HUMAN BRAIN NETWORKS FOR SEMANTIC ROLES

by

SHULIN ZHANG

(Under the Direction of John Hale)

ABSTRACT

This study explores how human brains react to semantic roles when people are listening to an audiobook story naturally. fMRI (functional magnetic resonance imaging) data were collected while Chinese participants were listening to an audiobook. Semantic roles were obtained from AMR (Abstract Meaning Representation) annotation results of the audiobook's text. Brain activations aroused by two main semantic roles, AGENT and PATIENT, were compared: AGENT's assignment activates left Heschl's area, right STG, right Precuneus; PATIENT's assignment activates broader brain regions compared with AGENT, including left side SFG, Parietal, Angular, MTG, IFG, and right-side Angular and Cerebellum. Brain activation contrast between PATIENT and AGENT showed: while human brain is processing PATIENT roles, higher activation can be found in left Insula, left Precuneus, and right side Angular, MFG, MTG, Insula, SFG, Cingulate, Precuneus.

INDEX WORDS: Semantic Roles, Agent, Patient, fMRI, Brain networks, GLM

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Chapter 1

Introduction

1.1 Problem Definition

Language comprehension ability has always been a unique strength of human intelligence. As a sub-field of linguistics, semantic representation, provides abstract meaning information, including semantic roles, for constituents in sentences. Semantic representation can be accomplished by automatic labeling systems or hand-annotation. For human, semantic roles help keep track of characters and describe who-did-what-to-whom. For technology, semantic roles can assist syntactical parsing in information extraction, question answering and machine translation (Palmer, Gildea, and Kingsbury 2005b; Gildea and Jurafsky 2002). How semantic roles are encoded in the human brain? What brain regions are involved in their processing? These will be explored in this study.

To delve into semantic roles' processing in the human brain, the following questions need to be clarified: 1. What technique should be used to collect brain activation data? 2. How can we provide a natural language comprehension task while collecting these data? 3. Which method can be used to annotate semantic roles? 4. After aligning semantic roles and brain activation signal in the time domain, what model/algorithm can be used to measure their synchronism? These questions will be answered in Section 3.2 and 3.3, and we can see the synchronism between semantic role stimulus and brain activation, and get clues for what brain regions are involved for semantic role processing.

1.2 Contributions

This interdisciplinary study takes perspectives from both cognitive science and linguistics, and explores what brain regions are responsible for semantic role processing using fMRI data analysis, and why brain networks are different between AGENT and PATIENT.

In this study, the processing of AGENT stimuli is found as demanding more processing efforts than PATIENT stimuli: AGENT stimuli has been found activating left Heschl's, right STG and Precuneus in the brain. PATIENT stimuli, however, provoked more extensive responses in regions including: left Insula, left Precuneus, and right AG, MFG, MTG, Insula, SFG, Cingulate, Precuneus. All these results had eliminated effects of words' phonetics features (sound pressure), words' relative position to their main verbs, and words' syntactical deepness (see Section 3.3.2 for details). These findings are consistent with previous theoretical studies about the asymmetry between the processing of AGENT and PATIENT, and this will be discussed in Section 2.3.

1.3 Structure of the thesis

In this thesis, chapter 2 presents the background of this study, and reviews previous semantic role assignment studies in theoretical linguistics and psycholinguistics. Chapter 3 describes the process of data collection and analysis method. Chapter 4 includes the main results, and shows brain networks related with AGENT and PATIENT processing. Chapter 5 states the conclusion and talks about possible future work directions.

Chapter 2

Background and Related Work

2.1 What is Semantic Role?

To represent the meaning of a sentence, either for a man or a machine, it is necessary to tag what entities are involved. In linguistics, a semantic role is defined as the underlying relationship that the participant has with the main verb in a clause (Payne 1997). It should be clarified that semantic roles are different from grammatical relations, and semantic roles are conceptual notions. For semantic role assignment in practice, a subject or an object can be assigned as various semantic roles based on its context. A subject can be 'AGENT' (such as active case sentences), and it can also be 'PATIENT' for some other circumstances (such as passive case sentences). There are many ways to get the semantic roles assigned. For example, with theta theory, if a transitive verb is acting as the main active verb of a sentence, the determiner phrase acting as the direct object in the deep structure will be assigned as a *theme* role , and the subject will be assigned as an *agent* role.

In this study, we will focus on two main semantic roles: AGENT and PATIENT. AGENT refers to the entity that gives actions (i.e. 'doer' or 'experiencer' of an event). PATIENT, on the other hand, is the entity undergoing an event or process (i.e. 'undergoer' or 'theme' of an action). Therefore, by looking at AGENT and PATIENT in a sentence, one can perceive 'doer' and 'undergoer' from the sentence structure. For example, in the sentence "A cat eats a fish", 'cat' should be labeled as AGENT of the action 'eat', and 'fish' should be labeled as PATIENT of the action 'eat'. It is not hard to imagine that when a long story involves more entities, it is crucial to keep track of semantic role information, especially when the same topic can be expressed in various surface structures.

2.2 Semantic Role Assignment Methods

In this study, we used *The Little Prince Corpus* with annotated semantic roles for Chinese version *The Little Prince* (Saint-Exupéry 1943). This corpus used AMR (Abstract Meaning Representation) as its annotation standard, which will be introduced in the following section.

To gain semantic role labels, a straight forward way is to label manually, and the AMR Bank corpus used in this study was manually constructed by human annotators in Brandeis University. While labeling by hand can be labor intensive, there are automatic semantic roles labeling methods realized by algorithms (Palmer, Gildea, and Kingsbury 2005b, Gildea and Jurafsky 2002). For example, an automatic semantic role labeling system developed from 50,000 manually annotated sentences and various lexical clustering algorithms was able to obtain 82 percent of accuracy for detecting semantic roles (Gildea and Jurafsky 2002).

2.2.1 Abstract Meaning Representation: The Labeling Standard

AMR is an abstract way to represent the meanings of natural language. AMR takes all the words into account and provides a single traversable structure. For example, as shown in Figure 2.1, it is an AMR representation result for a sentence in *The Little Prince Corpus*. Key words related to meaning are pulled out to form a hierarchical annotation structure, and labeled with semantic roles. With the hierarchical labeling result, for a given verb, we can tell which words are serving as its AGENT(marked as 'ARG0') and PATIENT(marked as 'ARG1').

Annotation label names used in AMR are inherited from PropBank, which is an annotation

```
# ::id lpp_1943.3 ::date 2012-06-07T17:06:23 ::annotator ISI-AMR-05 ::preferred
# ::snt It was a picture of a boa constrictor in the act of swallowing an animal .
# ::zh 画的是一条蟒蛇正在吞食一只大野兽。
# ::save-date Mon Apr 15, 2013 ::file lpp_1943_3.txt
(p / picture
  :domain (i / it)
  :topic (b2 / boa
          :mod (c2 / constrictor)
          :ARG0-of (s / swallow-01
                    :ARG1 (a / animal))))
```

Figure 2.1: An AMR representation example from the *The Little Prince Corpus*. This example shows the original sentence in English (the second line) and Chinese (the third line), and the AMR annotation for the sentence. As shown in the nested parenthesis AMR structure, each line has the form of ": semantic role (word label/original word)".

of syntactically parsed structures with 'predicate-argument'. In PropBank Annotation Guidelines (Babko-Malaya 2005), the annotation goal is to label verb arguments with numbers, so that we have labels like 'ARG0' and 'ARG1'. The annotation also includes functional tags to all modifiers and all empty arguments of the verb. With AMR labeling, a 'predicate-argument' network can provide abstract meaning information for further analysis. In this study, 'ARG0' and 'ARG1' label words are used to explore their corresponding brain activation, and other semantic roles might be explored in future studies.

2.3 Semantic Role Processing: Theoretical Models

There have been studies exploring how semantic roles and structures affect language comprehension. In this section, we will review some of these models and their related studies.

2.3.1 Grammar Internal Principles

Grammar internal principles refer to the "built-in" mechanism in our brain for sentence processing, and some theories have been proposed to support the existence of the internal principles and describe the mechanism features. In Crocker's study (1992), it is mentioned that there is a human sentence processor aiming at realizing maximal incremental comprehension as each word in a sentence is encountered. In this processor, thematic structures are one of the modules that works together with others to achieve the comprehension goal. With examples of "garden path sentences", Pritchett (Pritchett 1992) brought up the idea that human has consistent preferences for sentence parsing. The number of semantic roles and their configurational positions, rather than the semantic content, play an essential role in the processor.

