Neural correlates of visual emotional word processing: An fMRI study

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The current study aimed to investigate the neural correlates of emotion-eliciting word processing in a visual lexical decision task (LDT). By examining processing patterns between real words and pseudowords, and between emotional and neutral words, we expected to at least partially dissociate semantic and affective components in emotional word processing.

Methods

Participants

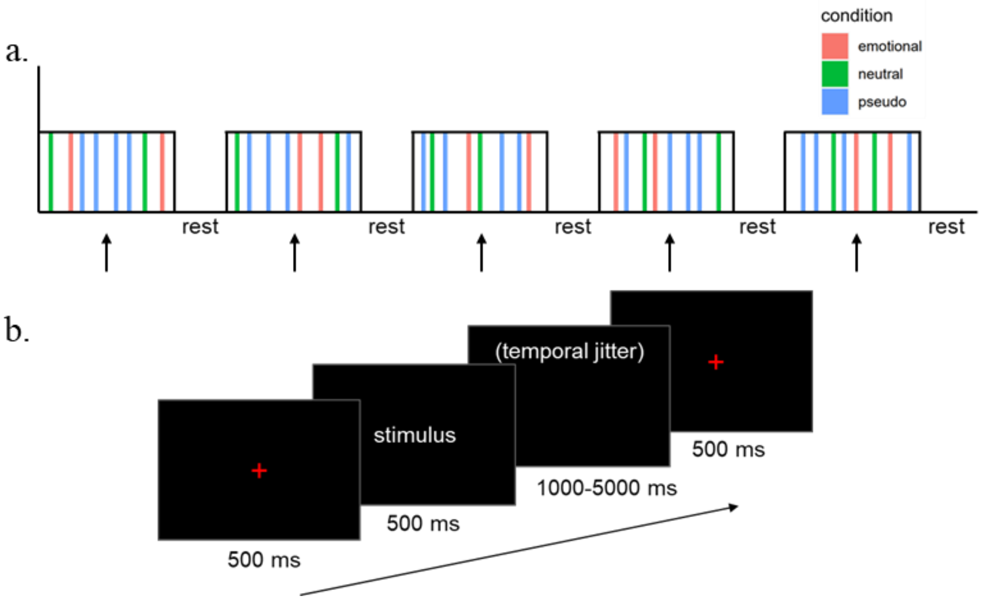
Four postgraduate students (3F, 1M; M_{age} = 22.75 years, SD = 1.71, range = 21-25) from University College London with no reported psychiatric and neurological disorders participated in the experiment. Two subjects were Asians and the other two were western Europeans. All subjects were fluent in English, were right-handed, and had normal or corrected-to-normal visual acuity. None of them participated in an fMRI experiment before. Notably, two subjects participated in the experimental design and, therefore, had expectations regarding their imaging results. A fifth subject (F, age=23 years) who only completed structural scanning was not included in any analyses. The study was approved by the UCL Psychology Ethics Steering Committee [Project ID: fMRI/ 2019/002], and all subjects provided written informed consent prior to taking part in the study.

Materials and Procedure

Subjects completed a visual LDT in the fMRI scanner. The task had a within-subjects design, with three types of letter strings constituting three conditions: stimulus could be real words, negatively-valenced (*n*=30, M_{valence}=2.75, M_{arousal}=6.69, condition “emotional”) or neutral (*n*=30, M_{valence}=5.12, M_{arousal}=4.35, “neutral”), or orthographically and phonologically word-like pseudowords (*n*=60, “pseudo”). Real words were high-frequency nouns drawn from Scott et al. (2009), whereas pseudowords were generated using the ARC Nonword Database (http://www.cogsci.mq.edu.au/research/resources/nwdb/nwdb.html). However, due to our lack of experience with LDT, word lengths were not precisely matched, with pseudowords being shorter (range = 4-5 letters, *M*=4.6, *SD*=0.6) than emotional words (range = 3-11 letters, *M*=6.0, *SD*=1.9) and neutral words (range = 3-11 letters, *M*=5.8, *SD*=1.6).

The task had a mixed design with both events (stimulus presentation) and blocks. During the LDT, each stimulus was presented non-repeatedly for 500ms following a red fixation cross for 500ms (Figure 1). Temporal jitters of 1-5s were added (to achieve a mean inter-stimulus interval of approximately 4s), which aided to optimise design efficiency. A 16-second rest period with a fixation cross in the display was included between blocks. The main experiment was split into three runs, with 5 blocks per run and 8 trials per block; trial order was pseudo-randomised to have 2 emotional, 2 neutral, 4 pseudowords within each block. The order of runs was randomised across subjects to avoid biases resulting from subject fatigue. All runs began with two dummy trials, whose volumes were discarded by the scanner, to allow for T1-equilibration effects of the pulse sequence.

Figure 1. Task Paradigm for the Study



Note. a. A total of five blocks in one run (stimuli order and ISI may differ); b. Stimulus presentation.

