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## **Neural basis of language switching in the brain: fMRI evidence from Korean–Chinese early bilinguals**

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### **Abstract**

Using fMRI, we conducted two types of property generation task that involved language switching, with early bilingual speakers of Korean and Chinese. The first is a more conventional task in which a single language (L1 or L2) was used within each trial, but switched randomly from trial to trial. The other consists of a novel experimental design where language switching happens within each trial, alternating in the direction of the L1/L2 translation required. Our findings support a recently introduced cognitive model, the 'hological' view of language switching proposed by Moritz-Gasser and Duffau. The nodes of a distributed neural network that this model proposes are consistent with the informative regions that we extracted in this study, using both GLM methods and Multivariate Pattern Analyses: the supplementary motor area, caudate, supramarginal gyrus and fusiform gyrus and other cortical areas.

### **Keywords**

Language switching; fMRI; Bilingualism; Cognitive model; GLM; Univariate Searchlight

## 1. Introduction

The term “bilinguals” refers to people who can use two languages selectively and effectively in their everyday life. The measure of bilingual abilities includes several dimensions such as the degree of proficiency, accuracy, context of acquisition and/or learning, age of appropriation, degree of motivation, context of use, and structural distance between the two languages, with each of these dimensions having several variables. In particular, the variable Age of Acquisition (AoA) is commonly used to class the speakers of two languages into early and late bilinguals. The early bilingual (EBL) is one who acquires two languages, at the same time, from infancy. The late bilingual (LBL), on the other hand, is one who acquires or learns a second language after the age of seven years (Paradis, 2003).

However, an important issue has not been thoroughly studied in this research field: the means by which bilinguals select between and process two languages in the brain. This process has important implications for advancing our understanding of how one brain supports two distinct languages and learns a second language more efficiently. There are two basic questions regarding brain processing of bilingualism (Hernandez, Martinez, & Kohnert 2000). One is about whether spatially overlapped or segregated neural substrates sub-serve two reciprocal languages, and the other one pertains to the functional areas or networks responsible for language switching, which is a key aspect of language control in bilingual individuals.

Studies that use late bilinguals to address the neural representation of language switching are abundant. A variety of regions, including the left inferior frontal region (Lehtonen et al., 2005, Price et al., 1999 and Abutalebi and Green, 2008), bilateral supramarginal gyri (Price et al., 1999), the left caudate (Crinion et al., 2006, Abutalebi & Green, 2007), the left anterior cingulate cortex (Wang, Xue, Chen, Xue, & Dong, 2007; Abutalebi & Green, 2008), and subcortical structures (Lehtonen et al., 2005 and Price et al., 1999), have been observed to be involved in language switching tasks. The studies also suggested that there were no single region responsible for language switching and that the direction of language switching was asymmetric. In contrast, the number of studies targeting proficient early bilinguals is relatively limited, and the results are inconclusive. From experiments involving early bilinguals, the involvement of the left dorsolateral prefrontal cortex (Hernandez et al., 2000), the right dorsolateral prefrontal cortex (Hernandez, Dapretto, Mazziotta, & Bookheimer, 2001), the left prefrontal and lateral temporal regions (Kim, Relkin, Lee & Hirsch, 1997; Chee, Soon, & Lee, 2003)

have been observed. These findings suggest that different languages are represented in overlapping areas of the brain for early bilinguals.

Both the neural basis of language switching and the proposed cognitive models of bilingualism remain controversial: the language-specific model (Costa, Santesteban, & Ivanova, 2006) is contrasted with the Inhibitory Control (IC) model (Green, 1986 and Green, 1998). The first one assumes that only the target language is activated, whereas the second one assumes that the selection of lemmas in one language is only achieved after the successful inhibition of the lemmas of the other. According to the IC model, the amount of inhibition would depend on two factors: the activation level of the words that need to be suppressed, and the speaker's proficiency level in the non-response language (Costa and Santesteban, 2004, Green, 1986 and Green, 1998).