2.3.2 Grammar External Reference

Aside from the integral processing algorithm that optimizes the comprehension process in the brain, there are also linguistic models arguing that semantic roles are processed based on syntactic clues.

Steedman brought up the concept *information structure* to refer to a unification between the separate notions of surface structure and intonation structure (Steedman 2000): the semantic type of an interpretation can be decided by its syntactic type, so that the processing of semantic roles is supported by the whole grammar structure and context.

Closely related with semantic roles' recognition, there are representative theories that describe the agent/theme processing mechanism, including TDH (Trace-deletion Hypothesis) (Grodzinsky 1995) and DDH (Double Dependency Hypothesis) (Mauner, Fromkin, and Cornell 1993). TDH of agrammatic aphasia suggests that there should be a default strategy for semantic role assignment, and patients' performance for passive sentence comprehension were assumed to be worse than that of active reversible sentences, because the aphasia patients might fail on processing the external traces which indicates the semantic roles. To explore this TDH assumption, sentence-picture matching tasks have been used on agrammatic aphasia patients. It turned out that patients with agrammatic symptoms have problems processing the linear order of NPs(noun phrases) mismatching semantic prominence (such as passive sentences). This results showed that aphasia patients' capability of categorizing distinct semantic roles might be malfunctioning (A. M. Meyer, Mack, and Thompson 2012).

In summary, grammar internal and external processing mechanisms suggests the importance of semantic role processing in language comprehension. In the following section, how semantic roles are processed in the brain will be reviewed.

2.4 Semantic Role Processing in the Brain

First of all, we should consider, what brain regions are responsible for semantic role processing with all categories taken into consideration? One of the hints is that semantic roles are perceived in verb arguments or dependencies, and previous studies revealed that Wernicke's area (left STG) is involved in verbal complements processing (Shetreet et al. 2006). Wu's study (Wu, Waller, and Chatterjee 2007) found that semantic role knowledge deficits are correlated with lesions in middle and anterior STG, and white matter undercutting STG and supramarginal gyrus. An ERP study found that P300 is related to the increasing numbers of thematic options(Shetreet et al. 2006). The N400 EEG component has been found related to meaning representation in event-related brain potential experimentation (Rabovsky, Hansen, and McClelland 2018; Kutas and Federmeier 2011; Lau, Phillips, and Poeppel 2008). The P600 EEG component has also been found when semantic violation of sentences in Chinese was presented (WANG, LI, and CHEN 2010).

Secondly, how can we breakdown verbal complements' processing? In addition to semantic roles, syntactic properties are also acting as mental-lexicon processing entries(L. Meyer 2013). The neuroanotomical dissociability of processing syntactic and semantic properties is described Meyer's study in which complexity of these properties were manipulated, so that activated brain regions are responsible as workload becoming higher. In Meyer's study, left Precuneus was found related with syntactic properties' processing, whereas left STG and left IFG were found activated for semantic properties processing (L. Meyer 2013).

Studies mentioned above had not looked into what brain regions are required by different semantic roles' processing, which means semantic roles were studied as a whole group. This study will take this aspect to explore how different semantic roles, especially AGENT and PATIENT, are processed in human brain.

Chapter 3

Data Collection and Analysis

3.1 Stimulus Text and Annotations

In PropBank (Palmer, Gildea, and Kingsbury 2005a), '`ARG0`' identifies verbal arguments that exhibit features of a Prototypical AGENTs, and '`ARG1`' labels Prototypical PATIENTs (Dowty 1991). The PropBank notation was adopted in the AMR(Abstract Meaning Representation) annotation convention (Banarescu et al. 2013). Relevantly for this project, there are AMR annotations for *The Little Prince* (Saint-Exupéry 1943) in both English and Chinese (B. Li et al. 2016). Figure 3.1 shows an example from the AMR-annotated English translation.

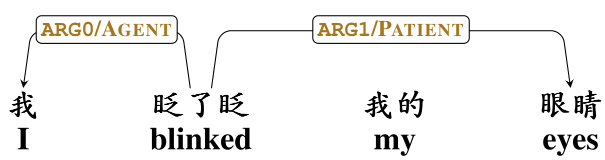

Figure 3.1: Semantic roles in the CAMR - annotated Chinese translation of *The Little Prince* (Saint-Exupéry 1943). In this example, 'I' is annotated as an AGENT word, and 'eyes' is annotated as a PATIENT word.

To explore human brain networks for semantic roles, we examined brain activation patterns while

[0]CAMR: `http://www.cs.brandeis.edu/~clp/camr/camr.html`

Chinese participants listened to a Chinese translation[1] of Saint-Exupéry's *The Little Prince* (1943) in the fMRI scanner. Words of this text were aligned with their pronunciation in the audio signal, and aligned with semantic role information from the Chinese AMR (B. Li et al. 2016).

The Chinese AMR annotation derives two regressors: the AGENT regressor assigns '1' to words that are annotated as AGENT role, and assigns '0' to all other words; the PATIENT regressor marks '1' for the PATIENT words and '0' for other words. These regressors facilitate a comparison, via regression against the fMRI BOLD signal (Penny et al. 2011). Figure 3.2 shows how AGENT and PATIENT words' BOLD signal is obtained by combining words' time information and the semantic role annotations to yield an expected BOLD signal. Detailed data collection and analyzing procedures is covered in the section 3.2 and 3.3.

Using syntactic analyses from ZPar (Zhang and Clark 2011), we restricted consideration to just noun-like arguments, i.e. those that receive a nominal part-of-speech tag.

The tokenization was aligned across the AMR and ZPar, and words with different segmentation in ZPar were also manually checked (For example, "Little Prince" was treated as a single entity in our AMR analysis, and the output of ZPar divided it into "Little" and "Prince", so that both words would be checked whether they should be included in our analysis). After the previous steps, the total number of words analyzed as AGENT was 1876, and PATIENT was 1401.

These same ZPar outputs also derive a nuisance regressor that models *syntactic* processing difficulty. Following "Syntactic structure building in the anterior temporal lobe during natural story listening" this value sums up the number of steps than an incremental bottom-up parser would take after each word. This co-regressor is used to eliminate syntactic interpretation effects from semantic roles' responses.

[1] `http://www.xiaowangzi.org/`

3.2 Neuroimaging Methods

3.2.1 fMRI Working Principle

Magnetic Resonance Imaging(MRI) uses strong magnetic fields to create images of biological tissue. The MRI scanner applies sequences of various magnetic gradients and oscillating electromagnetic fields. In these fields, atomic nuclei of atoms in the tissue absorbs energy and shows alignment, so that a well-tuned magnetic field can detect the alignment of atomic nuclei while they absorb and emit the energy. With appropriate magnetic field settings, the MRI scanner is able to detect different tissue properties and types. (Huettel, Song, McCarthy, et al. 2004)

Functional Magnetic Resonance Imaging(fMRI) uses MRI scanner to record the brain activation. With fMRI, the magnetic signal from hydrogen nuclei in water molecules is detected over time. In human brain, oxygen is essential to neuron activation and is delivered to neurons by haemoglobin in capillary red blood cells. Haemoglobin changes orientation when oxygenated. Therefore, fMRI is also known as Blood Oxygen Level Dependent(BOLD) imaging. As neural activation is getting stronger, the detected energy emission is stronger as well. (Logothetis 2008)

In this study, while participants are lying down in the MRI scanner and listening to the audiobook, their brains process the information and the BOLD signal is recorded on a second-by-second basis to reflect the neural activation. As a participant's brain region has greater activation, a stronger BOLD signal is recorded with larger value in a voxel in our results. When a brain region's activation goes up and down, the corresponding voxel records higher and lower values.

In this study, we want to look for brain regions that are responsible for processing AGENT and PATIENT words. The brain areas processing AGENT or PATIENT stimulus should be correlated with the presenting of AGENT or PATIENT stimulus, which means they go up and down simultaneously. In this study, the activation maps (Section 4.1.1, 4.1.2) presents the voxel which has BOLD signal highly correlated with each condition.

3.2.2 Participants

Chinese participants were 35 healthy, right-handed, young adults (15 female, mean age=19.3, range = 18-25). They self-identified as native Chinese speakers, and had no history of psychiatric, neurological or other medical illness that could compromise cognitive functions. All participants were paid for, and gave written informed consent prior to participation, in accordance with the guidelines of the Ethics Committee at Jiangsu Normal University.

