

## Understanding an implicated causality: The brain network for processing concessive relations

Xiaodong Xu<sup>a</sup>, Hongbo Yu<sup>b</sup>, Xiaoxue Gao<sup>c</sup>, Bo Shen<sup>d</sup>,



frequently in natural language (Blumenthal-Dramé, 2021; König, 1985; Verhagen, 2005). Concession has been argued to be semantically and pragmatically more complex than causality (König & Siemund, 2000). A causal sentence like “*people like to live in a warm place in the winter because people move from a cold place to a warm place*”. The same causal connection ( ), however, is implicit in a concessive sentence “*people generally like to live in a warm place in winter although people move from a cold place to a warm place*”. Therefore, inferential processes have to be deployed to reach the implicated meaning (people generally like to live in a warm place in winter) in concessive relations but much less so in causal relations. Moreover, in concessive sentences, the two propositions and are inherently contradictory (preferring to live in a warm place vs actually moving to a cold place). The presence of a concessive conjunction *although* would help resolve such a conflict by prompting the comprehender to make an inference and bridge the gap between the two propositions (Grandma moved to Harbin *not* out of her preference; her preferred place was actually Hainan because of its warmth in

interpreted as reflecting the increased processing costs of establishing and keeping a reversed (vs chronological) temporal representation (Chen et al., 2022; Münte et al., 1998; Xiang et al., 2014), it seems that readers with larger working memory span are better at retrieving and maintaining a discourse representation in a reverse temporal order. fMRI studies revealed increased activations in the frontal-temporal regions for syntactically complex vs simple sentences as a function of increasing verbal working memory span (Fiebach et al., 2004; Newman et al., 2013; Prat et al., 2007; Prat & Just, 2011). Prat and Just (2011), for example, investigated how the comprehension of syntactically complex sentences (containing an object-relative clause) vs simple sentences (composed of two active-conjoined clauses) is related to working memory capacity. They found that the syntactic complexity effect, as measured by subtracting the activation of simple sentences from complex sentences in a number of control/memory related regions (e.g., prefrontal, hippocampus, precuneus), was positively correlated with participants' working memory span, suggesting that individuals with larger working memory capacity are better at computing more syntactically complex structures. Considering the potential influence of individual differences in pragmatic skills and working memory capacity on understanding implicated meanings and complex structures, the present study will take both into consideration when comparing the neurocognitive processing of concessive vs causal relations.

Although there are currently no studies on the neurocognitive mechanisms of understanding concessive relations, a number of neuroimaging studies have explored the neural correlates of *co u i n g n e g a t i o n* and *r o c e s s i n g i l l i c a e e a n i n g*. The brain structures involved in computing negation have been located in the left premotor cortex (Christensen, 2009) and the bilateral anterior temporal pole (Kumar et al., 2013), which seem to be different from the classical perisylvian language areas. It has been proposed that the processing of negation is implemented at the neural level by the recruitment of inhibitory and cognitive control mechanisms – the comprehension of negation reuses the inhibitory mechanism of motor control (Aron et al., 2014; Beltrán et al., 2018; de Vega et al., 2016; Vitale et al., 2022). Specifically, the right inferior frontal gyrus (rIFG), as a core region in inhibitory control, plays a crucial role in suppressing a negated statement (e.g., by reducing motor activities for a negated action in the primary motor cortex; Vitale et al., 2022). On the other hand, the core brain areas responsible for processing implicated meaning are located in the frontal-parietal network, including the left IFG, medial prefrontal cortex (mPFC), bilateral middle temporal gyrus (MTG), temporal parietal junction (TPJ)/angular gyrus (AG) (Cocchi et al., 2014; Feng et al., 2017; Jang et al., 2013; Li et al., 2014; Prado et al., 2015; Ye et al., 2009a, 2009b, 2012; Zhan et al., 2017). Within this left brain network, the pMTG plays a crucial role in controlled semantic retrieval, such as when linguistic inputs or retrieved meanings are ambiguous or unexpected (Davey et al., 2015; 2016; Jackson, 2021; Lambon Ralph et al., 2017).

Both the access to the implicated meaning and the computation of negation could lead to difficulties in processing concessive relative to causal relations. This cognitive complexity could be manifested in the activation of brain structures as well as the functional connectivities between the involved brain areas. Based on the role of the left premotor cortex and the bilateral anterior temporal pole in processing negation and the left IFG, mPFC/MFG, pMTG, and the bilateral TPJ in processing implicated meaning, we could not only reveal the brain structures involved in processing concessive and causal relations but also discern the critical cognitive components involved in processing concessive (vs. causal) relations.

Specifically, if the processing difficulty of concessive relations is primarily due to the additional operation of *n e g a t i o n* relative to causal relations (e.g., C vs A in Table 1), we should find stronger activations in those areas responsible for *n e g a t i o n c o u a i o n*, such as the left premotor cortex (Christensen, 2009), the bilateral anterior temporal pole (Kumar et al., 2013), or at least the core region responsible for suppressing a negated statement (i.e., the right inferior frontal gyrus; Vitale

et al., 2022). If, however, the difficulty arises mainly from inferring the implicated meaning rather than the additional computation of negation, we should observe not only the recruitment of the core network of language comprehension like the left frontal-temporal cortex (e.g., IFG, STG, MTG) but also other extra-linguistic areas that are crucial for inferential processing or semantic/cognitive control such as left mPFC/MFC, pMTG and bilateral TPJ/AG (Frank, Baron-Cohen, & Ganzel, 2015; Feng et al., 2017; 2021a; 2021b; Friese, Rutschmann, Raabe, & Schmalhofer, 2008; Jang et al., 2013; Mason & Just, 2011; Noonan et al., 2013). In particular, given the important role of the left pMTG in processing complex event semantics (e.g., Davey et al., 2016; Jackson, 2021; Lambon Ralph et al., 2017; Tyler et al., 2011), the effective connectivity from the left pMTG to core linguistic and extra-linguistic areas could be different in the processing of concessive vs causal relations.