During the LDT, subjects were asked to decide as quickly as possible whether visible strings were a word or not, and press two different buttons accordingly. The strings in white font were projected on a backlit screen outside the scanner and viewed through a mirror mounted on the head coil. Ceteris paribus, font sizes of stimuli were adjusted from 40 (default) to 52 due to unexpected visual difficulties experienced by multiple subjects. Nonetheless, as the change was applied to all subjects, their data should remain comparable and integrable.

Hypotheses

To replicate prior research, we had two hypotheses regarding response times for different types of stimuli. Specifically, we expected faster responses for real words than pseudowords (Carreiras et al., 2007; Heim et al., 2005), and faster responses for emotional words than for neutral words (Sylvester et al., 2021).

Meanwhile, we had two hypotheses regarding the neural underpinnings of emotional word processing, investigating respectively semantic and affective contributions to lexical decisions. Firstly, we expected greater activations for real words (both emotional words and neutral words) compared to pseudowords in brain areas involved in semantic processing, such as middle frontal gyrus, left inferior frontal gyrus (IFG; especially Broca's area), supramarginal gyrus (SMG) angular gyrus and middle temporal gyrus (MTG) (Stoeckel et al., 2009; Wu et al., 2012). Secondly, we expected greater brain activation for emotional words compared to neutral words due to affective processing. Specifically, activated brain areas may include orbitofrontal cortex (OFC), anterior cingulate cortex (ACC), insula and amygdala (Pessoa, 2008; Schlochtermeier et al., 2013; Sylvester et al., 2021). More generally, we expected common activations for the lexical task in the left hemisphere, including left inferior frontal gyrus (IFG; especially Broca's area).

Data Acquisition and Pre-processing

Behavioural data including responses (which button was pressed for each trial) and button press time (what time subjects pressed buttons) were recorded by Cogent 2000 (v1.33) toolbox in MATLAB (version R2021b). The accuracy rates were calculated based on the percentage of responses that matched stimuli categories, whereas average RTs were calculated as the average time differences between stimulus presentation and button press.

Whole-brain MRI scanning was performed on a Siemens Avanto 1.5T MRI scanner with a head coil gradient set at the Birkbeck-UCL Neuroimaging (BUCNI) centre. Throughout the experiment, foam padding was used to minimise head motion, and earplugs were used to protect subjects from scanner noise. T_2*-weighted functional data were obtained with a gradient-echo EPI sequence (TR = 3000ms; TE = 50ms; FOV = 192×192; matrix = 64×64; voxel size = 3×3×3 mm). T_1-weighted structural images in resting state (MPRAGE sequence, TR = 8.4ms, TE = 3.57ms, flip angle = 7°, matrix = 224×256, 176 axial slices, voxel size = 1×1×1 mm) were obtained for localising functional data on subjects' brain anatomy. All subjects completed three runs of functional scanning, each consisting of 84-88 volumes (duration ≈ 4m20s, differs slightly due to inter-stimulus jitters). Each session with three runs took approximately 15 minutes.

Imaging data were pre-processed and analysed using SPM12 (Wellcome Trust Centre for Neuroimaging, www.fil.ion.ucl.ac.uk/spm/) implemented in MATLAB. Firstly, functional data were resliced and realigned by rigid body transformations to correct for motion artefacts. The estimated head motions of all four subjects in all sessions were fairly small with a maximum translation of approximately 0.6 mm and a maximum rotation of 0.7 degrees. Since the head movements did not exceed 1.0 mm or 1.0 degrees in any direction across subjects, all pre-processed volumes were included for further analyses.

After the realignment, the functional volumes and structural images were co-registered and spatially normalised to the T_1-weighted MNI-152 template using SPM default linear and nonlinear transformations. Importantly, the voxel sizes in normalisation were adjusted to 3×3×3 mm for functional data and 1×1×1 mm for structural data to match their acquisition resolutions. Following the realignment, the functional volumes were smoothed using an 8mm full-width at half-maximum (FWHM) Gaussian smoothing kernel. As lexical tasks generally implicate cortical regions with relatively large activation sizes, we chose 8×8×8 mm voxels rather than double the acquisition size (i.e., 6×6×6 mm) to improve signal-to-noise ratio. Finally, subjects' normalised structural scans were added together and averaged using SPM ImCalc function to create a mean structural scan, which served as an overlay background for the functional data.

Prior to analyses, we found that two pseudowords drawn from the ARC database were in fact real neutral words. To match the fact that the two words were indeed real words and that all participants identified them as so, we corrected the relevant onset times of pseudowords and real words based on factual knowledge. As a result, the total number of pseudowords in two runs was changed from 20 to 19, and neutral words from 10 to 11.

