiomatic sentences	0.04 (0.11)		-0.01 (0.10)	
Quadratic valence - literal sentences	0.08 (0.10)	$t(22) = -1.19$, ns	0.09 (0.14)	$t(22) = -2.51$, $p < .05$
Linear valence - idiomatic sentences	0.04 (0.09)		0.04 (0.10)	
Linear valence - literal sentences	0.11 (0.22)	$t(22) = -1.43$, ns	0.20 (0.20)	$t(22) = -3.35$, $p < .01$
Idiomatic > Literal sentences, with arousal and familiarity controlled				
dummy regressor coding idioms with 1 and literal sentences with -1	0.10 (0.22)	$t(22) = 2.14$, $p < .05$	0.18 (0.20)	$t(22) = 4.41$, $p < .001$
Idiomatic > Literal sentences, simple model used for gPPI				
Idiomatic sentences	0.11 (0.13)		0.08 (0.10)	
Literal sentences	0.05 (0.10)	$t(22) = 3.14$, $p < .01$	0.05 (0.10)	$t(22) = 2.64$, $p < .05$

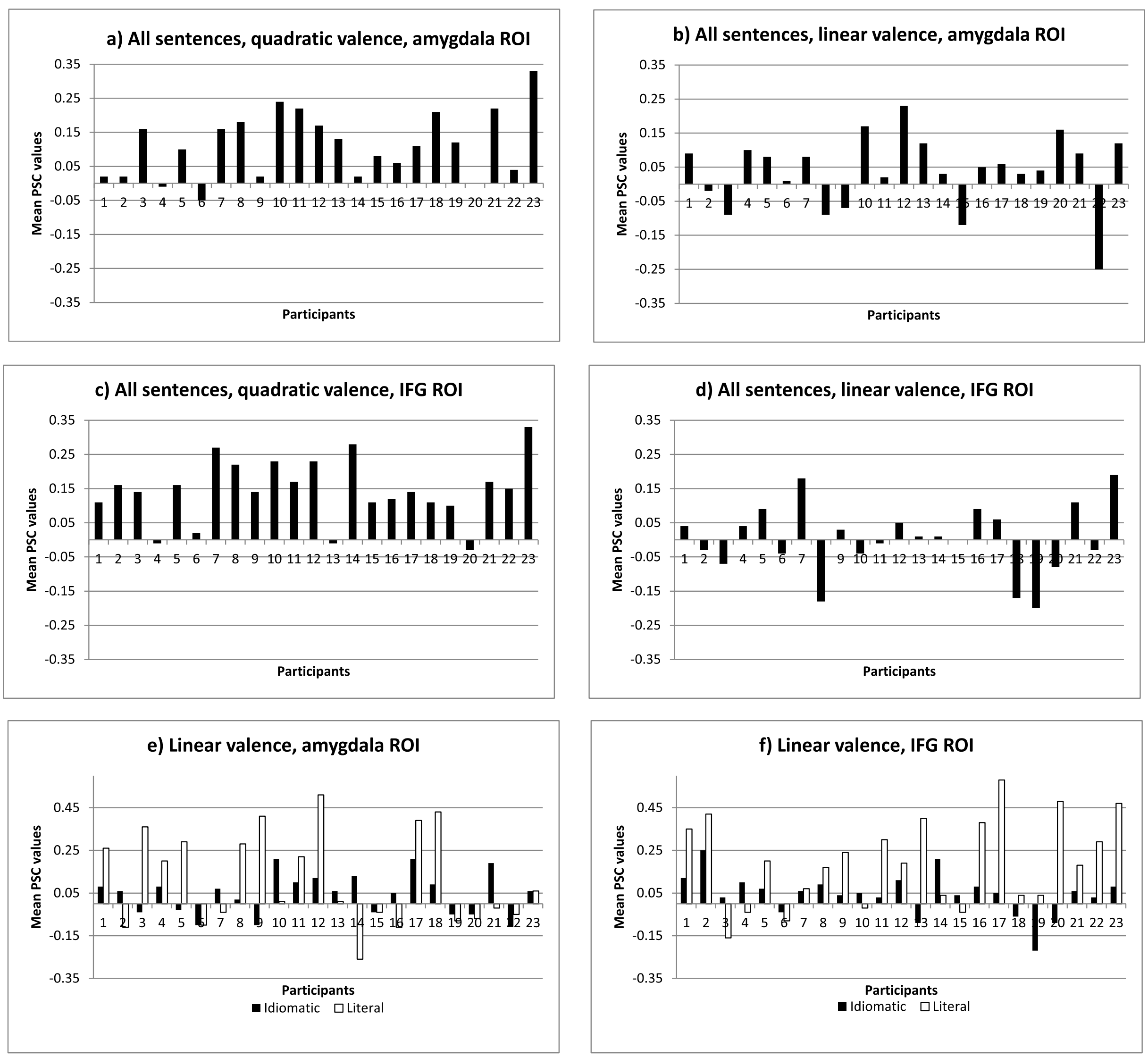

Fig. 3. **(a-d)** Mean PSC values for all sentences as a function of quadratic and linear valence, in both left amygdala and left IFG ROIs. While PSC as a function of quadratic valence significantly differed from chance (zero) in both ROIs, no significant differences were found as a function of linear valence. **(e-f)** Mean PSC values for idiomatic and literal sentences separately, as a function of linear valence, in both ROIs. PSC only differed significantly between idiomatic and literal sentences in the left IFG, but not in the amygdala.

asymmetry in arousal level between positive and negative sentences, i.e., no linear relationship between valence and arousal, was found. Interestingly, the largest percentage of variance in arousal ratings for idioms was accounted for by figurativeness (30%, while quadratic valence explained 11%), supporting the idea that increasingly figurative verbal materials