Moreover, the neural correlates of processing pragmatic anomalies could be different for concessive and causal relations as well (Xu et al., 2015; 2018). The brain areas subserving semantic retrieval/integration such as the left IFG (Hagoort et al., 2004; Hagoort & Indefrey, 2014) could be activated by pragmatic anomalies. In addition, brain areas responsible for non-literal inference (e.g., pragmatic enrichment) such as TPJ/STG and MFG could also be activated (Kuperberg et al., 2000; Li et al., 2014; Rüschemeyer et al., 2005; Shibata et al., 2010), since an inferential process might be initiated to rationalize the pragmatic incongruence. By contrast, the areas showing enhanced activation in the processing of causal anomalies (relative to felicitous causal relations) would show less activation enhancement in the processing of concessive anomalies (relative to felicitous concessive relations) due to a higher baseline activation triggered by the processing of normal concessive relations (e.g., Xu et al., 2015; 2018).

Finally, given individual variations in pragmatic abilities (Feng et al., 2021b; Nieuwland et al., 2010), we predicted that individuals who had low abilities in pragmatic inference (as indexed by a high score on the AQ-Communication subscale) would depend more on the areas responsible for pragmatic inference (e.g., dmPFC, pMTG; Feng et al., 2021b; Nummenmaa et al., 2012) to reach the implicated meaning in concessive relations. Moreover, since understanding concessive relation involves more complex cognitive operations such as computing negation and/or making inference, it could have a closer association with one's memory capacity compared to comprehending causal relations. Thus, individuals who have a smaller working memory span might depend more on those areas responsible for working memory (e.g., left prefrontal cortex, MFG; Fiebach et al., 2004; Li et al., 2014; Luerding et al., 2008; Prat & Just, 2011) to process concessive relations.

## 2. Methods

### *a r c i a n s*

Thirty-four healthy right-handed university students took part in this experiment. Six participants were excluded from data analysis due to excessive head movements (>3 mm of locomotion or 3 degrees of rotation), leaving 28 participants (14 women, mean age 22.1 years, age ranging from 19 to 26 years) for the final data analysis. This sample size (N = 28) was determined with reference to published fMRI studies on pragmatic/semantic inference adopting a 2 × 2 factorial design (e.g., N = 28, Feng et al., 2021b; N = 20, Li et al., 2022; N = 28, Nieuwland, 2012). We also conducted a simulation-based power analysis using the function R2power in the R package mixedpower (Kumle et al., 2021) based on the behavioral data of a previous relevant study (which used the same stimuli and acceptability rating task (see Table 3 in Xu et al., 2015). The simulation analysis showed that 28 participants were needed to reach 90 % power. The finally recruited 28 participants were all native speakers of Chinese, had normal or corrected-to-normal vision, and no history of neurological or psychiatric disorders. Each of them gave informed written consent before the experiments. This study was carried out in accordance with the Declaration of Helsinki and was

approved by the Ethics Committee of the Nanjing Normal University.

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The stimulus materials consisted of 128 quartets of written Chinese two-clause sentences, which were taken from a previous ERP experiment (Xu et al., 2015). As shown in Table 1, the main clause stated that a protagonist moved from location A to location B, the subordinate clause either provided a statement addressing the cause of the movement in a *ecause* structure (see sentence A/B) or a statement conceding an attitude towards the movement in an *al hough* structure (see sentence C/D). The subordinate clause always contained a positive attitude-biased verb (it could be one of the following verbs: /like, 81; /prefer, 25; /believe, 8; /be used to, 8; others, 6) to explain the reason for the movement. The two locations mentioned in the main clause have certain characteristics that distinguish them from each other (e.g., *ar vs col*, *e ensi e vs chea*) or have been featured by different symbols known throughout China (e.g., the *rea all* is in Beijing), which leads to an unambiguous resolution of the locative pronoun in the subordinate clause.

Each critical sentence in a quartet was assigned to a different test list with a Latin square procedure, such that in each list there were 32 sentences per experimental condition. A set of 40 filler sentences were added to each list. To reduce the potential influence induced by the positive attitude words (e.g., *li e refer*), the subordinate clauses in half of the fillers (20 sentences) contained negative attitude words (e.g., *isli e*) or neutral words (e.g., *no*). The other half of the fillers (20 sentences) had various types of sentence structures (connected by *ecause* or *al hough*) and described a variety of situations. All of the 168 sentences in each list were pseudo-randomized, with the restriction that no more than three consecutive sentences were of the same condition and no more than three consecutive sentences were pragmatically correct or incorrect. Participants were randomly assigned to one of the four lists. The fMRI scanning was divided into three sessions, lasting approximately 15 min per session.

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In the fMRI experiment, each sentence was presented segment-by-segment in rapid serial visual presentation (RSVP) mode at the center of the screen. Each segment was presented for 300 ms followed by a 300 ms blank screen. Each segment was printed with a white font against a black background, subtending 1° to 3° in visual angle horizontally and 1° vertically. Participants were instructed to silently read and understand the meaning of each sentence, and to perform a comprehensibility rating task (the plausibility of the sentence) at the end of each sentence on a 7-point visual analog scale. This was done by repeatedly pressing a response button with the right hand to move the cursor on the scale; the rating was confirmed by pressing a button with the left hand. The permutation order from left to right was 1–7 (1 indicating the least acceptable and 7 indicating the most acceptable) in one half and 7–1 in the other half. To optimize the design’s statistical efficiency, a fixation point (“+”) between successive sentences was presented in different durations (“jittered”) across trials.

Before scanning, each participant received written instructions about the experimental procedure and completed 28 practice trials that had structures similar to the sentences in the fMRI scanning. To test individual variations in social communication and working memory, all the participants were asked to return to the lab a few days later after scanning and to complete the following two questionnaires, one testing their pragmatic inference abilities (communications abilities) by using the Chinese version of the Autism-Spectrum Quotient questionnaire (AQ; Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001), and the other testing their reading span (i.e., verbal working memory). In the verbal working memory test, participants pressed a key to judge whether the sentence presented on the screen was true or not and at the

same time memorized the last word of each sentence. The number of sentences in a set was incrementally increased from one to eight. Participants were asked to type in the memorized words in order after each set. Reading span capacity scores were calculated by summing the number of words recalled in correct sequence with correct judgment of each sentence (Daneman & Carpenter, 1980).