Analyses

To identify brain regions that are implicated in semantic and affective processing of words, a fixed-effects (FFX) model that combined pre-processed functional volumes was specified. A first-level general linear model was employed to model individual subject's blood oxygen level dependent (BOLD) time series using delta functions at stimulus onsets, convolved with a canonical haemodynamic response function (HRF). Event durations were set to 0.5s to match our task paradigm. A high-pass filter of 128s cut-off was applied to remove low-frequency BOLD signal drifts. Since there were relatively few error trials, we did not consider them as individual events (i.e., separate them as a condition) for the analysis. To account for structured residual noise related to temporal jitters, time derivatives were incorporated into the model as a covariate-of-no-interest. Motion parameters were not included as regressors, however, considering minor head motions across subjects.

To address our hypotheses regarding functional data, the contrasts below were examined:

1. Task (emotional, neutral, pseudo) > rest, [1 1 1] (contrast vector with temporal derivatives omitted). This contrast intended to provide a "sanity check", i.e. checking that the task had worked, and stimuli presentation elicited some form of activation. The analysis was inclusively masked by three contrasts, namely three conditions relative to rest (p=0.001) to identify brain regions commonly activated across conditions. Multiple comparisons were then corrected with a family-wise error (FWE) rate of p=0.05 (extent threshold k = 10 voxels).
2. Words (emotional, neutral) > pseudowords [1 1 -2]. Inclusive masking (p=0.001) with emotional > rest [1 0 0] and neutral > rest [0 1 0] contrasts were applied to ensure that detected differences did not result from relative deactivation for pseudowords. In the meantime, emotional > pseudo [1 0 -1] and neutral > pseudo [0 1 -1] contrasts were applied separately and integrally as additional inclusive masks to detect whether there existed any differences within the real-word category as compared to pseudowords.
3. Emotional > neutral [1 -1 0]. Inclusive masking (p=0.001) with the emotional > rest [1 0 0] contrast (p=0.001) was applied to ensure that detected differences did not result from deactivation for neutral words relative to emotional words and rest.

As the second and third contrasts only included one-tailed effects, we also checked the reversed activation patterns for pseudowords > words [-1 -1 2] (inclusively masked by pseudowords > rest [0 0 1], p=0.001), and neutral > emotional [-1 1 0] (inclusively masked by neutral > rest [0 1 0], p=0.001).

The Harvard-Oxford (HO) probabilistic atlas (https://fsl.fmrib.ox.ac.uk/fsl/fslwiki/Atlases) in MRIcron (version 2019) was used to label locations of peak coordinates in MNI space. We restrained from using popular single-subject atlases such as automated anatomical labelling (AAL) atlas (Tzourio-Mazoyer et al., 2002), as probabilistic atlases based on population samples (e.g., HO) generally provide more representative inferences for anatomical interpretations than the former (Devlin & Poldrack, 2007; Poldrack et al., 2008). Nevertheless, recent research has also revealed significant ethnicity differences (e.g., Chinese versus Caucasian) in brain structures (Tang et al., 2010). Given that two participants in this study were Chinese and that the HO template was developed based on Western populations, the estimated anatomical regions should be interpreted with caution. For all contrasts, voxel-wise statistics were used to report main peak activations in clusters with three local maxima at least 8mm apart. Where the cluster spans across multiple anatomical regions, sub-peaks were also reported.

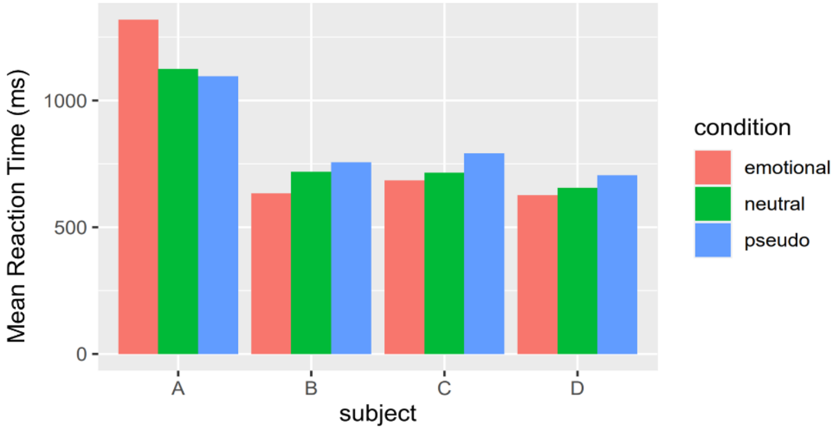
Results

Behavioural data

Average accuracy rates across subjects were 97.50% (SE=1.90%), 96.67% (SE=1.36%), and 91.23% (SE=0.83%) for emotional, neutral and pseudo conditions respectively. The relatively high accuracy rates indicated that the task was performed properly by subjects, which enabled further analyses.