are perceived as increasingly emotive (e.g., Citron and Goldberg, 2014). This is in line with findings in PANIG, the large dataset of German idioms from which our idiomatic sentence subset was extracted (Citron et al., 2016b); and with results of a recent dataset showing that metaphorical formulations are rated higher in arousal level than their literal counterparts (Citron et al., 2019b). Figurativeness in idioms also showed a large positive correlation with concreteness, suggesting that the more figurative an idiom is perceived the stronger its association to sensorimotor representations (Gibbs et al., 1997). However, this result may apply to this specific subset of stimuli only, as it was not found in PANIG (Citron et al., 2016b); a similar relationship between metaphoricity and imageability was found in metaphorical and literal *stories*, but less consistently so in the case of *isolated sentences* Citron et al., 2019b). In line with previous literature, idioms were also rated as more familiar (Bonin et al., 2013; Tabossi et al., 2011) while, in contrast with previous findings, more figurative idioms were also rated as more semantically transparent (a negative correlation is usually reported and expected, see Citron et al., 2016b), perhaps due to the fact that we only employed unambiguous idioms.

Finally, only when considering all sentences together, increasingly positive sentences were also rated as more familiar, in line with existing datasets of written words (Citron et al., 2014b; Yao et al., 2017), idioms (Citron et al., 2016b), and with the idea of a positive bias toward positive stimuli (Citron et al., 2014b; Kousta et al., 2009; Lewis et al., 2007).