It is also noteworthy that recently, a new model of cognitive processes and neural foundations of language switching has been proposed (Duffau, 2008 and Moritz-Gassera and Duffau, 2009). This model is based on a 'hodological' rather than a 'localisationist' view of language processing and suggests that language switching is underlain by a dispersed system that involves cortico-cortical and cortico-subcortical parallel and distributed networks. In particular, the authors emphasised the presence of extensive language sub-networks that span lobes, with the superior longitudinal fasciculus as their edges and the supramarginal and angular gyri, Broca's area, postero-temporal areas, and fusiform gyrus as their nodes. In addition, Abutalebi et al. (2007) proposed there is a left cortico-subcortical network for language switching and the regions involved are also involved in cognitive control or executive control more generally. This network consisted of prefrontal cortex, anterior cingulate cortex, basal ganglia and inferior parietal lobule. The hodological view is crucial in the sense that it allows us to ensure consistency in the analysis and meta-analysis for bilingualism, by treating widely spread regions in a coherent framework of interpretation.

In spite of such an abundance of literature, several questions remain to be addressed regarding the neural basis of language switching. First, most previous studies covered bilingual participants whose two languages of competence were both alphabetical languages. It is still not clear whether a switch between two types of languages (such as between a logographic language such as Chinese and an alphabetic language such as Korean) would involve different and/or additional brain regions. Currently, reading and picture naming are two commonly used tasks, (reading tasks: Bai et al., 2011,

Buchweitz et al., 2012 and Chee et al., 2003; picture naming tasks: Hernandez et al., 2000, Hernandez et al., 2001, Rodriguez-Fornells et al., 2005 and Wang et al., 2007). In this study, a purely orthographic condition was used to evaluate the effects resulting from the stimuli. Because of the differences between the two writing systems, a purely orthographic condition is required for evaluating the effects caused by a stimulus set on bilingual participants.

Second, there has been ambiguity with respect to the definition of 'language switching', particularly depending on how the researchers set contrasts for the use of two languages. In most cases, the contrasts were established based on a context where the language switching is required between monolingual block conditions. However, the other type of language switching is also experienced in real life, in code-switching or everyday translation situations (both common in immigrant and minority group communities). This switching requires not only diachronically parallel but also synchronous concomitant use of two languages as targets of simultaneous translation. There has been no study that deals with both types of language switches.

Third, the regions of interest for language switching have been extracted in almost all studies using a General Linear Model (GLM), which typically assumes a monotonic relation between conditions, and activity in contiguous regions. In this research domain, there are few investigations that have employed Multi-Variate Pattern Analysis (MVPA) – a notable exception is Buchweitz et al. (2012). MVPA, especially Searchlight methods (Kriegeskorte and Bandettini, 2007a, Kriegeskorte and Bandettini, 2007b and Kriegeskorte et al., 2006), should be useful for elucidating neural representation of language switching in the functional mapping of bilingual brains. A Searchlight analysis primarily aims at identifying brain regions that carry information for the given experimental conditions, without assuming local homogeneity in activations. It enables us to decode fMRI data by focussing the analysis around a single voxel at a time, while combining the signals within a certain radius from the centred voxel to compute a multivariate effect statistic at every location (Haynes and Rees, 2006, Alink et al., 2012 and Corradi-Dell'Acqua et al., 2011; Bode et al., 2011, Gilbert, 2011, Kahnt et al., 2011, Kotz et al., 2012 and Momennejad and Haynes, 2012). Based on the methodological research regarding univariate Searchlight (Jimura & Poldrack, 2012), MVPA is more sensitive to distributed coding of information than GLM, which seems better at identifying global engagement in ongoing tasks. Therefore, MVPA might also be useful for detecting some aspects of the cortico-cortical and cortico-subcortical networks that

subserve the functions in bilingual language switching, while still being sensitive to the contiguous areas of homogenous activation that might be detected by the GLM.