Next, RT was analysed as a dependent variable of interest. Average RTs were 815ms (SD=336ms), 802ms (SD=216ms), and 837ms (SD=176ms) for emotional, neutral and pseudowords across participants, which defied greatly our predictions. Considering the large standard deviation, we added Subject as a covariate with Condition to test the possibility that individual differences contributed to the results (Figure 2). The two-way ANOVA did not reveal any significant effects of condition (p=0.11), whereas the effects of subject on average RTs were significant (F(3, 474)=23.95, p<0.001), but were entirely contributed by subject A according to post hoc Tukey test. Therefore, we excluded subject A in this analysis, and found that average RTs were strongly correlated with conditions (F(2, 342)=13.44, p<0.001). Specifically, subjects were significantly slower in responding to pseudowords than to real words (Cohen's d=0.50, 95% *CI* [0.29, 0.71], p<0.001), and slower in responding to neutral words than to emotional words (Cohen's d=0.36, 95% *CI* [0.06, 0.65], p<0.05). In other words, condition effects on average RTs were consistent with our hypothesis among subjects except for A. Outlier data from subject A possibly resulted from the fact that the subject participated actively in the experimental design and attempted to reflect longer and more deeply on stimuli in order to activate relevant brain regions.

Figure 2. Effects of Conditions and Subjects on Average Reaction Times



Due to the small sample size, our data were highly sensitive to individual differences and less robust in detecting subtle differences at group level, thereby may not fully support previous research. On the other hand, the results also highlighted a necessity to take into account individual differences and experimenter effects, which could be overlooked in large-scale data.

fMRI data

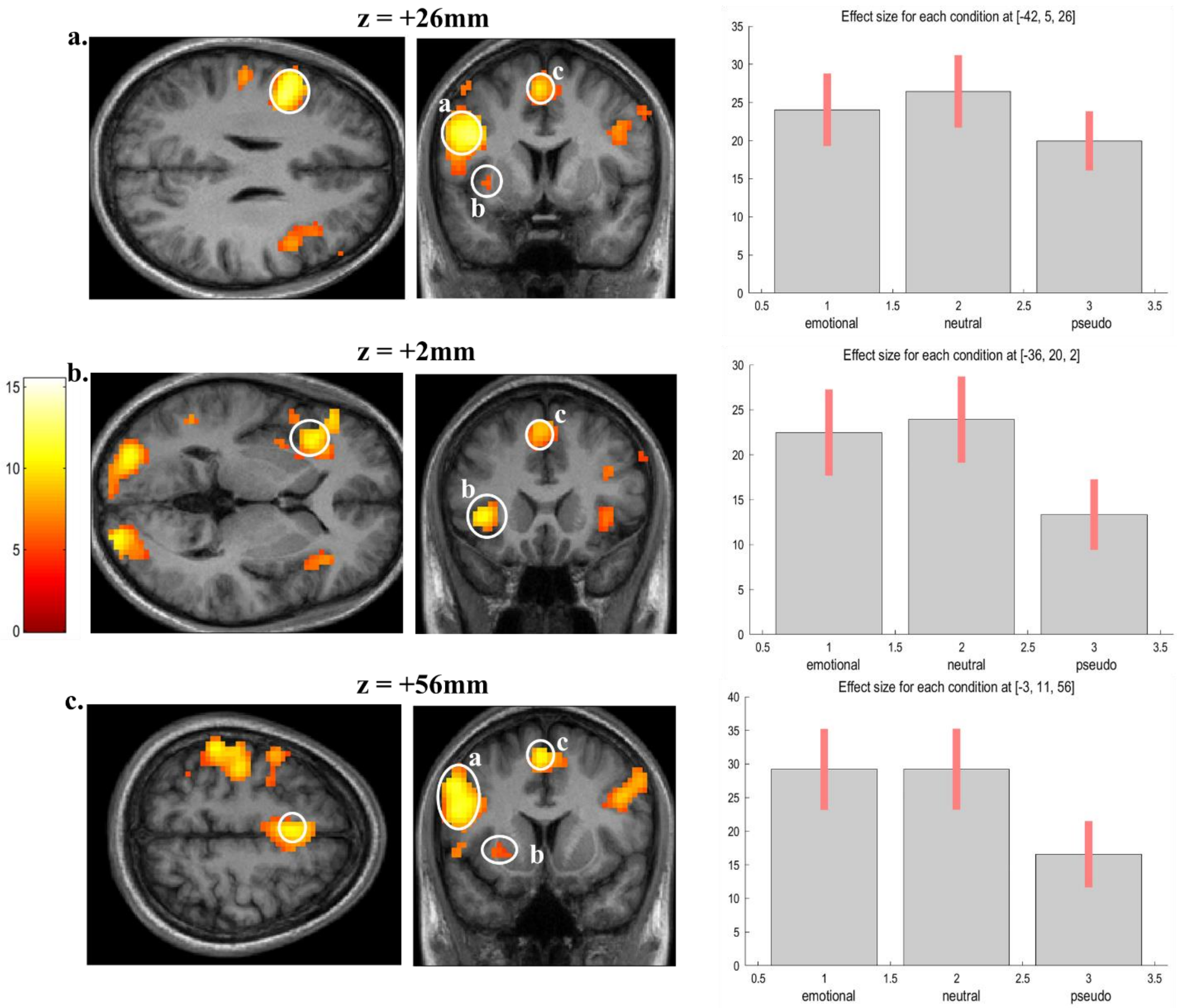
Firstly, the task > rest contrast was examined to identify commonly activated brain regions across Emotional, Neutral and Pseudo conditions in order to demonstrate regions involved in the lexical tasks (Table 1). In line with subjects' right-handedness, their left primary motor and somatosensory cortices (i.e., precentral and postcentral gyri) were activated. Furthermore, bilateral occipital fusiform gyri and left IFG (Broca's area, Figure 3a) were activated. Given that these areas are typically implicated in visual processing and language processing (Carreiras et al., 2007; Heim et al., 2005; Sylvester et al., 2021), the activations suggest that our task paradigm functioned properly. Interestingly, we also found that insula (Figure 3b) and superior frontal gyrus (Figure 3c) were activated across three conditions, with activations for real words greater than that for pseudowords but similar within the real-word category, which seemed to suggest that even the processing of pseudowords somehow engaged emotion and working memory, although to a less extent than real-word processing.