4.2. Neural correlates of idiom processing

In line with the literature on the neural bases of figurative language processing (Bohrn et al., 2012a; Cacciari and Papagno, 2012; Romero Lauro et al., 2008), the comprehension of idiomatic sentences elicited enhanced activation of the left IFG, bilateral visual areas including left fusiform and occipito-temporal gyri, and the medio-temporal lobe including the left amygdala. This network is functionally associated with the integration of verbal material and world knowledge into meaningful sentences and the retrieval of semantic representations (Ferstl, 2010; Ferstl et al., 2008; Menenti et al., 2009). Activation of the IFG is consistently reported in neuroimaging studies of idiom processing and in meta-analyses (bilaterally in Bohrn et al., 2012a; only in the left hemisphere in Reyes-Aguilar et al., 2018). This region is typically associated with response selection and inhibition, problem solving, and working memory (Bunge et al., 2001; McNab et al., 2008; Osaka et al., 2004), suggesting that idiom processing also triggers activation of part of their literal meanings which need to be subsequently inhibited in order to extract and retain the appropriate, and contextually relevant, idiomatic meaning. This is consistent with behavioural evidence showing that working memory and inhibitory control processes explain a large portion of variance in reaction times to target words presented after predictable idioms (Cacciari et al., 2018). According to Hagoort (2005) neurobiological language model, the Memory, Unification, Control (MUC) Model, the left IFG is responsible for the unification gradient, i.e., the interactive and concurrent integration of phonology, syntax, and semantics into a complex whole. Thus, similarly to Forgács et al. (2012) 's finding of graded left IFG activation as a function of gradual semantic processing demand, the present results reflect increased processing demands for idioms. Activation of visual cortices in previous studies of idiom processing was found in response to both idiomatic and literal stimuli (Boulenger et al., 2012; Romero Lauro et al., 2008). An early activation of these cortices in a MEG study was accompanied by a differentiation between idiomatic and literal conditions in temporal and prefrontal cortices (Boulenger et al., 2012). In line with this, the stronger activation of ventral occipito-temporal cortices bilaterally, including the fusiform gyrus, inferior and middle occipital and inferior temporal gyri, in response to idioms may index stronger recruitment of semantic representations.

Most importantly, the enhanced activation of the left amygdala is consistent with the observation reported by a few studies that figurative language comprehension activates part of the same neural circuit associated with intense emotional experiences and the detection of evolutionary or contextually relevant stimuli (Bohrn et al., 2012a; Citron and Goldberg, 2014). In addition, this result generalises evidence obtained with metaphors to more conventionalised expressions like idioms.

These findings allowed us to further explore possible functional coupling of the left amygdala with other regions, and in particular the left IFG. Visual areas were not included in the functional connectivity analysis, as they may be more generally associated with the processing of any type of visual verbal information and not specifically with figurative language. We found stronger functional coupling for idiomatic than literal sentences from the left IFG, when used as seed, to the left amygdala. This suggests that, during idiom comprehension, activation of multiple meanings, inhibition and working memory processes, indexed by IFG activation, take place concurrently with the engagement of the reader at the emotional level in the amygdala. This supports the idea that working out a plausible semantic interpretation of idiomatic sentences is cognitively demanding since it requires forming and selecting a mental representation of the context, identifying the correct interpretation of the idiom string, and inhibiting alternative interpretations. Paradoxically, this cognitively challenging activity may in turn generate a more pleasurable, rewarding experience in the reader, as in a sort of successful problem solving: successful interpretation and comprehension minimises prediction errors and optimises value or reward (Friston, 2010) by activating the amygdala, historically and nowadays still consistently associated with stimulus-reward learning (Baxter and Murray, 2002). Related to this finding, a study by Schaefer et al. (2006) showed that amygdala activation supports working memory (WM) function in highly-performing individuals, specifically, enhanced amygdala activation correlated with faster reaction times in high cognitive-load conditions (3-back WM task). This finding held true in the absence of affectively-loaded stimuli or mood manipulation, suggesting a role of amygdala in higher cognition, beyond its central role in emotion processing (Schaefer et al., 2006). In addition, Bohrn et al., 2012b showed involvement of affect-related brain regions including amygdala, temporal poles and medial prefrontal cortex during comprehension of defamiliarised proverbs. Even though these stimuli are quite different from our highly conventional idiomatic sentences, their comprehension required attention and error monitoring for the integration of contextual information (as indexed by the activation of dorsal anterior cingulate cortex and dorso- and ventro-lateral prefrontal cortex) and these operations in turn evoked stronger affective engagement or reward due to successful comprehension.

The alternative hypothesis based on the detection of idioms' salience seems to be less plausible. In fact, if idioms were perceived as more salient - because they represent more familiar and highly conventionalised, stored expressions compared to literal sentences (see also Giora, 1999) - and therefore were to engage the reader emotionally, amygdala activation would have led to a weaker functional coupling with activity in the left IFG, i.e., the more processing demand the smaller the emotional engagement. The fact that we found no interactive effects when we used the amygdala as seed may be due to the fact that FWE correction in the left IFG mask is statistically much more stringent, but perhaps also suggestive of an emotional engagement primarily driven by cognitive engagement rather than a response to salience (Cunningham and Brosch, 2012). Finally, it may also be the case that amygdala activation does not represent stronger emotional engagement but rather *cognitive* engagement *per se* (Schaefer et al., 2006; Strigo et al., 2010). Admittedly, this interpretation cannot be ruled out given our experimental design and data. However, our rating data, as well as the ratings from PANIG and from a metaphor database, show a strong positive relationship between figurativeness and arousal (Citron et al., 2016b, 2019b). This suggests that increasingly figurative stimuli tend to be perceived also as more emotionally charged.