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Functional images were acquired on a 3-Tesla MRI scanner (GE MR750, General Electric, Fairfield, Connecticut), using a T2\*-weighted echo planar imaging ( ) sequence, with a TR of 2000 ms, a TE of 30 ms, and a 90° flip angle. Each image consisted of 32 axial slices covering the whole brain and was acquired in an interleaved sequence. Slice thickness was 4 mm and inter-slice gap was 1 mm, with a 200 mm field of view (FOV), 64 × 64 matrix, and 3 × 3 × 4 mm<sup>3</sup> voxel sizes. Head motion was minimized using pillows and cushions around the head and a forehead strap.

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Image preprocessing and analysis were conducted with the Statistical Parametric Mapping software SPM12 (Wellcome Trust Department of Cognitive Neurology, London). Following the standard procedures implemented in SPM12, images were slice-time corrected (with the middle slice as the reference), motion corrected, normalized to MNI space (resampled to 3 × 3 × 3 mm<sup>3</sup> isotropic voxel), spatially smoothed using an 8 mm FWHM Gaussian filter, and temporally filtered using a high-pass filter with 1/128 Hz cutoff frequency. For each participant, the extent of head movements did not exceed one voxel size.

The preprocessed data were analyzed using a general linear model (GLM) approach. To identify brain areas that encode concessive and causal relations, in GLM1, we defined 7 critical regressors at the participant-level (Huettel et al., 2014). The first four regressors corresponded to the four critical conditions (i.e., regressors of interest), namely, *ecause*-congruent, *ecause*-incongruent, *al hough*-congruent, and *al hough*-incongruent. Each started from the onset of the initial word (i.e., *in ei/ ecause* or *in'guan/al hough*) of the second clause until the offset of the last one. The other three regressors (i.e., regressors of no interest) were the initial clauses of the experimental sentences (starting from the onset of the initial word and spanning the duration of the initial clause), the filler sentences (the actual onset and the duration), and the after-sentence rating, respectively. In addition, six rigid-body movement parameters calculated from the realignment procedure were also included to correct for head-motion artifacts. All regressors were convolved with a canonical hemodynamics response function (HRF). The onset and duration of each regressor were defined according to the actual onset and duration of each experimental stimulus.

We defined two contrasts for the main effect of *con unc ion e* and main effect of *congruenc* :

Main effect of conjunction type (Contrast 1): (*al hough*-incongruent + *al hough*-congruent) > (*ecause*-incongruent + *ecause*-congruent).

Main effect of congruency (Contrast 2): (*al hough*-incongruent - *ecause*-incongruent) > (*al hough*-congruent - *ecause*-congruent).

For the simple effects, we defined the following four contrasts: (*al hough*-congruent > *ecause*-congruent), (*al hough*-incongruent > *ecause*-incongruent), (*al hough*-incongruent > *al hough*-congruent), and (*ecause*-incongruent > *ecause*-congruent).

Second-level models were constructed as one-sample *t*-tests using contrast images from the first-level models. All results were corrected for multiple comparisons using the threshold of peak-level < 0.001 (uncorrected) combined with cluster-level < 0.05 (FWE-corrected). This cluster-level threshold was determined using a Monte Carlo simulation as implemented in the AFNI AlphaSim package (<https://afni.nimh.nih.gov/pub/dist/doc/manual/AlphaSim.pdf>). Statistic parametric maps

are presented at this threshold unless otherwise noted.

#### *the correlations between brain activations and individual differences*

We used the statistical maps from the  $t$ -tests in the first-level analysis to examine brain activations that correlated with individual differences in pragmatic inference (i.e., AQ scores; Baron-Cohen et al., 2001) and verbal working memory (i.e., Reading span; Daneman & Carpenter, 1980). In the second-level analysis, we used measures of AQ and working memory scores as covariates and activations in the contrasts ‘*although*-congruent vs *because*-congruent’ recorded from  $t$ -tests in the first-level analysis as dependent variables. We also carried out a correlation analysis of the main contrast of conjunction type, (*although*-incongruent + *although*-congruent) > (*because*-incongruent + *because*-congruent), based on the same procedure.

To confirm the correlations obtained at the whole-brain analysis, we also performed the ROI-based correlation analysis. The ROI data corresponding to the main contrast of *conjunction* were extracted from a 3-mm-radius sphere centered at peak voxels, including the left MTG ( $[-60, -7, -11]$ ) and the mOFC ( $[-6, 56, -5]$ ).

#### *analytic causal modeling*

To reveal the

2014; Mar 2011; Ye et al., 2012), we specified an intrinsic connectivity between the pMTG/IFG and other related brain areas. The driving input was set to either IFG or pMTG, or to combinations between the two areas (See Fig. 1), resulting in 9 model families in total. Within each model family, modulator effects of conjunction type (*al hough congruent or ecause congruent*) were placed on different intrinsic connectivities in different individual models. Given the important role of the pMTG in complex semantic control/retrieval (Davey et al., 2015; Lambon Ralph et al., 2017; Noonan et al., 2013) and the TPJ in pragmatic inference (Feng et al., 2017), our main hypothesis was that the connectivity between the pMTG and IFG might be different from the connectivity between the pMTG and TPJ during the processing of concessive vs causal relations. We therefore specified eight single models within each family. Within each model, the information flow between the pMTG and IFG/TPJ, and between the IFG and MFG could be bidirectional or in one direction only. Table 2 summarizes the structure of the modulatory connectivities in the eight models.

These models and model families were then compared using Bayesian model selection (BMS), which appeals to a Bayesian framework to calculate the “model evidence” of each model. The model evidence represents the trade-off between model simplicity and fitness (Penny et al., 2010). Here, BMS was implemented using a random-effects analysis (i.e., assuming that the model structure might vary across participants) that is robust to the presence of outliers (Stephan et al., 2010). Based on the estimated model evidence for each model, random effect BMS calculates the exceedance probability of each model, reflecting the probability that this model is a better fit to the data than any other models. When model families were compared, all models within a family were averaged using Bayesian Model Averaging, and the exceedance probabilities were calculated for each model family (Penny et al., 2010). Model parameters were estimated based on the averaging of the winning family and were tested using one-sample  $t$ -tests.