3.2.3 Procedure

After giving their informed consent, participants were familiarized with the MRI facility and assumed a supine position on the scanner. The presentation script was written in PsychoPy (Peirce 2007). Auditory stimuli were delivered through MRI-safe, high-fidelity headphones (Ear Bud Headset, Resonance Technology, Inc, California, USA) inside the head coil. The headphones were secured against the plastic frame of the coil using foam blocks. An experimenter increased the sound volume stepwise until the participants could hear clearly.

The Chinese audiobook lasted for about 99 minutes, and was divided into nine sections, each lasted for about ten minutes. Participants listened passively to the nine sections and completed four quiz questions after each section (36 questions in total). These questions were used to confirm their comprehension and were viewed by the participants via a mirror attached to the head coil and they answered through a button box. The entire session lasted for around 2.5 hours.

3.2.4 MRI Data Collection and Preprocessing

The brain imaging data were acquired with a 3T MRI GE Discovery MR750 scanner with a 32-channel head coil. Anatomical scans were acquired using a T1-weighted volumetric Magnetization Prepared RApid Gradient-Echo (MP-RAGE) pulse sequence. Blood-oxygen-level-dependent (BOLD) functional scans were acquired using a multi-echo planar imaging (ME-EPI) sequence with online reconstruction (TR=2000 ms; TE's=12.8, 27.5, 43 ms; FA=77°; matrix size=72 x 72; FOV=240.0 mm x 240.0 mm; 2 x image acceleration; 33 axial slices, voxel size=3.75 x 3.75 x 3.8 mm). Cushions and clamps were used to minimize head movement during scanning. All fMRI data were preprocessed using AFNI version 16 (Cox 1996). The first 4 volumes in each run were excluded from analyses to allow for T1-equilibration effects. Multi-echo independent components analysis (ME-ICA) (Kundu et al. 2012) were used to denoise data for motion, physiology and scanner artifacts. Images were then spatially normalized to the standard space of the Montreal Neurological Institute (MNI) atlas, yielding a volumetric time series resampled at 2 mm cubic voxels.

3.3 Statistical Analysis

A whole brain analysis was carried out with two stages: first level analysis based on individual participants and group level analysis among all the subjects. Both stages employ the General Linear Model, and were carried out with SPM12 (Penny et al. 2011). The predictors were convolved using SPM's canonical HRF (hemodynamic response function).

3.3.1 GLM Method in fMRI

GLM (General Linear Model) is a widely used technique for analyzing task-based fMRI experiments. A linear model is an equation or a set of equations that models data and corresponds geometrically to straight lines, planes, hyperplanes. The equation satisfies the properties of additivity and scaling. The mathematical representation of a linear model can be simple linear regression, multiple linear regression, one-way ANOVA, or repeated measure ANOVA and so on. For a task-based fMRI experiment, subjects' brain activation is measured while they are doing tasks. The task in this study is listening to a story, which can be considered as a sequence of words. To explore what brain regions/voxels' activation is most likely correlated with the stimulus(words), we need to consider whether a voxel's signal has the same pattern as the stimulus's in the time domain (i.e. whether they have high synchronism in the time domain). Therefore, it is the time to get linear model involved to test whether a voxel and a stimulus have the same pattern, or saying, highly correlated. As shown in Figure 3.3, a voxel's signal in one subject's brain is represented on the left side of the equation. In this study, a subject's brain activation in a certain voxel or brain region is affected by the audio stimulus. The main idea of this study is to find brain regions that has activation pattern highly correlated with showing up of AGENT or PATIENT stimulus. Supposing the green block represents a AGENT word, and the red block is a PATIENT word, GLM algorithm is used to decompose the original brain activation signal to linear combination of brain's haemodynamic response to AGENT and PATIENT. At the right side of the equation, β_1 and β_2 refer to the parameters estimated with GLM computation. If a brain region with more than 50 voxels had been found constantly responsive to AGENT or PATIENT stimulus after single-subject and group analysis, we will say that this brain region is closely related with processing this semantic role.

3.3.2 Step One: First Level Analysis

The first-level analysis uses several different per-word regressors to model fMRI time courses from participants who listened *The Little Prince* audiobook. As detailed in Table 3.2, several different features are included for each word as regressors in a GLM analysis (Poldrack, Mumford, and Nichols 2011). The correlation coefficient heat map matrix is shown in 4.7, referred to simply as the 'correlation matrix' below.

As mentioned in the previous section, to explore the brain region related with processing AGENT or PATIENT signals, it seems quite straightforward to binary code AGENT and PATIENT as two regressors. However, AGENT words show up more often before its main verb, whereas PATIENT words are more often later than its main verb (see Table3.1). To elimi-

[1] `https://www.brainvoyager.com/bvqx/doc/UsersGuide/StatisticalAnalysis/TheGeneralLinearModel.html`, Figure 3.3

Table 3.1: This table shows the numbers of AGENT and PATIENT words that show up before or after their main verbs.

Semantic Role	Before Its Main Verb	After Its Main Verb
AGENT	1585	291
PATIENT	408	993

nate the bias caught by position, AGENT and PATIENT regressors are orthogonalized based on `Pre-verb` regressor to reduce collinearity between them (Mumford, Poline, and Poldrack 2015), and the orthogonalization result is the residual value of the two regressors, i.e. the residual ϵ of: $agent = \beta * pre\text{-}verb + \epsilon$. As shown in Table3.2, regressor $AGENT \perp Pre{-}verb$ will catch brain activation responsible for processing AGENT words, without being affected by AGENT's 'Pre-verb' tendency. Similarly, regressor $PATIENT \perp Pre{-}verb$ will catch brain regions processing PATIENT words that not resulted by 'Post-verb' tendency.

In Section 4.1.3 and 4.2, unlike bare regressors (such as '`RMS`') and orthogonalized regressors, contrast PATIENT-AGENT is obtained from subtraction between brain activation of $AGENT \perp Pre{-}verb$ and $PATIENT \perp Pre{-}verb$ using the first level analysis result.

3.3.3 Step Two: Group Level Analysis

In the group level analysis, each contrast was analyzed separately across all participants. An 8 mm FWHM Gaussian smoothing kernel was applied on the contrast images from the first-level analysis to counteract inter-subject anatomical variation (Poldrack, Mumford, and Nichols 2011). All the group-level results reported in the next section underwent FWE(Family-wise Error Rate) voxel correction for multiple comparisons which resulted in T-scores > 5.20. Family-wise Error Rate, which is also named as alpha inflation or cumulative Type I error, is used to control Type I error when carrying out a series of tests. The formula to estimate FWE is: $FWE \leqslant (1 - \alpha_{IT})^c$, with α_{IT} refers to alpha level for an individual test, and *c* refers to number of comparisons. In this

Table 3.2: GLM Regressors

Regressor (name in correlation matrix)	**Motivation**
`RMS` (*'rms'*)	This regressor is used to determine the "average" sound pressure of a length of speech signal, and used as a regressor to rule out brain's reaction towards sound intensity.
`Pre-verb`	This regressor marks each word's position compared with its main verb: if the word comes before the main verb, it is categorized as 1 for this feature, otherwise as 0.
`Word frequency` (*'frequency'*)	This regressor is the log frequency of each word in *The Little Prince* based on Google Books
$AGENT \perp Pre{-}verb$ (*'agent'*)	This regressor is calculated with two steps: 1. Code whether a word is marked as AGENT in the Abstract Meaning Representation markup; 2. Orthogonalization is applied on AGENT based on 'Pre-verb' (code whether a word shows up earlier than the its main verb).
$PATIENT \perp Pre{-}verb$ (*'patient'*)	Similar to the *'agent'*, this regressor marks the PATIENT words, and is also orthogonalized based on 'Pre-verb' regressor.
`Bottom Up Parsing Syntactic Complexity` (*'BU'*)	This regressor is added to exclude syntactic effects. It is based on phrase structure trees returned by ZPar

study, we set the FWE with a boundary of FWE $p < 0.05$.

This group level analysis provides brain activation for words in the AGENT and PATIENT role. A distributional analysis of the stimulus text itself (Figures 4.4 & 4.5) identified the most frequently-occurring word, which is the first person pronoun 'I/me'. Both of these English words correspond to the same Chinese morpheme 'wǒ'("我"). As discussed below in section 4.1.4 this motivates an additional, more targeted analysis at the group level.