The results of the functional connectivity analysis (gPPI) do not allow us to infer the direction or causality of this connectivity. Thus, it could still be the case that the amygdala may quickly detect salient stimuli, i.e., idioms, and project to the IFG in order to enhance their processing. This is in line with a similar modulation of extra-striate cortices from the left amygdala during emotion word processing, leading to enhanced perceptual processing compared to neutral words (Herbert et al., 2009). A similar modulation has been reported for emotional pictures (Sabatinelli et al., 2005) and in brain lesion studies employing words and faces (Anderson and Phelps, 2001; Vuilleumier et al., 2004). In addition, the analyses of percentage signal change conducted on the two models coding for idiomatic versus literal sentences confirmed that the idiomatic condition affects activations in both amygdala and IFG.

4.3. Neural correlates of emotional valence

The quadratic function of emotional valence showed significantly enhanced activation of the right posterior superior temporal gyrus, extending into the right posterior insula. This pattern was replicated bilaterally for idiomatic sentences only, with right-hemispheric dominance. The insula is part of the emotion neural network and the salience network (Lindquist et al., 2012; Seeley et al., 2007). Its posterior part has been specifically identified as the primary interoceptive cortex, coding internal states such as thirst, hunger, and physiological arousal more generally (Craig, 2008; 2009), while its anterior part is associated with the integration of perceived internal, viscero-sensory states and external information, giving rise to conscious feelings - i.e., interoceptive awareness (Craig, 2011; Critchley et al., 2004). Activation of the posterior superior temporal gyri has been consistently reported in response to multisensory integration during perception and processing of emotive stimuli such as audio-visual presentation of (non-verbal) voices and faces (Kreifelts et al., 2007), auditory and visual object features (Beauchamp et al., 2004), dynamic verbal audio-visual stimuli (Robins et al., 2009), and in some study the posterior STG activation extended to include insula (Bushara et al., 2003; Olson et al., 2002) and amygdala (Dolan et al., 2001). In line with these studies, posterior insula activation has also been shown to correlate with cardiac activity during listening to emotionally valenced audio films (Nguyen et al., 2016). Hence, in the present study, increasingly positive and negative emotional valence seemed to evoke interoceptive, physiological sensations, and integration of different senses, and more strongly so during the processing of idiomatic sentences. This makes sense if we consider that our idiomatic stimuli contained body-part and concrete words that rely on somatosensory representations (Boulenger et al., 2009; Carota et al., 2012; Desai et al., 2013).

A decrease in quadratic valence, i.e., increasingly more neutral sentences, instead led to enhanced activation of a language-related network, involving bilateral temporo-occipital cortices and right prefrontal cortices including the IFG. These effects seemed to be mostly driven by literal sentences which showed a very similar pattern of activations with the addition of left prefrontal cortices that extended to the anterior insula as well as to the left superior temporal gyrus. Hence, the less emotionally charged and the more literal a sentence, the larger the involvement of the bilateral extended language network (Ferstl et al., 2008).

Increasingly more positive and negative valence significantly affected variation in activation (percentage signal change) in the left amygdala, but with no distinction between idiomatic and literal sentences, whereas it affected variation in activation in the left IFG differently (just significantly so) for idiomatic versus literal sentences. These results suggest that a quadratic function of valence affects both affective and cognitive engagement during sentence comprehension. Together with the lack of amygdala activation in response to the emotional valence dimension (either linear or quadratic), our findings suggest that the stronger amygdala activation in response to idiomatic versus literal sentences may be due to idioms representing more motivationally salient stimuli (Cunningham and Brosch, 2012; Sander et al., 2003) rather than being more emotionally impactful (Costafreda et al., 2008; Sabatinelli et al., 2005).