### 3. Results

#### Behavioral results

We carried out linear mixed effect model analysis in R (version 4.0.2, R Development Core Team, 2020) on the behavioral rating data (Table 3). Results from the finally fitted model (R formula:  $\text{Lmer}(\text{scale}(\text{rating}) \sim \text{conjunction type} * \text{congruency} + (1 + \text{congruency} | \text{item}) + (1 + \text{conjunction type} + \text{congruency} | \text{subject}))$ ) showed a significant two-way interaction between *conjunction type* and *congruency* ( $\beta = -3.85, S = 0.04, t = -9.70, p < 0.001$ ). Follow-up analyses to resolve the interaction showed that *ecause*-incongruent sentences were less acceptable than *ecause*-congruent sentences ( $\beta = -1.72, S = 0.07, t = -25.23, p < 0.001$ ), and *al hough*-incongruent sentences were less acceptable than *al hough*-congruent sentences ( $\beta = -1.34, S = 0.07, t = -19.59, p < 0.001$ ; See Table 3). Moreover, *ecause*-congruent sentences were more acceptable than *al hough*-congruent sentences ( $\beta = 0.30, S = 0.04, t = 8.59, p < 0.001$ ), whereas *ecause*-incongruent

**Table 2**

The structure of the modulatory connectivities in DCM.

Models		1	2	3	4	5	6	7	8
pMTG	IFG	1	1	1	1	0	1	1	1
pMTG	IFG	0	1	1	1	1	1	1	1
pMTG	TPJ	0	0	1	1	0	1	1	1
pMTG	TPJ	1	1	1	1	1	1	1	1
IFG	MFG	0	1	1	1	0	0	1	1
IFG	MFG	1	1	1	1	1	1	1	1
TPJ	MFG	1	1	1	1	0	0	1	1
TPJ	MFG	0	0	1	1	1	1	1	0
IFG	TPJ	0	0	0	1	0	0	0	0
IFG	TPJ	0	0	1	1	0	0	0	0
MTG	MFG	0	0	0	0	0	0	0	1
MTG	MFG	0	0	0	0	0	0	1	1

**Table 3**

Results from both the on-line (this study) and the off-line (Xu et al., 2015) acceptability rating tests using the same stimuli.

	On-line rating		Off-line rating	
	Mean	SD	Mean	SD
<i>ecause</i> _congruent	6.56	0.50	6.46	0.31
<i>ecause</i> _incongruent	1.68	0.39	1.40	0.33
<i>al hough</i> _congruent	5.70	1.04	5.71	0.70
<i>al hough</i> _incongruent	1.92	0.59	1.52	0.32

sentences were less acceptable than *al hough*-incongruent sentences ( $\beta = -0.08, S = 0.04, t = -2.34, p = 0.019$ ).

#### Whole-brain analysis

Results of the whole-brain analysis are presented in Table 4 and depicted in Fig. 2a-b. As revealed by the main effect of *conjunction type* (*al hough*-incongruent + *al hough*-congruent > *ecause*-incongruent + *ecause*-congruent), a left frontoparietal network including (bilateral) MFG, (bilateral) IFG, pMTG, and IPL/AG was significantly activated by concessive relations relative to causal relations. However, the contrast for the main effect of *congruency* only revealed activations in the right Supramarginal Gyrus/IPL. In particular, similar to the activation pattern observed under the main effect of *conjunction type*, a left brain network including the left IFG, pMTG, (bilateral) MFG, mPFC, and (bilateral) AG/TPJ was strongly involved in the contrast of *al hough*-congruent condition vs *ecause*-congruent condition (see Fig. 2a and Table 4). On the other hand, the contrast of *ecause*-congruent condition vs *al hough*-congruent condition mainly activated the left Precentral/Postcentral Gyrus, the left Medial Frontal Gyrus, and the right MTG. The contrast of *al hough*-incongruent vs *ecause*-incongruent mainly activated the left IFG, MFG, and the (bilateral) IPL (Fig. 2b). Interestingly, while the contrast of *ecause*-incongruent vs *ecause*-congruent activated the right Supramarginal Gyrus/STG and the right MFG (Fig. 2c), there were no robust activations in the contrast of *al hough*-incongruent vs *al hough*-congruent sentences.

#### Independent region of interest analysis

We also performed independent region of interest (ROI) analysis on the critical areas (IFG [ $-46, 22, 12$ ]), MFG [ $-32, 18, 42$ ]), TPJ [ $-48, -52, 28$ ]), and pMTG [ $-58, -34, -12$ ]), which have been previously reported to be crucial for pragmatic inference (Mason & Just, 2011) and semantic control (Noonan et al., 2013; Tyler et al., 2011). Consistent with the whole-brain analysis, *al hough*-congruent sentences evoked stronger brain activations than *ecause*-congruent sentences (all ROIs), *al hough*-incongruent sentences elicited stronger activations than *ecause*-incongruent sentences (IFG, pMTG), and *ecause*-incongruent sentences elicited stronger activations than *ecause*-congruent sentences (MFG). One difference from the whole-brain analysis, however, was that stronger activations were observed in TPJ for *al hough*-congruent sentences than for *al hough*-incongruent sentences, ( $t = 2.79, p = 0.01$ ).

#### Behavioral correlations between ratings and individual differences

For the contrast of *conjunction type* (*al hough*-incongruent + *al hough*-congruent) vs (*ecause*-incongruent + *ecause*-congruent), activation in the left MTG was positively correlated with AQ scores ( $r = 3.07, S = 1.92, \text{range} = 0-6$ ; Fig. 3a), as confirmed by the ROI-based analysis ( $r = 0.607, p < 0.01$ ; Fig. 3c), suggesting that individuals with low communication abilities would depend more on this region to get to the implicated meaning. Moreover, activation in the left medial Prefrontal Cortex (mOFC) was positively correlated with verbal working memory scores ( $r = 3.08, S = 0.86, \text{range} = 1-5$ ; Fig. 3b), as confirmed by the ROI-based analysis ( $r = 0.605, p < 0.01$ ; Fig. 3d).