Table 1. Activation Across Three Conditions (Emotional, Neutral, Pseudo) Compared to Rest

	Anatomical Location	**Peak Coordinates**			**Z-value**
		x	**y**	**z**	
	Temporal-Occipital				
L	Temporal occipital fusiform gyrus	-45	-55	-19	>8
L	*Occipital fusiform gyrus*	-30	-85	-16	>8
R	Occipital pole	21	-97	-1	>8
R	*Occipital fusiform gyrus*	24	-79	-22	>8
	Frontal				
L	IFG, pars opercularis	-42	5	26	>8
L	*Precentral gyrus*	-36	-19	71	>8
L	*Postcentral gyrus*	-48	-31	50	>8
L	Insula	-36	20	2	>8
L	*IFG, pars triangularis*	-45	35	8	>8
L	Superior frontal gyrus	-3	11	56	>8
R	Frontal Pole	51	35	17	>8
R	*Middle frontal gyrus*	57	11	41	>8
R	OFC	36	26	-1	7.42
	Parietal				
L	Superior parietal lobule	33	-55	41	7.29

Note. Correlations met the criteria of FWE corrected, $p < 0.05$ and extent threshold of 10 voxels. Regions in italic are sub-peaks. *x, y, z* peak coordinates according to MNI stereotactic space, *L* left, *R* right, *IFG* Inferior frontal gyrus, *OFC* Frontal Orbital Cortex.

Figure 3. Three Particular Areas Activated Across Conditions



Note. The bar plots indicate effect sizes of activations across three conditions in peak voxels identified by the task > rest contrast. Effects are shown at $p < 0.05$ level (FWE corrected) for inclusive masking: emotional > rest; neutral > rest; pseudo > rest (p=0.001). The y-axis represents BOLD signal change and the x-axis represents conditions. The t-value colour bar applies to all the images. Anatomical locations are: a) IFG (pars opercularis), b) insula c) superior frontal gyrus.

The second contrast (words > pseudowords) revealed activations specific to semantic processing in our study (Table 2.1). Activations in peak voxels across three conditions identified for the second contrast along with respective effect sizes are displayed below (Figure 4). Significant effects were elicited in left IFG, OFC and middle frontal gyrus, which corresponded closely to the brain network identified in processing semantic word knowledge (Binder et al., 2003; Gupta, 2014; Kuchinke et al., 2005; Sylvester et al., 2021). There was little difference within the real-word category, suggesting that emotional and neutral words share many semantic features. Interestingly, strong activation was observed in Broca pars triangularis, an area likely associated with simultaneous translation from a secondary (or tertiary) language to one's own language (Elmer, 2016), which arguably reflected subjects' bilingualism in the current study.

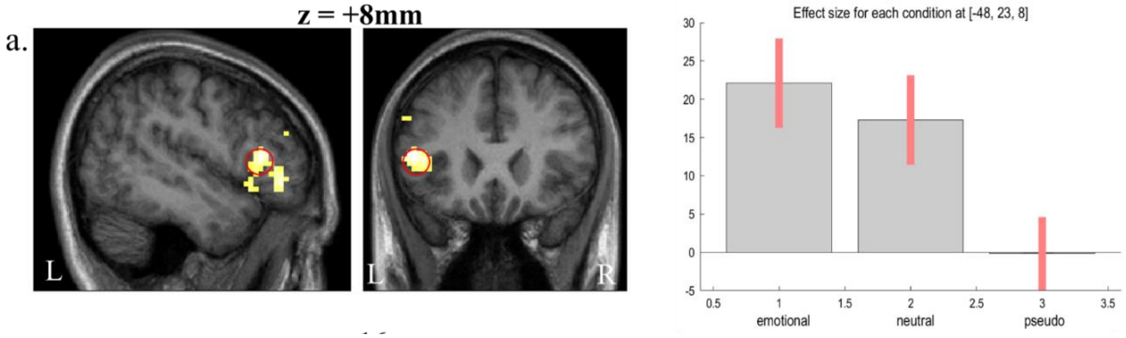
Table 2.1. Activation specific to semantic processing (*p*=0.001 masks, FWE *p*<0.05)