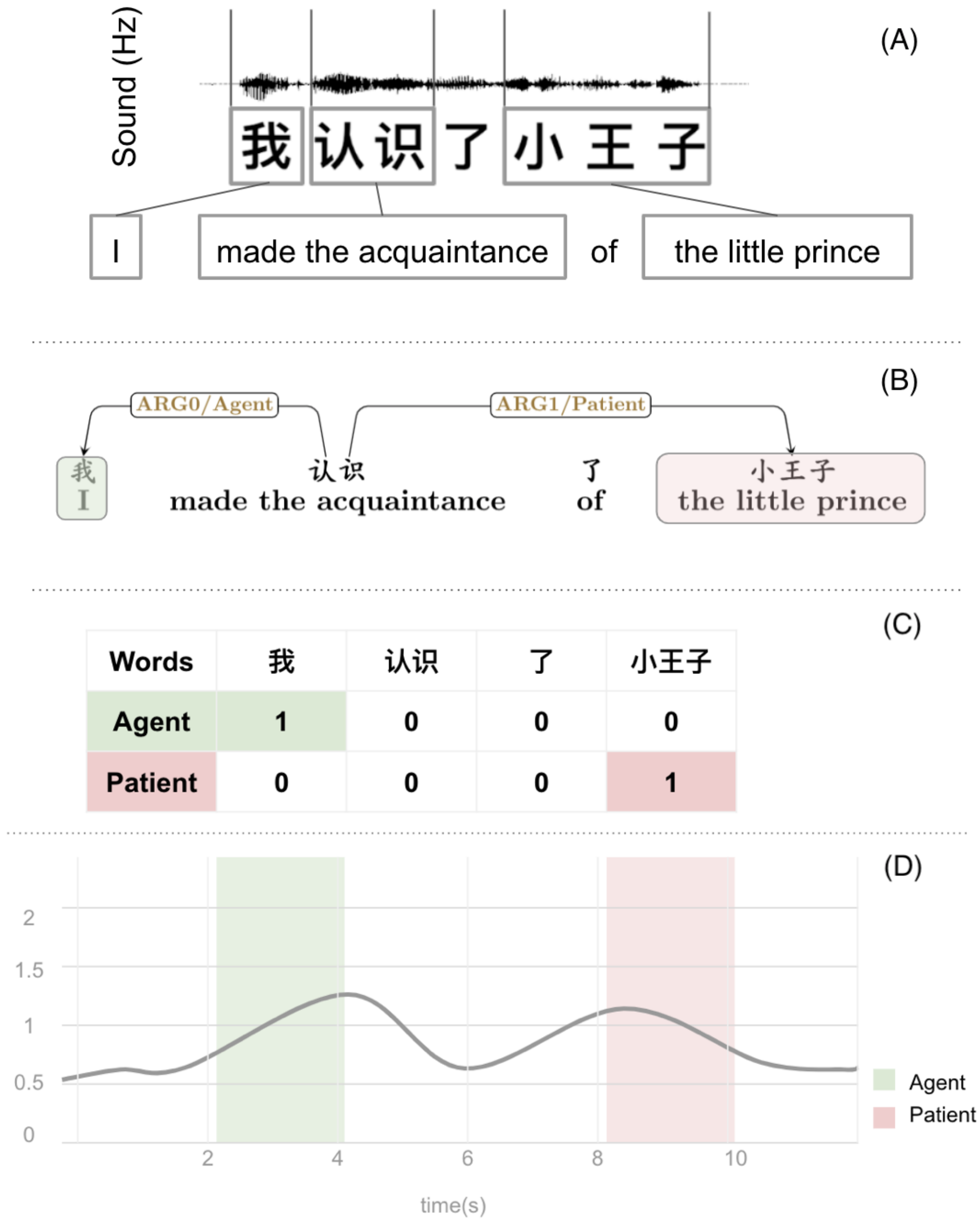

Figure 3.2: Deriving the expected BOLD signal from PropBank style semantic role annotations. Panel (A) shows the relationship between the audio signal in time and the sequences of Chinese characters that qualify as entities in the AMR annotation. The following English sentence shows the corresponding translation. Panel (B) is the AMR annotation of this sentence, and entities annotated as AGENT and PATIENT were extracted. Panel (C) depicts the 0/1 coding process for AGENT and PATIENT. Panel (D) expected BOLD signal using the canonical Hemodynamic Response Function from SPM12. Based on these steps, the brain activation of AGENT and PATIENT can be compared.

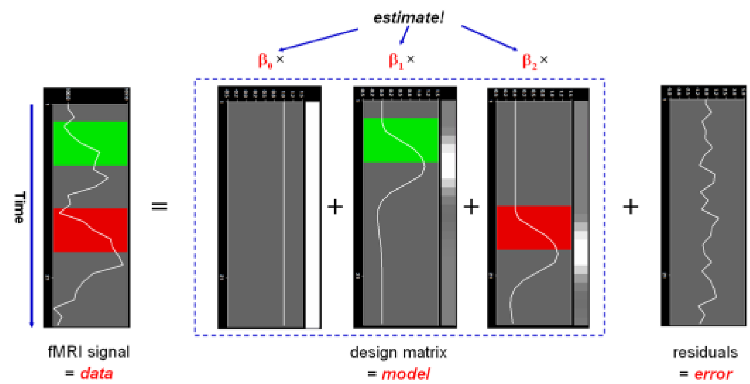

Figure 3.3: Single voxel fMRI signal being regressed by multiple regressors: The original fMRI signal of a single voxel is represented on the left side of the equation, which goes through a linear regression model with multiple regressors. On the right side of the equation, all regressors in the design matrix are included (represented as $\beta_0, \beta_1, \beta_2$). The regression results for each regressor are used to calculate the statistical distribution map when all voxels are included.

Chapter 4

Results

4.1 Main Results

4.1.1 Results for AGENT Words

AGENT words give rise to 3 clusters of activation, as shown in Figure 4.1, Table 4.1: right STG (Superior Temporal Gyrus), left Heschl's Gyrus, right Precuneus.

4.1.2 Results for PATIENT Words

PATIENT words give rise to 9 clusters of activation, as shown in Figure 4.2, Table 4.2. Left side activation has been found in SFG, ITG/MTG, IFG, Cerebellum, AG. Right side activation has been found in Cerebellum, AG, IFG.

4.1.3 Contrast Results: PATIENT - AGENT

The subtraction (PATIENT − AGENT) shows brain regions that work harder when processing words in the PATIENT semantic role. This contrast yields 11 clusters of activation, as shown in Figure 4.3. There is bilateral activation in Precuneus, Insula, and right hemisphere activation in Cingulate