**Table 4**  
Activations from the whole brain analysis.

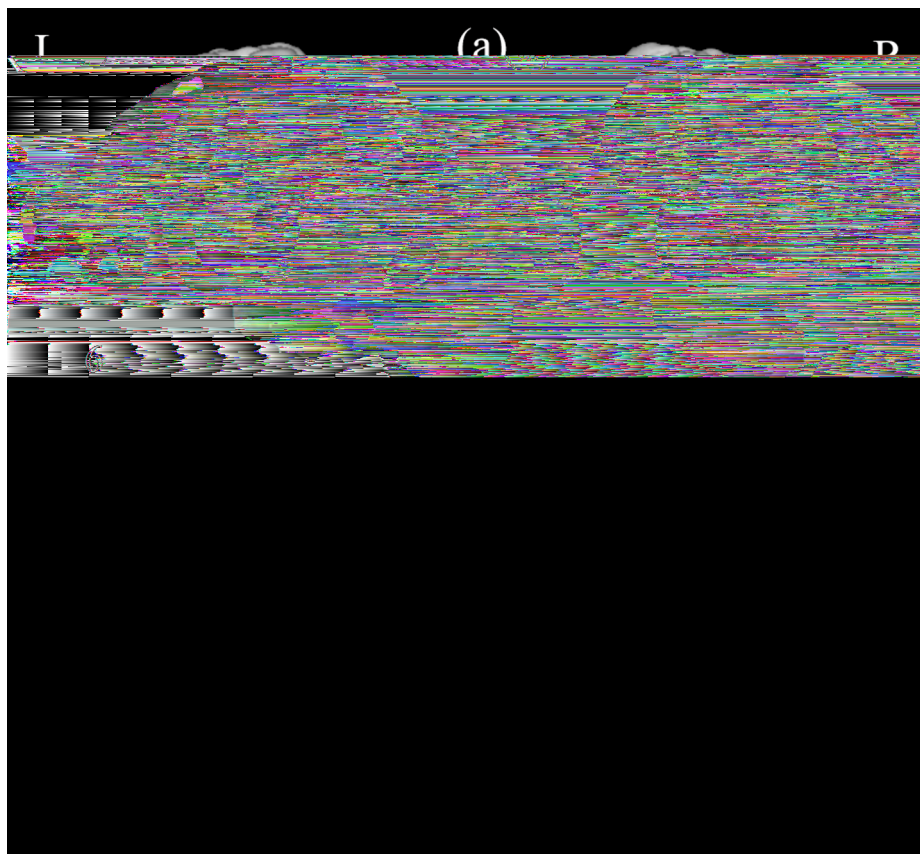
		Cluster Size	Peak T	Cluster p (FWE-cor)	x	y	z	
<i>al hough</i> > <i>ecause</i>	Middle Frontal Gyrus_L	900	7.99	<0.01	-42	17	49	
	Inferior Frontal Gyrus_L	-	7.43	-	-54	20	16	
	Supp_Motor_Area_L	306	6.67	<0.01	-3	23	49	
	Middle Temporal Gyrus_L	132	6.02	0.05	-54	-34	-11	
	Middle Frontal Gyrus_R	218	5.32	0.01	48	20	43	
	Inferior Frontal Gyrus_R	-	4.61	-	51	23	22	
	Inferior Parietal Lobule_L	375	5.06	<0.01	-42	-52	43	
	Angular_L	-	5.02	-	-42	-49	31	
	Inferior Frontal Gyrus_R	30	4.57	0.5	33	29	-5	
	Precuneus_R	174	4.34	0.02	9	-70	37	
	Precuneus_L	-	4.25	-	-6	-76	37	
	<i>incongruen</i> > <i>congruen</i>	Supramarginal Gyrus_R	44	4.27	0.32	45	-46	34
		Inferior Parietal Lobule_R	-	3.86	-	54	-52	40
	<i>al hough_con</i> > <i>ecause_con</i>	Middle Frontal Gyrus_R	26	3.86	0.54	36	26	40
Middle Frontal Gyrus_L		612	8.7	<0.01	-42	17	49	
<i>ecause_con</i> > <i>al hough_con</i>	Inferior Frontal Gyrus_L	-	7.37	-	-54	20	16	
	Middle Temporal Gyru_L	146	6.63	0.03	-54	-31	-11	
	Supp_Motor_Area_L	238	6.32	0.01	-9	17	61	
	Medial Frontal Gyrus_L	-	6.32	-	-6	26	46	
	Middle Frontal Gyrus_R	153	5.77	0.03	48	20	46	
	Angular_L	382	5.73	<0.01	-54	-55	31	
	Insula_L	30	4.43	0.5	-30	26	-8	
	Precuneus_L	47	4.32	0.33	-6	-67	40	
	Angular_R	27	3.81	0.54	57	-55	31	
	Cingulate Gyrus_R	83	5.13	0.14	15	-37	43	
	Postcentral_L	360	4.76	<0.01	-33	-22	43	
	Precentral Gyrus_L	-	4.64	-	-30	-22	61	
	Sub-Gyral_R	234	4.22	<0.01	51	-1	16	
	Middle Temporal Gyrus_R	-	4.13	-	60	-7	-5	
Medial Frontal Gyrus_L	68	4.17	0.20	-3	53	-8		
<i>ecause_incon</i> > <i>ecause_con</i>	Supramarginal Gyrus_R	238	4.58	<0.01	45	-46	34	
	Inferior Parietal Lobule_R	-	4.56	-	60	-55	37	
	Superior Temporal Gyrus_R	-	4.44	-	60	-64	25	
	Middle Frontal Gyrus_R	121	4.5	0.05	45	26	43	
<i>ecause_con</i> > <i>ecause_incon</i>	Sub-Gyral_R	75	4.5	0.15	48	-1	16	
	Middle Frontal Gyrus_L	259	5.94	<0.01	-54	23	25	
<i>al hough_incon</i> > <i>ecause_incon</i>	Precentral_L	-	5.34	-	-39	8	43	
	Inferior Frontal Gyrus_L	-	3.99	-	-51	23	1	
	Inferior Parietal Lobule_R	161	4.98	0.03	48	-37	52	
	Sub-Gyral_R	-	4.65	-	30	-46	34	
	Angular_R	-	3.73	-	36	-58	46	
	Middle Frontal Gyrus_L	70	4.94	0.19	-39	53	10	
	Corpus Callosum	64	4.72	0.22	0	-22	25	
	Cingulum_Mid_R	123	4.54	0.06	9	20	43	
	Supp_Motor_Area_L	-	4.48	-	0	23	46	
	Supramarginal Gyrus_L	164	4.44	0.03	-45	-43	37	
	Inferior Parietal Lobule_L	-	4.43	-	-39	-49	40	
	Frontal_Sup_R	820	5.97	<0.01	15	47	43	
	<i>ecause_incon</i> > <i>al hough_incon</i>	Frontal_Sup_Medial_R	-	5.61	-	6	62	7
		Middle Occipital Gyrus_R	66	4.49	0.21	51	-73	37
Angular_R		-	4.24	-	48	-64	25	
Inferior Temporal Gyrus_L		34	4.31	0.46	-54	-13	-35	
Posterior Cingulate_R		52	4.07	0.3	9	-58	16	
Precuneus_L		-	3.94	-	-3	-58	19	

Note: (1) *f here is ore han one rain region in the sa e cluster the cluster size for other rain regions and the corresponding values are in the 'z' column*; (2) 'con' refers to congruent, 'incon' refers to incongruent.