Hence, in the current study, we focused on highly proficient Korean–Chinese early bilinguals (Bai et al., 2011) by using language-switching tasks with written stimuli to explore the neural basis of their bilingual behaviour. We also considered the Age of Acquisition and the language proficiency of the bilinguals. The tasks were subdivided into two-day sessions with different levels of difficulty: situational non-translation language switching condition (abbreviated as ‘SnT’) and focused simultaneous translation language switching condition (abbreviated as ‘FST’). The SnT refers to the conventional language switching task used in previous studies in which subsequent trials switch from L1 to L2 and vice versa, without interlingual translation being required within a trial. In the FST condition, switching is required within the trial, and the direction of translation is randomly varied from trial to trial. We applied the univariate Searchlight and GLM in a complementary manner as methods to identify the informative regions of fMRI activity for different types of language switching.

## 2. Results

### 2.1. Summary of results

Our findings from Korean–Chinese early bilinguals, especially under the focused simultaneous translation language (FST) condition, supported the new ‘hodological’ view of language switching by detecting several regions of interest that play important roles in the network for executive control and in the cortico-subcortical sub-networks (Abutalebi and Green, 2008 and Moritz-Gassera and Duffau, 2009).

### 2.2. Results of univariate Searchlight

Fig. 1(a–c) shows the results of the univariate Searchlight method used to elicit the voxels that are sensitive to the difference in language conditions, by classifying the stimulus language in each trial. Figs. 1(a) (SnT condition) and 2(b) (FST condition) show participant-based results from univariate Searchlight analysis, as MVPA is essentially a single-subject analysis. Fig. 1(c) shows group-based results from the two conditions.

For the situational non-translation (SnT) language switching condition, we found two large and some small clusters in the results of the univariate Searchlight. The peak of the first cluster was located in the left fusiform gyrus, and that of the second one was found in the right inferior occipital gyrus. The other small clusters were distributed in

the right superior temporal gyrus, the right precuneus, and the left superior temporal gyrus.

For the focused simultaneous translation (FST) language-switch condition, the most informative voxels were concentrated in the left fusiform gyrus, the left cerebellum and the left lingual gyrus. Other large clusters observed were in the right lingual gyrus, the right middle occipital gyrus and the right calcarine. One small cluster was also found in the left middle temporal gyrus and the supramarginal gyrus.

### 2.3. Results of GLM

The GLM analysis also revealed some significant clusters for the following contrasts (Table 1 and Fig. 1(d)). For the SnT condition, we use the acronyms “k2k-vs-c2c” standing for “Korean (as stimulus) to Korean (as task)” versus “Chinese (as stimulus) to Chinese (as task)”, and “c2c-vs-k2k”, meaning “Chinese (as stimulus) to Chinese (as task)” versus “Korean (as stimulus) to Korean (as task)”. For the FST condition, we use the acronym “c2k-vs-k2c” standing for “Chinese (as stimulus) to Korean (as task)” versus “Korean (as stimulus) to Chinese (as task)”. The contrast of the opposite direction is noted here as “k2c-vs-c2k” following the same notation.

k2k-vs-c2c: significant activation was found in the left middle frontal gyrus (Broca’s area), the left precentral and the left caudate.

c2c-vs-k2k: we found that the right superior frontal gyrus, the left postcentral as well as the left medial superior frontal gyrus were activated at the peak level but were not significant at a cluster level.

k2c-vs-c2k: this condition significantly activated a wide range of brain regions distributed in the frontal, temporal and parietal areas. The strongly activated areas were the left middle frontal gyrus, the right supplementary motor area, the left middle temporal gyrus, the right middle temporal gyrus, the left inferior parietal gyrus, the left postcentral, and the right postcentral.

c2k-vs-k2c: the occipital regions of the brain were significantly activated, including the left middle occipital gyrus, the left inferior occipital gyrus and the right superior occipital gyrus.