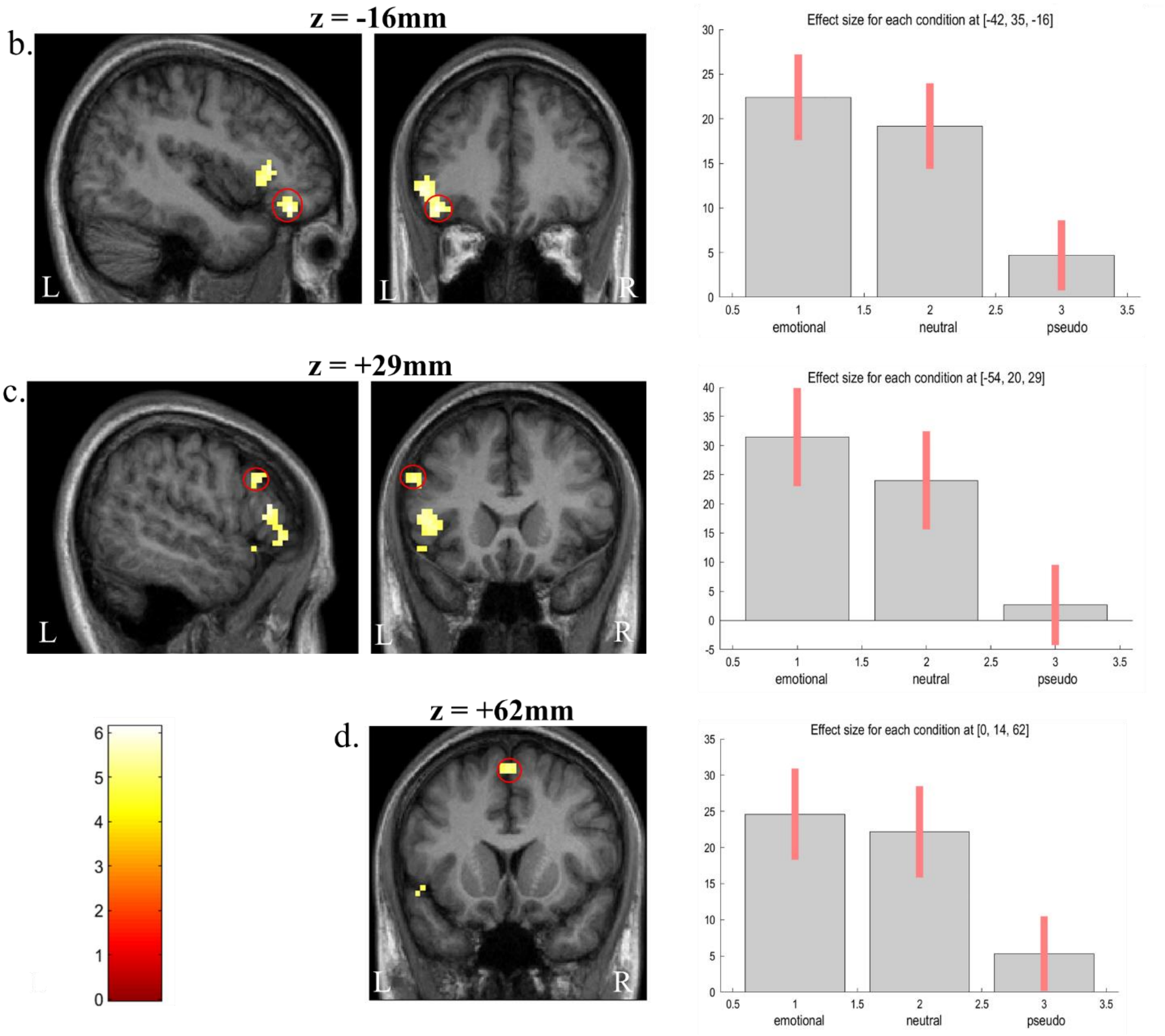
	Anatomical Location	**Peak Coordinates**			**Z-value**
		x	**y**	**z**	
L	IFG, pars triangularis$^{a, b}$	-48	23	8	6.06
L	*OFC* $^{a, b}$	-42	35	-16	5.98
L	Middle frontal gyrus$^{a, b}$	-54	20	29	5.32
L	Precentral gyrus^{a}	-36	2	41	4.84
/	Superior frontal gyrus$^{a, b}$	0	14	62	5.12