*na ic casual o elling*

The Bayesian model comparison between the nine families of models with different driving inputs showed that the model family with driving input to IFG (the seventh model family) fitted the data better; its family exceedance probability was more than 90 % (See Figs. 1 and 4). The model parameters estimated based on the average of the winning model family are depicted in Fig. 5 (See Table 5 for the estimated model

parameters). As demonstrated in the Figure, the concessive relation significantly enhanced the connectivity from the left pMTG to the left TPJ, whereas the same connection was not influenced by causal relation. The modulation effect was significantly different between causal relation and concessive relation ( $t = 2.30, p < 0.05$ ). On the other hand, however, the causal relation significantly enhanced the connectivity from the left pMTG to the left IFG, whereas the same connection was not influenced by concessive relation. In addition, the connectivity from the



**Fig. 2.** Whole-brain activations for (a) the contrast *al hough*-congruent vs *ecause*-congruent, (b) the contrast *al hough*-incongruent vs *ecause*-incongruent, and (c) the contrast *ecause*-incongruent vs *ecause*-congruent (The  $t$  value for activation is from 2 to 6).

left IFG to the left MFG was commonly modulated by both relations.

#### 4. Discussion

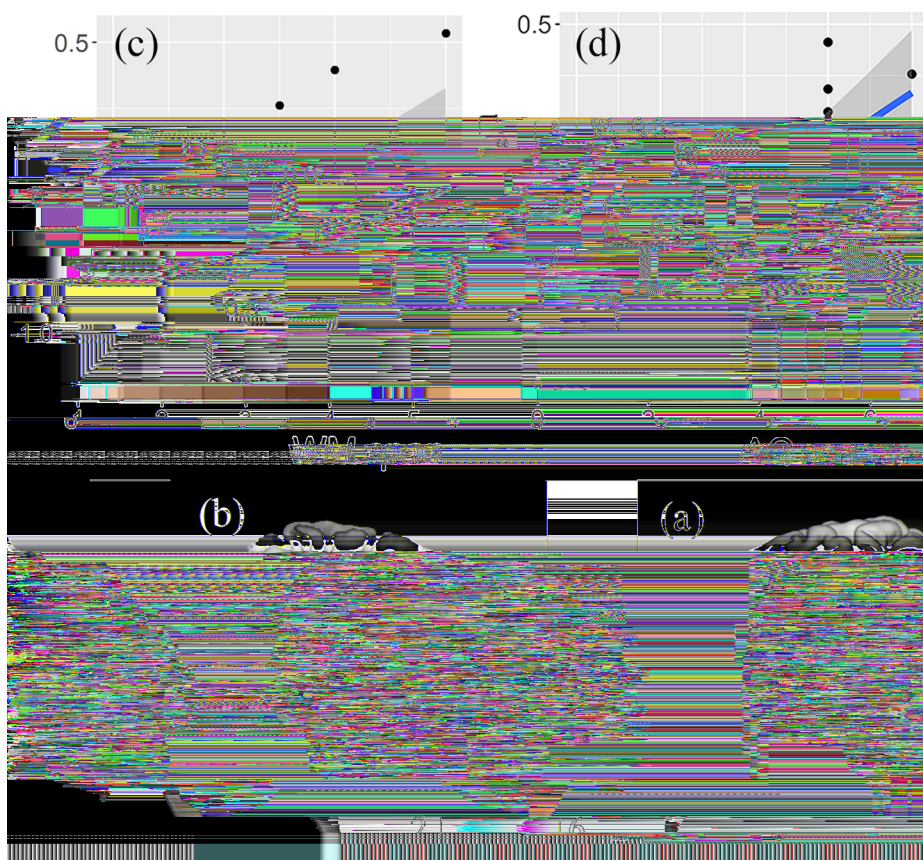
This study examined the neural correlates and functional connectivities underpinning concessive and causal relations. Compared to *ecause*-congruent sentences, *al hough*-congruent sentences yielded increased activations in the left IFG, (bilateral) MFG, mPFC, pMTG and TPJ/AG, a brain network which is crucial for understanding implicated meaning (e.g., conventional implicature) and semantic control; none of these brain areas were significantly activated in the reversed contrast (i.e., *ecause*-congruent vs *al hough*-congruent). Meanwhile, while stronger activations were found in the right Supramarginal Gyrus/STG and the right MFG in the comparison of *ecause*-incongruent vs *ecause*-congruent sentences, no significant activations were observed in the comparison of *al hough*-incongruent vs *al hough*-congruent sentences. Importantly, the DCM analysis revealed that, while the effective connectivity from the pMTG to IFG was enhanced during the processing of causal relations, the connectivity from the pMTG to TPJ was enhanced during the processing of concessive relations. Finally, activations in the left MTG (extended to the left STG) and the left ventromedial prefrontal cortex significantly correlated with individuals' communication abilities and verbal working memory scores, respectively. These findings suggest that compared to processing causal meaning, processing concessive meaning requires the engagement of an extensive left brain network, especially those areas subserving pragmatic inference (e.g., mPFC/MFC and TPJ) and semantic control (e.g., IFG, pMTG), presumably because understanding concessive relations requires the inhibition of an implicated causal association and access to the intended meaning.