### 3. Discussion

In the present study, we focused on Korean–Chinese early bilinguals and language-switching tasks to explore the nature of bilingualism. Two different methodologies were applied to analyse the two language-switching conditions. The univariate Searchlight revealed that individual variability was larger in the situational non-translation (SnT) language-switching condition than in the focused simultaneous translation (FST) language-switching condition. In the SnT session, the informative voxels were spread in the bilateral occipital, temporal lobe, and some discrete regions. In contrast, the results of the FST were concentrated along the routes connecting regions around the left fusiform, left and right lingual and left supramarginal gyri. In FST, all of the participants showed a similar trend, with a coherent and intense band of sensitivity. This result suggests that in the relatively difficult FST language-switching task, the participants needed more attentive control, and so the activations of the brain were more intense and regulated. Note that the lingual region is believed to play a role in visual search and attentional control during language switching (Wang et al., 2007).

An interesting finding is that the Searchlight did not detect any important voxels in the frontal lobe. In contrast, GLM detected a significant activation in the frontal region for the k2k-vs-c2c and k2c-vs-c2k conditions. Because Korean uses an alphabetic writing system, the activations in the left middle frontal gyrus (Broca's area), left precentral and left caudate might be related to alphabetic reading. In contrast, it is possible that the clusters of informative voxels and significant activations found in the occipital lobe by both the Searchlight and GLM (c2k-vs-k2c) methods during the presentation of the Chinese stimuli were due to the logographic aspect of the Chinese character stimuli (Liu and Perfetti, 2003, Siok et al., 2004, Tan et al., 2001 and Wang et al., 2007). Furthermore, Crinion et al. (2006) found that the left caudate played a role in monitoring and controlling bilinguals' use of languages, which is also endorsed by our GLM result from k2k-vs-c2c. Left temporal activation may be related to general language processing, while activation in the right temporal gyrus (k2c-vs-c2k) may be related to attentional demand required for language processing (Sabri et al., 2008).

Literature investigating language switching has also implicated the left fusiform. Notably, an investigation by Abutalebi et al. (2007) that applied auditory stimuli to detect language switching demonstrated that the left BA37 (-38,-25,-18) was important for controlling lexical-semantic processing. Other studies illustrated that activity in the fusiform gyrus might be indicative of some other cognitive processes (Guo et al., 2011,

Hernandez, 2009, Hernandez and Meschyan, 2006 and Price et al., 1999; Moritz-Gassera & Duffau, 2009). Investigations using invasive techniques (Duffau et al., 2014, Kho et al., 2007 and Moritz-Gassera and Duffau, 2009) also support the idea that the left fusiform (BA 37) is involved in language switching. In addition, studies involving Chinese-English bilinguals (Xue, Chen, Jin, & Dong, 2006) and adults who have been blind since birth (Mahon, Anzellotti, Schwarzbach, Zampini, & Caramazza, 2009) found that the left fusiform gyrus is not restricted to processing visual word forms (Price & Devlin, 2003).

To date, the cognitive model of language switching is still under debate. Despite the traditional 'localisationist' view, where the language switching is mainly controlled by the frontal regions of the brain (e.g., the left prefrontal cortex, the left dorsolateral prefrontal cortex, etc.), some regions of interest, namely the left fusiform, bilateral lingual, and left precentral frontal gyri, were implicated by either MVPA or GLM in our study. This finding is consistent with the view that the frontal-subcortical circuit is critical for language control (Abutalebi & Green, 2008), suggesting that there is no single brain region that is solely responsible for bilingual language switching. (The areas that we discovered that are different from those of Abutalebi et al. are probably due to the sample used and the analytical methods. However, this warrants further investigation.) Our experimental data also prove that both the precentral and the fusiform regions are important in our language-switching tasks for early Korean-Chinese bilinguals. It might be possible that there is a strong connection between cortico and subcortical regions for switching between two different languages. In this sense, our results also support the 'hologarchical' model for language switching (Moritz-Gassera & Duffau, 2009) because several important areas of the distributed neural network of language switching were implicated in our investigation. However, more sophisticated experiments would be needed to clarify the core controlling brain region for the language switching in the cortico-subcortical network. Further studies will aim to elucidate the details of this model, such as how the network is connected during language switching.