Note. Correlations met the criteria of FWE corrected, $p < 0.05$. Regions in italic are sub-peaks. *x, y, z* peak coordinates according to MNI stereotactic space, *L* left, *IFG* Inferior frontal gyrus, *OFC* Frontal orbital cortex.

a. Inclusive masks: emotional > rest, neutral > rest, emotional > pseudo, *p*=0.001
b. Inclusive masks: emotional > rest, neutral > rest, neutral > pseudo, *p*=0.001

Figure 4. Areas activated for the words > pseudowords contrast





Note. Effects are shown at $p < 0.05$ level (FWE corrected) for inclusive masking: emotional > rest, neutral > rest, emotional > pseudo, neutral > pseudo, p=0.001). The bar plots indicate effect sizes of activations across three conditions in peak voxels identified by the words > pseudowords contrast. The y-axis represents BOLD signal change and the x-axis represents conditions. The t-value colour bar applies to all the images. Anatomical locations are: a) IFG (pars triangularis), b) OFC c) middle frontal gyrus d) superior frontal gyrus.

Contrary to our expectations, no activation was detected in STG, SMG or angular gyrus. However, the usage of more lenient thresholds (i.e., p=0.05 for masks, p=0.001 uncorrected for main contrast of interest) revealed activations in bilateral STG, SMG and angular gyri (Table 2.2), with most activations stronger in the left hemisphere than in right hemisphere, which converged our hypotheses and prior research (Stoeckel et al., 2009). No activation was observed for the reversed pseudowords > words contrast, regardless of lenient thresholds.

Table 2.2. Additional activation for semantic processing (*p*=0.05 masks, *p*<0.001 uncorrected)

	Anatomical Location	**Peak Coordinates**			**Z-value**
		x	**y**	**z**	
	Temporal				
L	MTG, posterior division	-63	-40	2	6.08
L	*MTG, temporooccipital part*	-60	-49	-1	5.58
R	MTG, posterior division	57	-16	-10	4.10
	Parietal				
R	SMG, posterior division	69	-40	23	3.92
L	SMG, posterior division	-54	-46	41	4.60
L	*Angular gyrus*	-45	-55	56	3.72
R	Angular gyrus	69	-40	23	3.92
	Occipital				
L	Occipital pole	-24	-91	-13	4.02
R	Occipital pole	39	-91	-1	3.48

Note. This table only shows activated regions that were not presented in Table 2.1. Correlations met the criteria of $p < 0.001$ uncorrected (inclusive masks: emotional > rest, neutral > rest, emotional > pseudo, neutral > pseudo, p=0.05). *x, y, z* peak coordinates according to MNI stereotactic space, *L* left, *R* right, *MTG* Middle temporal gyrus, *SMG* Supramarginal gyrus.