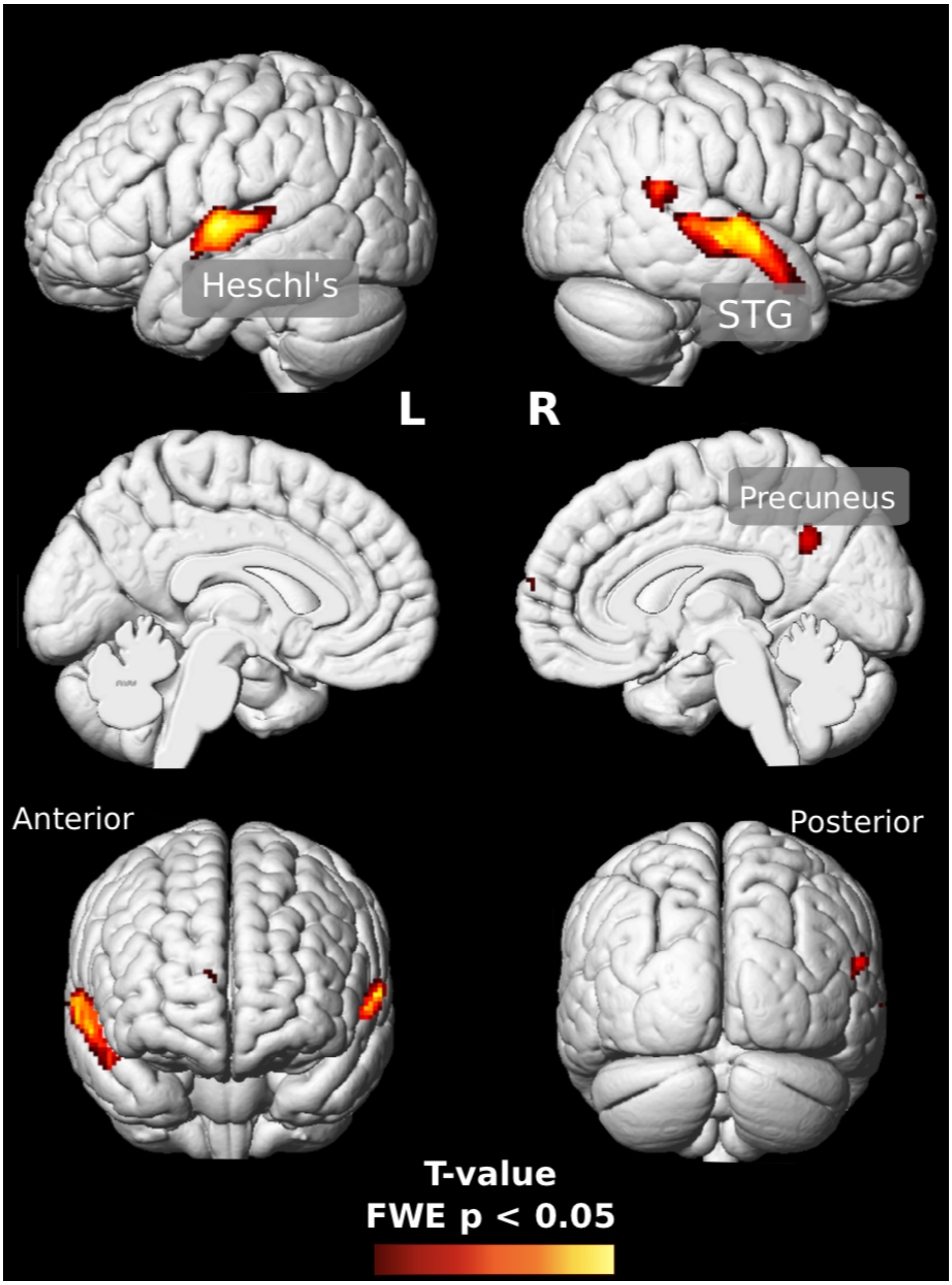

Figure 4.1: AGENT significant clusters (voxel > 50, FWE $p < 0.05$) projected on the whole brain

Table 4.1: Significant clusters for AGENT, after FWE voxel correction for multiple comparisons with $p < 0.05$ and cluster-extent threshold ($k > 50$). Peak activation is given in MNI Coordinates, and brain region labels come from the Harvard-Oxford Cortical Structure Atlas and MNI Structural Atlas.

		MNI Coordinates				
Regions for bottom-up parser action count	**Cluster size (in voxels)**	*x*	*y*	*z*	*p-value* (corrected)	*T-score* (peak level)
R Superior Temporal Gyrus (anterior division)	1862	62	-4	-4	0.000	8.70
L Heschl's Gyrus	1154	-52	-10	6	0.000	8.21
R Precuneus	91	8	-56	34	0.004	6.24

Table 4.2: Significant clusters for PATIENT, after FWE voxel correction for multiple comparisons with $p < 0.05$ and cluster-extent threshold ($k > 50$). Peak activation is given in MNI Coordinates, and brain region labels come from the Harvard-Oxford Cortical Structure Atlas and MNI structural Atlas.

		MNI Coordinates				
Regions for bottom-up parser action count	**Cluster size (in voxels)**	*x*	*y*	*z*	*p-value* (corrected)	*T-score* (peak level)
L Superior Frontal Gyrus	1201	-18	16	54	0.000	7.93
L Inferior/Middle Temporal Gyrus	955	-52	-54	-12	0.000	7.51
L Frontal Pole, Inferior Frontal Gyrus	600	-40	38	8	0.001	6.90
R Cerebellum	72	10	-76	-22	0.003	6.35
L Lateral Occipital	160	-30	-68	50	0.005	6.13
L Parietal/Angular Gyrus	243	-52	-48	48	0.005	6.10
R Parietal/Angular Gyrus	66	60	-42	20	0.008	5.92
R Cerebellum	72	30	-70	-32	0.010	5.84
R Frontal Pole, Inferior Frontal Gyrus	52	52	34	-2	0.010	5.83

Gyrus, Angular Gyrus (AG), MFG (Medial Frontal Gyrus), SFG (Superior Frontal Gyrus), MTG (Middle Temporal Gyrus). Table 4.3 reports detailed statistics.

4.1.4 Distributional Analysis of Stimulus Text

As shown below, due to nature of natural text material used in this study, AGENT words and PATIENT words have different distribution features.

AGENTs are very often first-person pronouns (26%; see Figure 4.4) in this book. It is possible that the more constricted brain network of AGENT is caught by this high percentage of first person pronouns, as suggested by Croft's 2002 Referentiality Scale. Indeed, experimental studies in neurolinguistics have supported this particular asymmetry (Bornkessel-Schlesewsky, Schlesewsky,

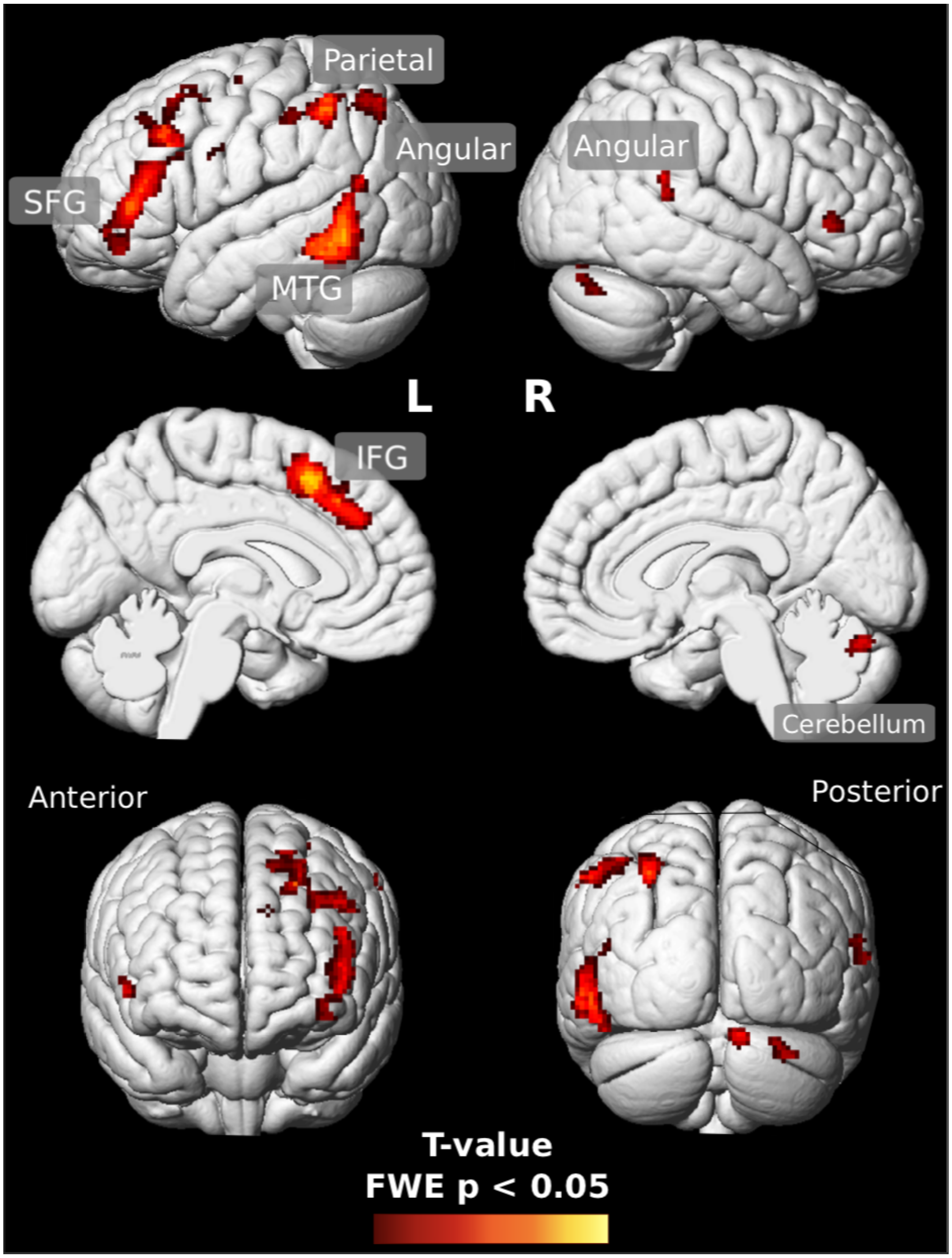

Figure 4.2: PATIENT significant clusters (voxel > 50, FWE $p < 0.05$) projected on the whole brain

and Cramon 2009). Therefore, it is necessary to take a further step and look at how the brain reacts to only first-person pronoun AGENT and PATIENT words. Here we use Chinese first-person