#### he neurological ases of un ers an ing concessi e relations

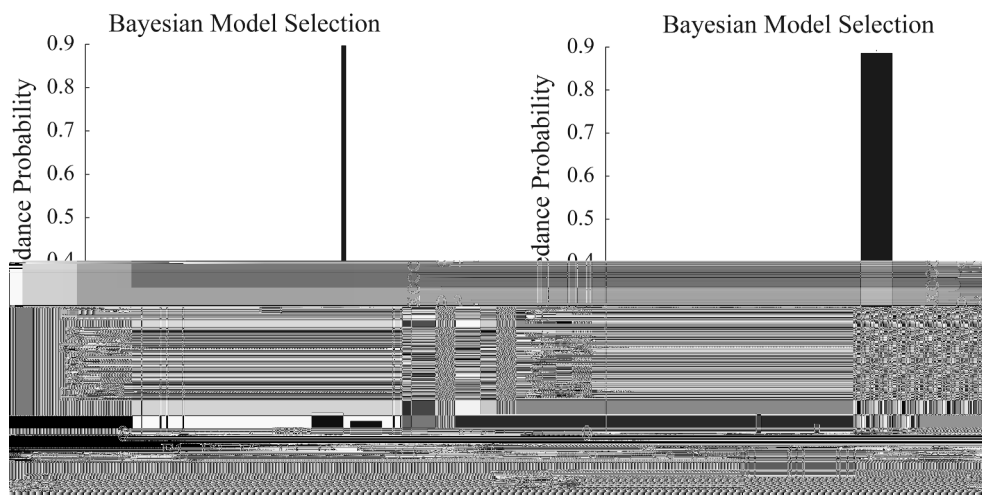
Linguistically, there are currently at least two potential explanations for the complexity of concessive relations, as it could result primarily from the computation of negation or from the inference of the implicated meaning. The engagement of a left brain network including the IFG, MFG/mPFC, pMTG, and TPJ in processing concessive vs causal relations suggests that the difference might arise from the processing of implicated meaning rather than the computation of *negation*, because the two sites of this network – mPFC/MFG and TPJ(AG), are core areas of the ToM network, which are commonly involved in making inference about other people's mental states (Amodio & Frith, 2006; Carrington & Bailey, 2009; Hagoort & Indefrey, 2014; Feng et al., 2021b). The computation of *negation*, on the other hand, has been reported to be dependent on the left premotor cortex (Christensen, 2009) or the bilateral anterior temporal pole (Kumar et al., 2013), which have not been observed in the current study. Moreover, it has been argued that negation processing might be implemented at the neural level by recruiting inhibitory and cognitive control mechanisms (Aron et al., 2014; Beltrán et al., 2018; de Vega et al., 2016; Vitale et al., 2022), with the right inferior frontal gyrus playing a critical role in inhibiting activations in the primary motor cortex (Vitale et al., 2022). Contrary to this assumption, however, neither the right inferior frontal gyrus nor the primary motor cortex was found to be involved in processing concessive relations.

Consistent with the implicated meaning account, previous fMRI studies on non-literal text processing have found that, relative to understanding asserted meaning, understanding the implicated meaning of an utterance activates a brain network including the mPFC, MTG, and TPJ (Bašnáková et al., 2014; Feng et al., 2017; 2021b; Jang et al., 2013; Li et al., 2014). With regard to sentences in the current study,





**Fig. 3.** (a) Activation in left MTG was positively correlated with AQ scores in the contrast ‘*al hough > ecause*’; (b) Activation in the left mOFC was positively correlated with WM scores in the contrast ‘*al hough > ecause*’; (c) The significant correlation based on parameter estimates ( $\beta$  values) extracted from the left MTG and individual differences in AQ ( $r = 0.607, < 0.01$ ); (d) The significant correlation based on parameter estimates ( $\beta$  values) extracted from mOFC and individual differences in VWM ( $r = 0.605, < 0.01$ ).



**Fig. 4.** The dynamic causal modeling (DCM) analysis for the left frontal-temporal network. The exceedance probabilities of the single models (left panel) and the nine model families (right panel). Family groups were divided according to different driving inputs.

comprehenders depend on this network to gain access to the causal association (e.g., *e er e oneself an conse uen l ass e a*) as implicated by the concessive marker *al hough*. This interpretation is further supported by the negative correlation between MTG activation and the individual’s performance in pragmatic communication (Note that higher AQ scores mean low communication abilities; see Fig. 3c), indicating that individuals who have low pragmatic abilities would depend more on the ‘social brain’ (ToM) network to reach the implicated causal association. Nevertheless, to further test whether the cognitive complexity underlying concessive relations is due to the computation of

implicated meaning, it would be interesting to directly compare the processing of explicit concession with implicit causality (e.g., causally related statements with no overt causal makers). A strong overlap in brain activations would provide direct evidence for the implicated meaning account.

Activations of the pMTG and IFG in processing concessive vs causal relations could reflect the cognitive processes deployed to inhibit an implicated causality (e.g., inhibiting an *i lica e* causal relation: *eo le in hina nor all li e osa a a ar lace li e ainan in in er ecause of i s co for a le ea her*; König & Siemund, 2000; Verhagen, 2000).



**Fig. 5.** The estimated DCM parameters of the average model of the winning family (\*\*\*)  $< 0.005$ ; \*\*  $< 0.01$ ; \*  $< 0.05$ ) with either the absence (left panel) or presence (right panel) of experimental modulations.

**Table 5**  
Model parameters estimated based on Model Family 7.

Parameter	Mean $\pm$ SD
Intrinsic connectivity	
IFG MFG	0.40 $\pm$ 0.41***
MFG IFG	0.13 $\pm$ 0.29*
IFG TPJ	0.19 $\pm$ 0.27***
TPJ IFG	0.14 $\pm$ 0.43
MFG TPJ	-0.03 $\pm$ 0.20
TPJ MFG	-0.01 $\pm$ 0.24
IFG pMTG	0.41 $\pm$ 0.51***
pMTG IFG	0.02 $\pm$ 0.15
TPJ pMTG	-0.03 $\pm$ 0.27
pMTG TPJ	-0.12 $\pm$ 0.38
Modulation of <i>ecause</i>	
IFG MFG	0.08 $\pm$ 0.15*
TPJ MFG	0.05 $\pm$ 0.15
pMTG IFG	0.16 $\pm$ 0.42*
pMTG TPJ	0.06 $\pm$ 0.21
Modulation of <i>al hough</i>	
IFG MFG	0.15 $\pm$ 0.28**
TPJ MFG	-0.00 $\pm$ 0.23
pMTG IFG	0.16 $\pm$ 0.50
pMTG TPJ	0.13 $\pm$ 0.22***
Driving input to IFG	
<i>ecause</i>	0.04 $\pm$ 0.04***
<i>al hough</i>	0.06 $\pm$ 0.06***

\*  $< 0.05$ ; \*\*  $< 0.01$ ; \*\*\*  $< 0.005$ .