The linear function of valence (from negative through neutral to positive) played a much more marginal role overall: in all sentences, it did not affect variation of activity (PSC) either in the amygdala or in the IFG; however, it differed significantly between idiomatic and literal conditions in the left IFG only. This suggests that linear valence affects the neural distinction between idiomatic and literal sentences in the IFG and seems to affect processing of literal sentences in particular. At the whole-brain level, increasingly more negative sentences activated the caudate nucleus, which is part of the emotion neural network: its activity is modulated by valence (Colibazzi et al., 2010) and has been shown to preferentially respond to negatively valenced pictures (Carretié et al., 2009). In contrast, increasingly more negative literal sentences activated bilateral visual cortices. Finally, increasingly more positive valence in idiomatic sentences activated the left IFG, MFG, IPL, and angular gyrus, possibly indexing enhanced processing of particularly emotionally salient stimuli (Citron, 2012; Herbert et al., 2008; Yiend, 2009).

4.4. Medial prefrontal cortex and idiom processing

The present study did not show activation of the medial prefrontal cortex in response to idiomatic compared to literal sentences. This area was instead previously reported by some neuroimaging studies of idiom processing (Hillert and Buračas, 2009; Romero Lauro et al., 2008; Yang et al., 2016), but not by others (Boulenger et al., 2009; Zempleni et al., 2007). The medial PFC has been associated with theory of mind, processing of internal mental states, and inference processing (Frith and Frith, 2012; Jenkins and Mitchell, 2010; Siebörger et al., 2007). Romero Lauro et al. (2008) showed that, for idioms, activation of medial PFC increased the functional connectivity between left and right fronto-temporal cortices, and interpreted this result as evidence for the medial PFC to sub-serve the selection between alternative sentence meanings. However, the task and stimuli used in their study may have specifically required the representation of alternative meanings and the ability to select one based on context, which are very similar processes to considering different perspectives and using inferences. In particular, half of the idioms employed by Romero Lauro et al. (2008) were ambiguous, i.e., their literal interpretation would be perfectly plausible, thus making the activation of literal meanings more likely, and the task consisted in matching an idiom's meaning (e.g., *to pull one's belt*, Italian idiom meaning "to be increasingly poor") to an image that depicted either the correct idiomatic meaning (someone starving because of poverty) or its opposite meaning (a rich man eating voraciously). Hence, participants had to represent at the same time two opposite meanings during idiom processing, resulting in a more demanding task than for literal sentences in which the two possible meanings differed less. Hence, the activation of the medial PFC may reflect the activation of alternative meanings which was more demanding for ambiguous idiom (Yang et al., 2016), and in the direct comparison of ambiguous > unambiguous idioms (Hillert and Buračas, 2009). In contrast, no medial PFC activation was found in the present study, that required silent reading of unambiguous idioms, and in studies in which either the sentential context (Zempleni et al., 2007) or the sentences (Boulenger et al., 2009) allowed only one interpretation, either idiomatic or literal.

4.5. Future directions

An important aspect that deserves ad hoc, future research is the direction of the relationship between the activation of the IFG and the amygdala. In addition, the time course of the emotional response to figurative and literal sentences is still poorly understood. If amygdala activation is automatic and immediate, one should find a difference between the electrophysiological responses to these different types of sentences primarily on early event-related potential (ERP) components associated with emotional stimulus processing. Alternatively, or additionally, differences in ERP amplitudes between figurative and literal expressions on later emotion-related components would point toward later engagement, at post-comprehension processing stages.

4.6. Conclusion

The present study tested whether the comprehension of idioms, the least creative and most conventionalised part of figurative expressions, evokes stronger emotional responses at the neural level compared to literal sentences as it happens for metaphors. The results showed that idiomatic sentences elicited enhanced activation of the left amygdala at the whole brain level, compared to literal sentences, thus generalising to idioms the higher capacity of figurative language to convey emotions. Functional connectivity analyses revealed stronger functional coupling between left IFG and the left amygdala during the comprehension of idiomatic sentences, suggesting that the more demanding the processing of idiomatic sentences in terms of inhibition and selection between competing semantic representations, the stronger the emotional engagement indexed by the amygdala.