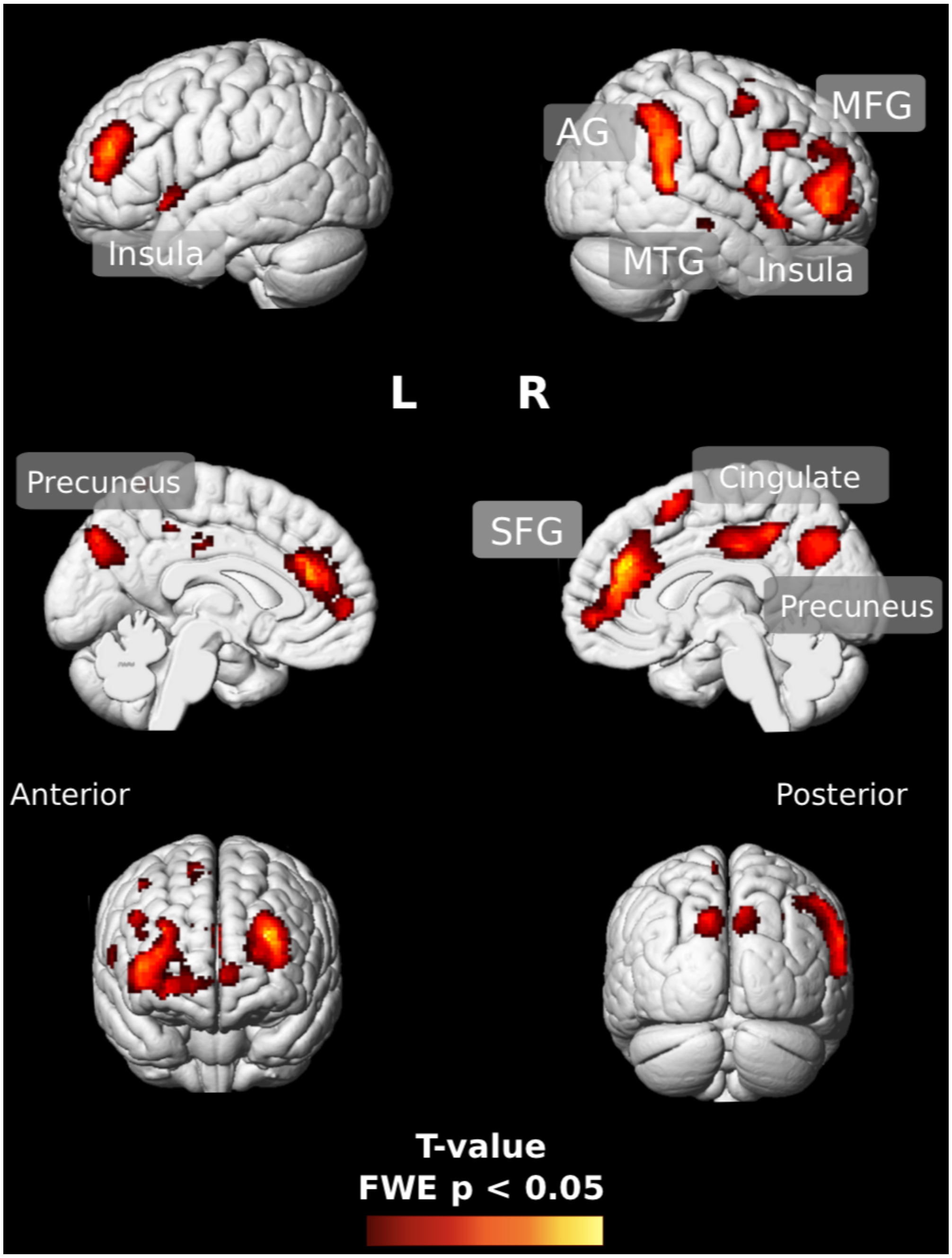

Figure 4.3: PATIENT−AGENT significant clusters (voxel $>$ 50, FWE p $<$ 0.05) projected on the whole brain

Table 4.3: Significant clusters for PATIENT−AGENT, after FWE voxel correction for multiple comparisons with $p < 0.05$ and cluster-extent threshold ($k > 50$). Peak activation is given in MNI Coordinates, and brain region labels come from the Harvard-Oxford Cortical Structure Atlas and MNI Structural Atlas.

		MNI Coordinates				
Regions for bottom-up parser action count	**Cluster size (in voxels)**	*x*	*y*	*z*	*p-value* (corrected)	*T-score* (peak level)
R Cingulate Gyrus (anterior division)	4626	6	40	16	0.000	12.24
R Angular Gyrus	1696	60	-42	14	0.000	10.70
R Superior Frontal Gyrus	268	12	10	60	0.000	9.63
R Cingulate Gyrus (posterior division)	653	8	-22	34	0.000	8.94
R Precuneus Cortex	643	12	-70	36	0.000	8.75
R Insula Cortex	804	34	18	-14	0.000	8.39
L Precuneus Cortex	352	-12	-78	38	0.000	8.21
R Middle Temporal Gyrus (posterior division)	74	48	-20	-12	0.000	7.88
L Insula Cortex	312	-34	16	-10	0.000	7.83
R Middle Frontal Gyrus	135	40	4	54	0.000	7.32
R Middle Frontal Gyrus	184	42	18	32	0.001	6.70

Table 4.4: This table shows the numbers and percentages of Unstressed Personal Pronouns in AGENT and PATIENT words.

Semantic Role	Total Analyzed Words	Number of Unstressed Personal Pronouns	Percentage
AGENT	1876	301	16.04%
PATIENT	1401	76	5.42%

pronoun ‘wǒ’ for this analysis.

4.2 Additional Results with First Person Pronoun Only

Here the same morpheme ‘wǒ’ is compared across two different semantic roles. The First Level design matrix was re-made, which gave first person pronouns a binary coding for `AGENT` and `PATIENT` roles, analogous to panel (C) of Figure 3.2. In this additional analysis, `Agent` and `Patient` regressors were not orthogonalized by Pre-verb condition, i.e. they are coded in binary from the AMR annotation.

The resulting contrast reveals 8 clusters of activation: bilateral Cingulate Gyrus, left Cerebellum, right Superior Frontal Gyrus (SFG), left frontal pole, left Insula Cortex, right Angular Gyrus