This is consistent with the recruitment of MTG, alongside IFG, for demanding semantic retrieval (Davey et al., 2015; Noonan et al., 2013; Lambon Ralph et al., 2017). The left IFG, and especially pMTG, has been specifically involved in tasks with demanding semantic control (Davey et al., 2015; Noonan et al., 2003; Whitney, Jefferies, & Kircher, 2010; Whitney et al., 2011), for example, in situations where the non-dominant rather than the dominant meaning of an ambiguous word (e.g., “bank” following the word “river”; Whitney, Jefferies, & Kircher, 2010) has to be retrieved. The involvement of the pMTG in processing concessive relations (vs causal relations) might be yielded by the inhibition of one representation (i.e., an implicated causal association) over the other (i.e., the negation of a causal association). In this regard, the involvement of the pMTG in processing concessive but not causal relations further confirms that concessive relations are different from causal relations in terms of semantic control and pragmatic implication (König & Siemund, 2000; Verhagen, 2000; Xu et al., 2015).

Since the locative pronoun was resolved toward the distant referent

in concessive relations but the close one in causal relations (see also Xu et al., 2015), the difference in referential distance might provide an alternative explanation for the observed activations in the left hemisphere (e.g., the left IFG, MFG/mPFC, pMTG, and TPJ). If this is the case, we should find significant correlations between the activation of these brain regions and the participants’ working memory span. However, we observed none. More importantly, in a previous behavioral study with similar stimuli (Xu et al., 2018), we replaced the critical positive verbs (e.g., *li e*, *refer*) with negative ones (e.g., *isli e*, *ha e*) so that the locative pronouns were coreferential with the closer (second) antecedents in both concessive (*ran a has o e fro ar in o ainan al hough she isli e he e in er here*) and causal relations (*ran a has o e fro ar in o ainan ecause she li e he ar in er here*). We found that it still takes longer to understand concessive relations than to understand causal relations. We therefore believe that the pronounced activations of the left hemisphere cannot be induced simply by the differences in referential resolution.

Nevertheless, we did find one region whose activation significantly correlated with working memory span during the processing of concessive (vs causal) relations, namely the ventromedial prefrontal cortex (e.g., the medial orbital frontal gyrus). This finding is consistent with previous studies showing that the medial orbital frontal gyrus plays an essential role in working memory performance (Lala, Kennerley, & Wallis, 2009; Nissim et al., 2017). This correlation suggests that participants may depend more on this area to maintain more than one mental representation (a causal connection: *no*), and a negative causal connection: *no*) and update the discourse model timely (Johnson-Laird, & Byrne, 2002; Verhagen, 2000).

Finally, the pragmatic incongruence activated several subareas in the right TPJ (including Supramarginal Gyrus and IPL) as well as the right MFG in causal relations, though no significant activations were observed for concessive relations. Given the important role of these areas in inferential processing and metaphor comprehension (Bašnáková et al., 2014; Feng et al., 2017; Mason & Just, 2004; Perfetti & Frishkoff, 2008; Yang et al., 2019), it is possible that the engagement of these brain areas indicates the deployment of a re-interpretation process to rationalize the pragmatic incoherence in causal relations (Xu et al., 2015). In concessive relations, however, because processing the concessive relations was already cognitively demanding, no extra resources were available to deal with such a pragmatic anomaly.

The differential neural substrates for concessive and causal relations are also reflected in the strength of effective functional connectivities between the involved areas in the left hemisphere. While the connection between the pMTG and IFG was involved in processing causal meaning, the connection between the pMTG and TPJ was involved in processing concessive meaning, suggesting that different architectures of the sentence comprehension network are responsible for processing concessive and causal relations. This is in line with the existing findings that pMTG has richer functional and structural connectivities with frontal and temporal areas (Vincent et al., 2008; Turken & Dronkers, 2011). For example, the pMTG is structurally interconnected with Broca's area via the long segment of the arcuate fasciculus and pSTS/TPJ via the short segment of the arcuate fasciculus (Turken & Dronkers, 2011).

The pMTG and TPJ (AG) support different components of semantic cognition, but they can at times function in a cooperative manner (Davey et al., 2016; Dietrich et al., 2019). The functional connectivity between pMTG and TPJ could reflect controlled semantic processing. Different from pMTG which is specifically involved in semantic control, the TPJ (AG) is argued to be a domain-general control area (Jackson, 2021; Noonan et al., 2013). One possible explanation is that the functional coupling between the pMTG and the TPJ (AG) subserves a domain-general control to inhibit an implicit causality (e.g., *eo le referosa in ar laces in in er*) in concessive relations; this connection could be an important part of the multi-demand network (MDN; Duncan, 2010) centered primarily on the more dorsal frontal and parietal cortices (Jackson, 2021). The pMTG is in dynamic communication with other areas in the MDN to process complex event semantics (e.g., *referential a igui*, Davey et al., 2016). Nevertheless, we cannot rule out the possibility that the involvement of the pMTG-TPJ/AG connection in concessive relations may not subservise any kind of control – whether it is domain-general or semantic-specific, but just for processing the implicated meaning – the “hidden causality” (König & Siemund, 2000). Such an interpretation would be in line with the activated left brain areas observed in the whole-brain analysis. Further studies with a dedicated design are therefore needed to distinguish these two interpretations.

The connection between the IFG and the pMTG has been previously interpreted to be associated with the controlled retrieval of lexical meanings (Davey et al., 2016; Mollo et al., 2018; Whitney et al., 2011). The stronger connection for the causal relations in the current study further suggest that this connection might play an important role in integrating concepts into a coherence representation, whether it is at the lexical or discourse-level. Specifically, the recruitment of the IFG-pMTG connection in a causal discourse might reflect the controlled retrieval of lexical/conceptual relations and their integration into a higher-order discourse representation (Feng et al., 2021b).

Despite the distinctive functional connectivities between the pMTG and frontal-parietal networks (i.e., IFG and TPJ) in processing concessive versus causal relations, the functional connectivity from the IFG to MFG was commonly involved in processing concessive and causal relations. This suggests that the neural interaction between IFG and MFG is crucial for establishing a coherent discourse representation (Ferstl & von Cramon, 2001; 2002; Tune et al., 2016), regardless of whether it is an explicit (asserted causality) or an implicit

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