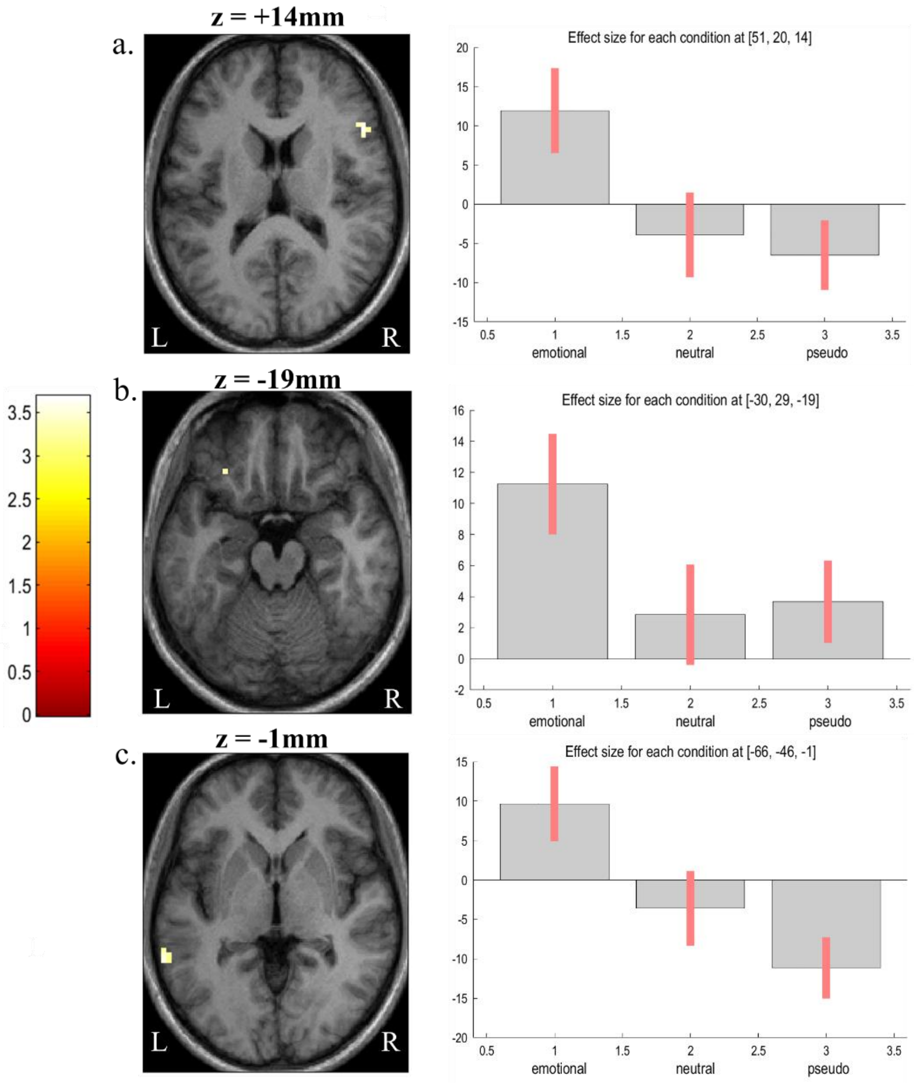
Finally, we examined the affective component in emotional word processing by emotional > neutral contrast. As no activation was significant enough to pass the FWE $p < 0.05$ threshold, we applied a more lenient threshold of $p < 0.001$ (uncorrected). Only small clusters were activated in this valence-specific contrast: left MTG, left OFC and right IFG (Table 3, Figure 5) were significantly more active for emotional words relative to neutral words, and the activated regions did not change when the masking threshold changed from p=0.001 to p=0.05. Regardless of more lenient thresholds, no greater activity was observed for the reversed neutral > emotional contrast. The results confirmed partially our hypothesis and previous research by showing greater activity in OFC (Kuchinke et al., 2005; Sylvester et al., 2021). In contrast, no activation was detected in ACC, insula and amygdala. We speculate that the lack of activation was caused by insufficient valence and arousal manipulations. Specifically, in most studies that have found significant activations of the emotional network during lexical tasks, emotional words had a mean valence of less than 2, whereas the negative words drawn from Scott et al. (2009) were "less" negative (M_{valence}=2.75). fMRI studies to date tend to use more "extreme" stimuli to detect more significant results. However, the inconsistencies we observed when using less-extreme stimuli suggest the need for further incremental studies of emotion effects during lexical processing.

Table 3. Activation for visual-affective stimuli processing

	Anatomical Location	**Peak Coordinates**			**Z-value**
		x	**y**	**z**	
	Temporal				
L	MTG, temporooccipital part	-66	-46	-1	3.5
	Frontal				
R	IFG, pars opercularis	51	20	14	3.66
L	OFC	-30	29	-19	3.26

Note. Correlations met the criteria of $p < 0.001$ uncorrected. *x, y, z* peak coordinates according to MNI stereotactic space, *R* right, *L* left, *IFG* Inferior frontal gyrus, *OFC* Frontal orbital cortex.

Figure 5. Areas activated for the emotional > neutral contrast



Note. Effects are shown at $p < 0.001$ (uncorrected). The bar plots indicate effect sizes of activations across three conditions in peak voxels identified by the emotional > neutral contrast. The y-axis represents BOLD signal change and the x-axis represents conditions. The t-value colour bar applies to all the images. Anatomical locations are: a) IFG (pars opercularis), b) OFC; c) middle temporal gyrus.

In general, the activations observed in the current study are consistent with previous findings, especially in semantic processing. Across three contrasts, OFC activation was identified, suggesting that this area was commonly involved in the current lexical task, and its degree of activation depended on the types of stimuli. Left inferior and middle gyrus, bilateral temporal and parietal lobes showed greater activity in response to real words than to pseudowords. However, activation of most areas involved in affective processing was not detected as predicted, which raises questions about our manipulation of word emotionality. Another explanation might be that the valence effects of positive words are generally more pronounced than those of negative words (e.g., Kuchinke et al., 2005). As we used negative words to represent emotional words in the study, the emotion effects were less obvious, or even non-existent. If future studies with exclusively positive words demonstrate significant emotion effects in brain activation, we might be able to deduce an asymmetry of sensitivity towards word valence.

Furthermore, the sample included three non-native English speakers (two Chinese, one French). As all the stimuli were drawn from English databases, the task might have also tested second-language processing rather than solely focusing on affective-semantic processing. The strong activation in Broca pars triangularis, an area related to simultaneous language translation may partially attest to this possibility. Importantly, we acknowledge that the resulting inferences in this study could be over-confident, given that the FFX approach used in the study could not distinguish between-subject variability and is not as robust in detecting outliers as random effects (RFX) approach (Stephan et al., 2009). Further research with larger sample sizes is needed to provide more robust evidence for all the hypotheses.

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