CRediT authorship contribution statement

Francesca M.M. Citron: Conceptualization, Project administration, Formal analysis, Writing - original draft, Writing - review & editing. **Cristina Cacciari:** Conceptualization, Writing - original draft, Writing - review & editing. **Jakob M. Funcke:** Data curation, Formal analysis. **Chun-Ting Hsu:** Methodology, Formal analysis, Writing - original draft, Writing - review & editing. **Arthur M. Jacobs:** Resources, Writing - original draft.

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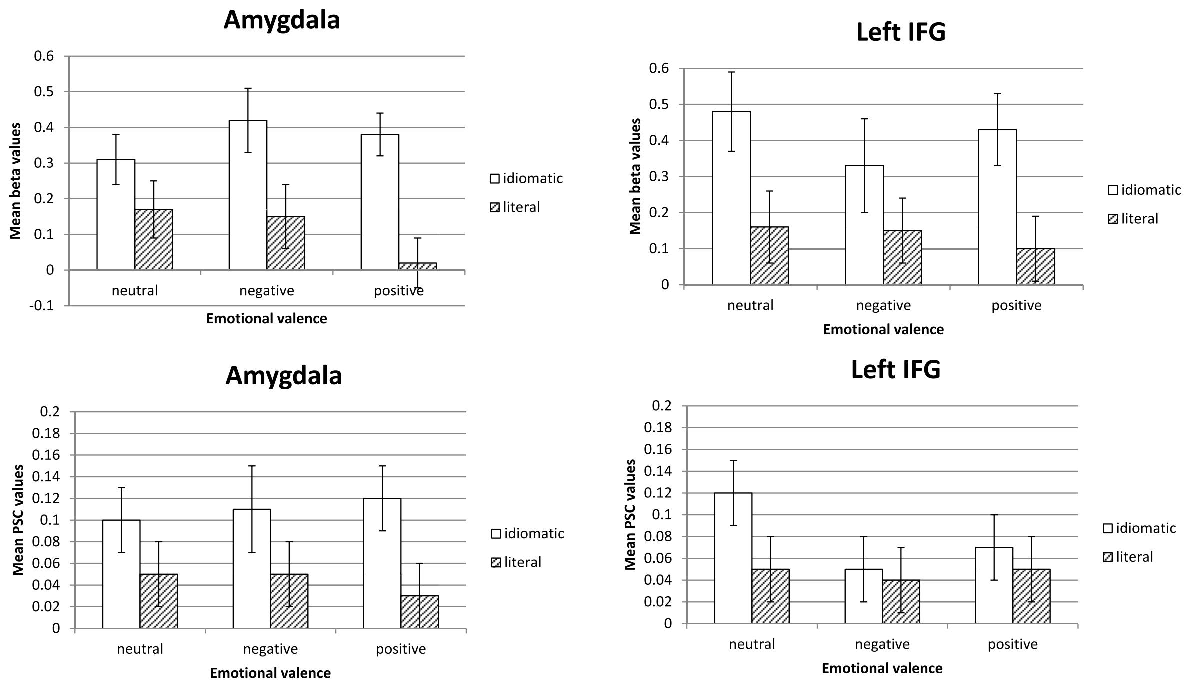
Appendix A. Regions showing significant BOLD signal change for the contrast Idiomatic > Literal sentences, without controlling for arousal and familiarity ratings; whole brain level with cluster-forming threshold of $p < .005$ uncorrected, and false-discovery rate (FDR) correction at the cluster level of $p < .05$.