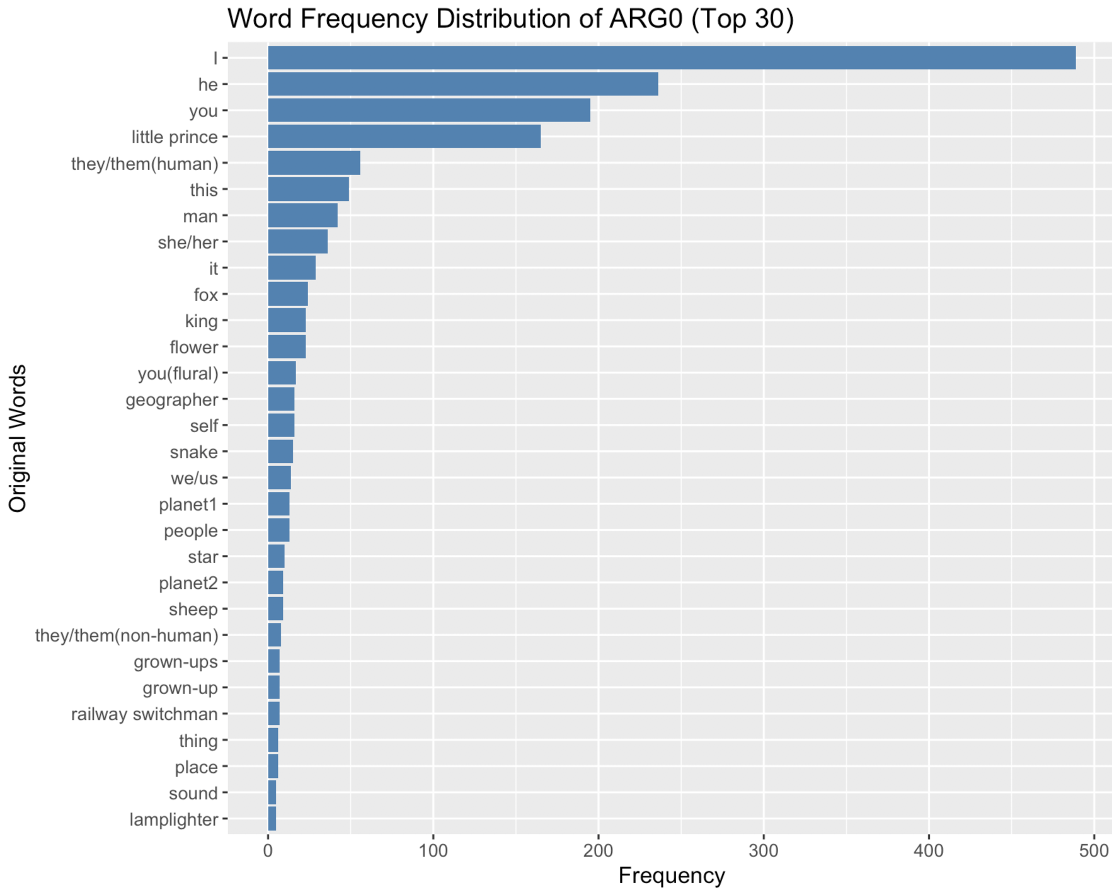

Figure 4.4: Top 30 AGENT words from *The Little Prince* translated from the Chinese text used in this analysis.

(AG) and left Precuneus (see Figure 4.6 and Table 4.5)

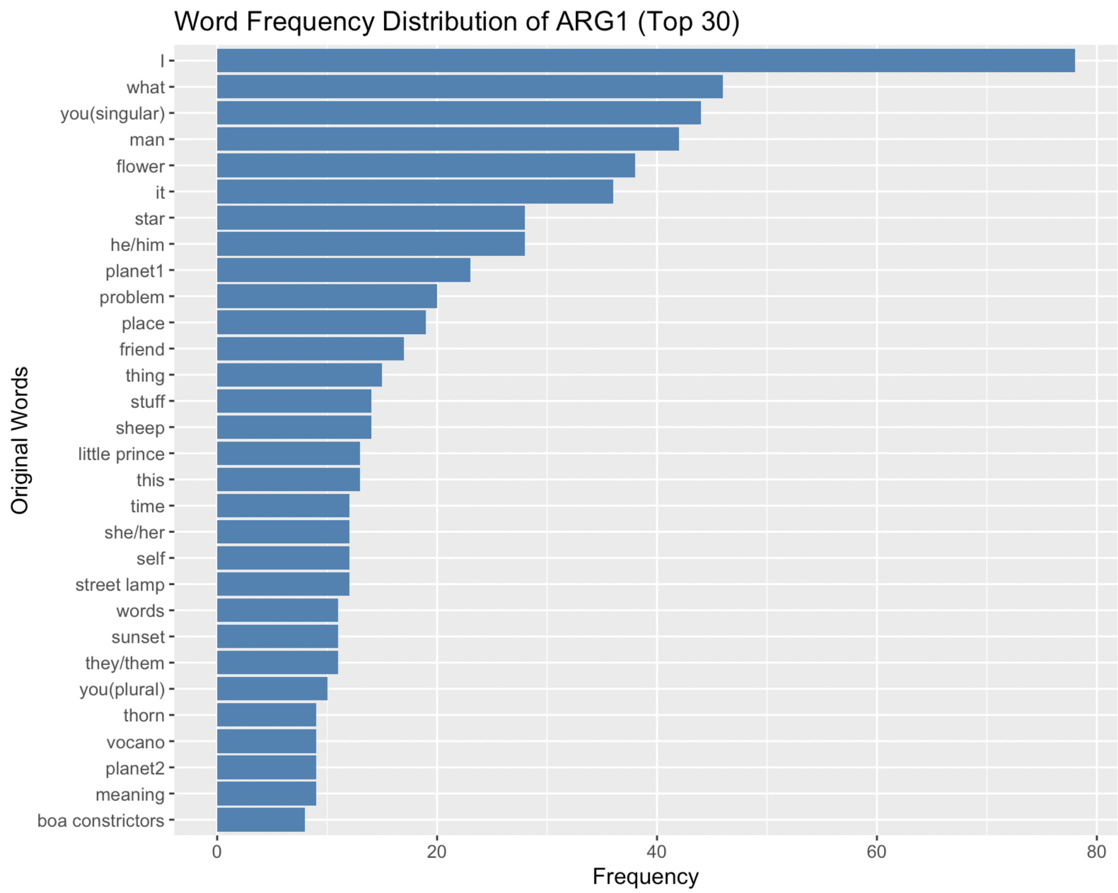

Figure 4.5: Top 30 PATIENT words from *The Little Prince* translated from the Chinese text used in this analysis.

Table 4.5: Significant clusters for PATIENT−AGENT for only 'I/me' words in both groups, after FWE voxel correction for multiple comparisons with $p < 0.05$ and cluster-extent threshold ($k > 50$). Peak activation is given in MNI Coordinates, and brain region labels come from the Harvard-Oxford Cortical Structure Atlas and MNI Structural Atlas.

		MNI Coordinates				
Regions for bottom-up parser action count	**Cluster size (in voxels)**	*x*	*y*	*z*	*p-value* (corrected)	*T-score* (peak level)
R Cingulate Gyrus (anterior division)	2317	8	38	22	0.000	8.96
L Cerebellum	1401	-12	-74	34	0.000	8.48
R Superior Frontal Gyrus	129	12	12	60	0.000	8.01
L Frontal Pole	86	-28	54	-6	0.001	6.89
R Cingulate Gyrus	78	6	-14	34	0.001	6.73
L Insula Cortex	136	-36	10	-8	0.002	6.62
R Angular Gyrus	114	56	-44	24	0.004	6.29
L Precuneus Cortex	133	-6	-62	60	0.005	6.20

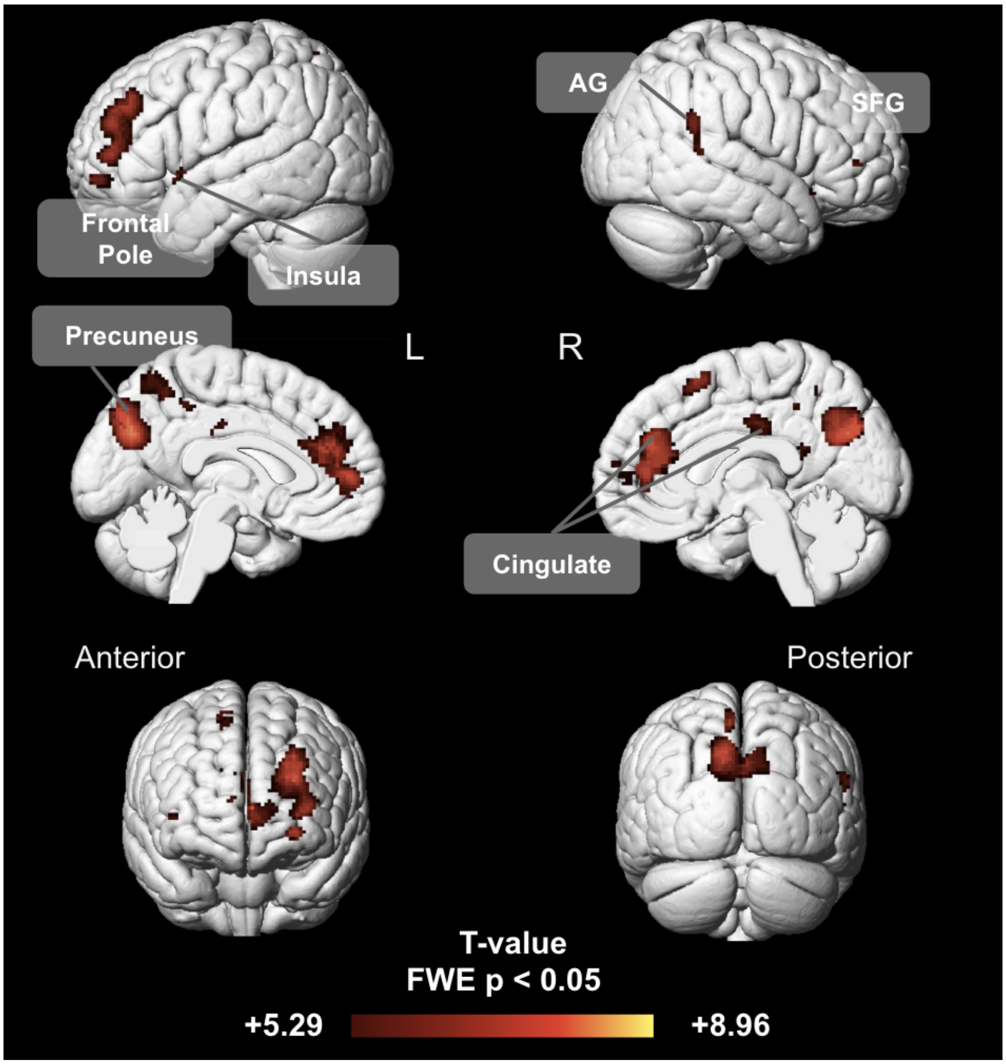

Figure 4.6: PATIENT-AGENT significant clusters while only 'I/me' words are taken into consideration (voxel > 50, FWE p < 0.05) projected on the whole brain