Lobe	Hemi.	Region	Cluster size	T	x	y	z
Idiomatic sentences > Literal sentences							
Frontal	L	Inferior frontal gyrus, pars triangularis	**2923**	6.22	**-45**	**30**	**16**
		Middle frontal gyrus, pars orbitalis		5.82	**-33**	**33**	**-15**
		Inferior frontal gyrus, pars triangularis		5.34	**-50**	**30**	**9**
Medial temporal	L	Anterior insular cortex	**342**	4.85	**-32**	**8**	**12**
		Inferior frontal gyrus, pars opercularis		4.64	**-44**	**8**	**25**
		Inferior frontal gyrus, pars opercularis		3.88	**-34**	**9**	**30**
Medial temporal	L	Amygdala	**635**	7.03	**-21**	**-4**	**-18**
Occipital		Fusiform gyrus		5.28	**-32**	**-3**	**-39**
		Fusiform gyrus		4.84	**-33**	**-10**	**-30**
Occipital	L	Fusiform gyrus	**810**	6.18	**-39**	**-42**	**-20**
		Fusiform gyrus		5.65	**-42**	**-52**	**-23**
		-		4.39	**-44**	**-45**	**-12**
Occipital	R	Inferior occipital gyrus (BA 18)	**790**	5.39	**34**	**-87**	**-9**
		Middle occipital gyus		4.93	**46**	**-76**	**10**
		Middle temporal gyrus (BA 39)		4.34	**54**	**-72**	**3**
Literal sentences > Idiomatic sentences							
Occipital	L/R	Cuneus	**2047**	4.54	**-14**	**-61**	**25**
		Calcarine fissure		4.46	**-6**	**-69**	**19**
		Cuneus		4.26	**16**	**-66**	**37**
Parietal and occipital	L/R	Cerebellum	**473**	4.34	**2**	**-48**	**49**
		Pre-cuneus (BA 7)		3.87	**-6**	**-49**	**52**
		Pre-cuneus (BA 7)		3.35	**3**	**-64**	**37**

Legend: Hemi. = hemisphere, L = left, R = right; cluster size is in voxels, T = peak t value; x, y, z = MNI stereotactic space coordinates.

Appendix B. Description of results of 2x3 factorial analyses with factors Idiomaticity (idiomatic, literal sentence) and Emotional valence (neutral, negative, positive) and bar graphs showing descriptive statistics.

A 2x3 ANOVA in a GLM model showed no significant clusters of activation for either main effects or the interaction. The same ANOVA was conducted twice more on PSC extracted from the left amygdala and from left IFG ROIs, and showed a significant main effect of Idiomaticity only, in both ROIs (both $Fs(1,22) > 6.41$, $ps < .02$, $\eta^2s > 0.23$), but no main effect of Emotional valence or interaction, in either ROI (all $Fs(2,44) < 1.16$, *ns*). Mean PSC values for all 6 conditions are reported in the bar graphs below. We also report mean beta values. Error bars represent +/-1 SEM.



Appendix C. Regions showing significant BOLD signal change as a function of emotional valence ratings (linear and quadratic), for all sentences together as well as for idiomatic and literal sentences separately; whole brain level with cluster-forming threshold of $p < .005$ uncorrected, and false-discovery rate (FDR) correction at the cluster level of $p < .05$.