4.3 Supplemental Material

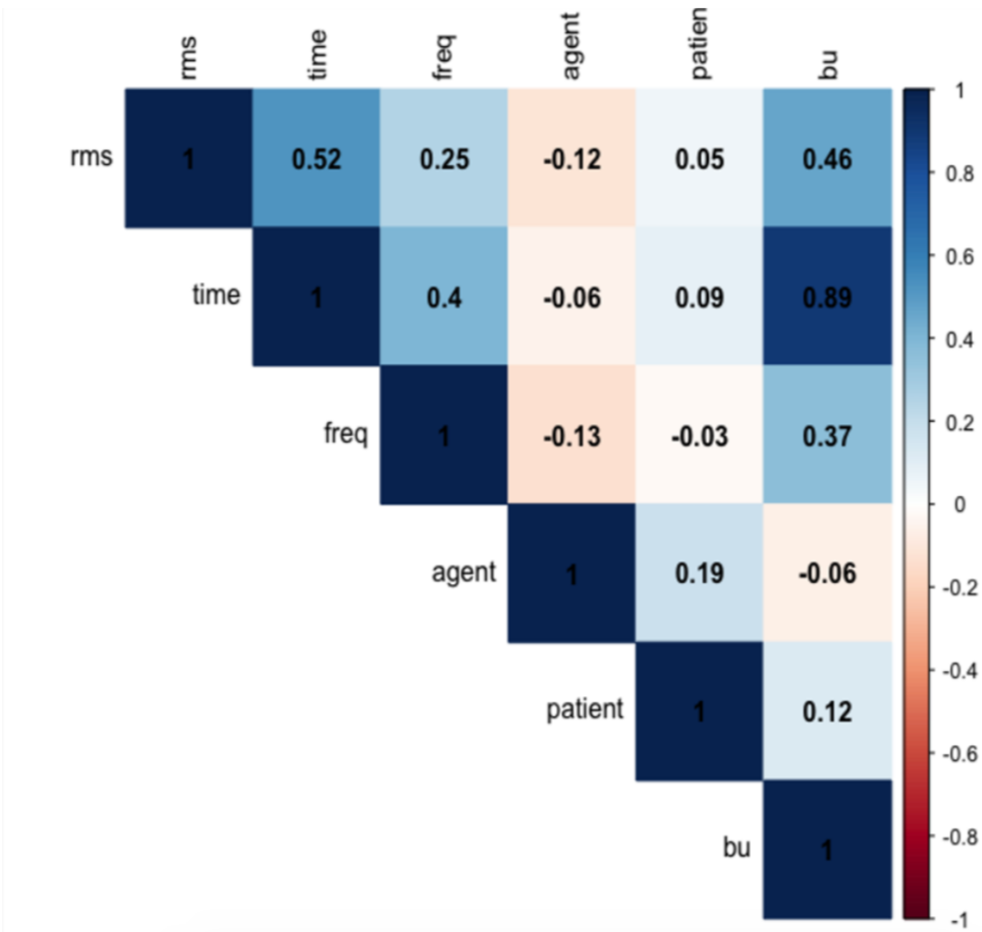

Figure 4.7: Pearson's correlation coefficients between each pair of predictors

Chapter 5

Conclusion and future work

5.1 Discussion

This study investigated how semantic roles, AGENT and PATIENT, are processed in the human brain. The comparison between the brain activation distribution of AGENT and PATIENT was carried out with three steps: (1) Individual Effect Analysis: the activation clusters provoked by AGENT and PATIENT were analyzed separately. From the results shown in Section 4.1.1 and 4.1.2, PATIENT words aroused broader brain activation than AGENT. (2) Contrast Effect Analysis: the contrast can be represented as 'PATIENT - AGENT', the results in Section 4.1.3 show PATIENT assignment did require higher activation in brain regions including AG, MFG, SFG, Precuneus, Cingualate, Insula. (3) Additional Analysis with First-pronoun Words: a post-hoc analysis was done with only first-person pronoun words 'I/me' for contrast between AGENT and PATIENT. The results in Section 4.2 show that 'I/me' contrast has aroused brain activation in Cingualte, SFG, Insula, AG, Precuneus.

Posterior STS has been implicated in the assignment of semantic roles during language comprehension (Bornkessel-Schlesewsky and Schlesewsky 2009). Other brain regions such as Precuneus and MFG might reflect the involvement of Mason and Just's Protagonist Monitor Network (2009) that contributes to narrative comprehension. The activation of Precuneus is particularly consistent with Leila Wehbe's observations in a story understanding task (2014), which might be responsible for tracking the main characters in the narrative stimulus and holding/retrieving related memory (Bhattasali, Hale, et al. 2018). Additionally, bilateral Precuneus activity has also been implicated for first person pronoun processing in Chinese (J. Li 2019), consistent with the current finding as the majority of the AGENT words consists of first person pronouns. Our finding of activation in the parietal lobe for PATIENT words is consistent with the eADM's particular proposal that the ventral stream goes through IPL(inferior parietal lobe) (Bornkessel-Schlesewsky and Schlesewsky 2016). The activation of the parietal lobe may also contribute to track the characters in the story (Saxe and Kanwisher 2003).

In our results, AGENT's assignment activated brain regions including bilateral STG and Precuneus. Among these regions, left anterior STG has been identified as a language comprehension hub by Dronkers et al.(2004), and Precuneus might relate with processing the protagonists in the story (Bhattasali, Hale, et al. 2018). As for PATIENT stimulus, brain activation had been found in regions like: MTG, ITG, Parietal, SFG, MFG, IFG. Comparing activation caused by AGENT stimulus, we can see assigning PATIENT requires broader areas including left frontal, left insula, and left posterior temporal areas that are not recruited in for AGENT-processing. One possible explanation for PATIENT's broader activation is that, to accomplish PATIENT assignment, the brain might have taken advantage of the dorsal pathways that bridge posterior temporal area and inferior frontal gyrus (Friederici 2011; Bornkessel–Schlesewsky and Schlesewsky 2013). An alternative explanation would be that PATIENT processing imposes a greater demand on the same processing network. The PATIENT - AGENT contrast suggests these demands are met in structures like the Cingulate Gyrus, Angular Gyrus, Middle Frontal Gyrus. From the contrast result of PATIENT - AGENT, we can see that stronger activation had been found in areas like cingulate, AG, SFG, Precuneus, MFG, insula, and the contrast result of 'I/me' words was consistent. In the contrast maps, we also see significant bilaterality. This accords with Hickok and Poeppel's Dual-Streams model

(Hickok and Poeppel 2004). The constrast maps also highlight medial brain structures such as the Cingulate Gyrus and the Precuneus. These regions have often come out in story-based studies (J. Li et al. 2018; Bhattasali, Fabre, et al. 2018).

In this study, we used Chinese audio as stimulus, and the same word does not have different case form or sound differently when playing the role as AGENT and PATIENT. So when subjects listening to the same word acting as different roles, there is not phonetics feature change getting involved.

5.2 Conclusion

AGENT and PATIENT assignments have activated distinct brain networks. The neural signature for AGENT assignment is considerably more focused within the superior temporal lobe and Precuneus, than the signature for PATIENT assignment. While AGENT's assignment has comparably low processing demands, PATIENT's assignment activates broader regions' involvement.

5.3 Future Work

In this study, we explore how `Agent` and `Patient` is perceived in Chinese using fMRI. For future work: 1. More languages can be used as materials to compare how semantic roles are processed; 2. More techniques can be used to explore the brain responses, such as EEG and MEG; 3. Other semantic roles can also be involved in the analysis.

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