Lobe	Hemi.	Region	Cluster size	T	x	y	z
All sentences: Increasingly positive and negative valence (increasing quadratic valence)							
Temporal	R	-	513	5.65	33	-15	24
		Posterior superior temporal gyrus/sulcus		4.34	42	-19	22
		Posterior insula (BA 13)		3.91	39	-15	12
All sentences: Increasingly neutral valence (decreasing quadratic valence)							
Frontal	R	Middle frontal gyrus	635	8.18	46	36	28
		Inferior frontal gyrus, pars triangularis		4.52	46	27	21
		Inferior frontal gyrus, pars triangularis		4.05	52	33	18
	R	Inferior frontal gyrus, pars opercularis	538	4.97	55	12	25
		Inferior frontal gyrus, pars opercularis		4.33	51	20	36
Temporal	R	Middle temporal gyrus	749	6.50	60	-48	-5
		Middle temporal gyrus		4.47	54	-37	-14
		Middle temporal gyrus		4.00	54	-52	0
Parietal/occipital	R	Superior occipital gyrus	539	4.39	33	-72	42
		Angular gyrus (BA 7)		3.83	28	-60	43
		Middle occipital gyrus		3.82	33	-78	30
Occipital	L	Middle occipital gyrus	502	4.23	-28	-85	19
		Middle occipital gyrus (BA 18)		4.21	-28	-97	4
		Middle occipital gyrus		4.07	-20	-90	7
	L/R	Calcarine fissure	1236	4.63	12	-78	3
		Calcarine fissure		3.95	0	-70	10
		Calcarine fissure		3.88	-12	-78	12
All sentences: Increasingly negative valence (decreasing linear valence)							
Basal ganglia	R	-	427	5.40	12	9	-3
		Caudate nucleus		4.57	18	26	1
		Caudate nucleus (head)		4.16	10	20	6
Idiomatic sentences: Increasingly positive and negative valence (increasing quadratic valence)							
Temporal	R	Posterior insula (BA 13)	2168	7.42	34	-15	22
		Posterior superior temporal gyrus/sulcus		5.59	40	-22	22
		Superior temporal gyrus		5.30	55	-4	1
	L	Posterior superior temporal gyrus/sulcus	507	4.87	-48	-16	16
		Superior temporal gyrus (BA 13)		4.57	-44	-19	3
		Posterior superior temporal gyrus/sulcus		4.53	-46	-9	13
Idiomatic sentences: Increasingly neutral valence (decreasing quadratic valence)							
Frontal	L	Middle frontal gyrus	442	5.05	-38	30	40
		Middle frontal gyrus (BA 9)		4.00	-45	30	36
		Middle frontal gyrus		3.92	-51	23	37
Literal sentences: Increasingly neutral valence (decreasing quadratic valence)							
Frontal	L	Anterior insular cortex (BA 47)		4.69	-38	18	-2
		Anterior insular cortex		3.77	-33	26	-3
Temporal	R	Posterior middle temporal gyrus		5.94	56	-51	-9

		Posterior middle temporal gyrus		4.30	**48**	**-63**	**1**
		Posterior middle temporal gyrus		3.93	**50**	**-51**	**-21**
	L	Superior temporal gyrus		4.70	**-52**	**-24**	**3**
		Superior temporal gyrus (BA 42)		3.85	**-60**	**-24**	**9**
		Middle temporal gyrus		3.18	**-58**	**-39**	**0**
Parietal/occipital	R	Superior occipital gyrus		5.13	**27**	**-66**	**43**
		Superior parietal lobule		5.12	**20**	**-70**	**52**
		Middle occipital gyrus		4.30	**30**	**-75**	**34**
	L	Lingual gyrus (BA 19)		4.45	**-22**	**-64**	**33**
		Superior parietal lobule (BA 7)		4.19	**-21**	**-70**	**45**
		Superior occipital gyrus		3.99	**-21**	**-79**	**28**
Occipital	R	Calcarine fissure		5.13	**16**	**-60**	**12**
		Lingual gyrus		4.98	**10**	**-82**	**-3**
		Calcarine fissure		4.81	**4**	**-72**	**10**
Idiomatic sentences: Increasingly positive valence (increasing linear valence)							
Frontal	L	Middle frontal gyrus	**502**	5.07	**-38**	**54**	**0**
		Inferior frontal gyrus, pars orbitalis		4.70	**-39**	**39**	**-8**
		Inferior frontal gyrus, pars orbitalis		3.50	**-32**	**45**	**-4**
	L	Middle frontal gyrus (BA 8)	**885**	5.40	**-20**	**24**	**52**
		Middle frontal gyrus		4.52	**-27**	**20**	**54**
		Middle frontal gyrus (BA 6)		4.17	**-32**	**10**	**57**
Parietal/occipital	L	Inferior parietal lobule	**1183**	5.00	**-34**	**-58**	**42**
		Angular gyrus		3.95	**-45**	**-68**	**39**
		Middle occipital gyrus		3.90	**-33**	**-74**	**28**
Literal sentences: Increasingly negative valence (decreasing linear valence)							
Occipital	L/R	Lingual gyrus	**1798**	5.15	**-20**	**-64**	**-9**
		Calcarine fissure (BA 23)		5.09	**6**	**-76**	**10**
		Calcarine fissure		4.47	**-18**	**-72**	**3**

Legend: Hemi. = hemisphere, L = left, R = right; cluster size is in voxels, T = peak t value; x, y, z = MNI stereotactic space coordinates.

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