## 4. Methods

### 4.1. Participants

A total of eight graduate student participants (four males, age ranging from 25 to 28 years) with a mean education of 18.0 years (ranging from 16 to 20 years) participated in the current experiment. All of the participants were strongly right-handed and had

normal or corrected-to-normal vision. They did not have a history of any medical, neurological or psychiatric illnesses and were not taking any medications for such diseases. They provided signed written informed consent in accordance with guidelines set by the Ethics Committee of the Tokyo Institute of Technology.

All of the participants belong to the Chinese Korean minority, which is called “Chaoxianzu Koreans from Yanbian Korean Autonomous Prefecture of Jilin Province in China”. They started to learn both Korean and Chinese as native languages (mother tongues) in their first year of life. All of the participants acquired the spoken language of their first language (Korean) and second language (Chinese) before 5 years of age and began to learn to read in these two languages before 7 years of age when they entered elementary schools. They continue to use both languages in daily life in a mixture of contexts. Therefore, all of the 8 participants in this group were considered to be proficient early bilinguals.

#### 4.2. Materials

A total of 20 concrete nouns were used in the present study. All of the words were chosen from a set of stimuli previously used for predicting fMRI activation patterns (Akama, Murphy, Li, Shimizu, & Poesio 2012) but without using pictures. They were classified into two categories and two languages: 10 tool words in Korean and their corresponding ones in Chinese, 10 mammal words in Korean and their corresponding ones in Chinese. Using the E-Prime 2.0-Standard software package, which synchronised during the experiments with the trigger pulses transmitted by the fMRI control PC, the 40 words were randomly shown on the screen.

#### 4.3. Task design

A slow event-related design was used in the present study. The participants participated in two separate scanning sessions carried out over two different days whose order was counter-balanced across participants over the two days. Each session lasted 50 min. Each session had 6 repeated runs for a total of 240 trials. In each trial, each word was presented for 3000 ms, followed by a fixation cross for 7000 ms. There were six additional presentations of a fixation cross, 40 s each, distributed immediately after each run to establish a BOLD baseline. During the 3000 ms stimulus period, the participants were asked to perform a silent property generation task (Mitchell et al., 2008) with these word stimuli by thinking of the appropriate features of the corresponding concept and caption in a required language. This step was followed by a

fixation cross presentation time of 7000 ms, during which the participants were asked to silently fix their eyes on the cross and no response was required.

In one session, the participants were asked to perform the task covertly using the same language as the orthographic stimuli on the screen. We refer to this session as the ‘situational non-translation language-switching condition’, abbreviated here as SnT. In the other session, the participants were asked to perform the task using the other language, which is not visually presented in each trial. We refer to the second session as ‘focused simultaneous translation language-switching condition’, abbreviated here as FST (Fig. 2). To ensure that each participant had a consistent set of properties to think about during the on-line tasks, the participants were asked to acquaint themselves with these stimuli and to perform a property rehearsal task before the scanning session (Mitchell et al., 2008).

#### 4.4. Data acquisition

Functional MRI scans were performed with a 3.0-T General Electric Signa scanner at the Tokyo Institute of Technology, Japan, with an 8-channel high-resolution head coil. The scanning parameters were based on those of Mitchell et al. (2008). Functional scanning was performed using an echo planar imaging sequence with a 1000 ms repetition time (TR), 30 ms echo time (TE), and 60° flip angle (FA). Each volume consisted of 15 \* 6 mm thick slices with an inter-slice gap of 1 mm; FOV: 20 \* 20 cm; size of acquisition matrix, 64 \* 64; NEX: 1.00. The parameter values of the anatomical scans were TR = 7.284 ms, TE = 2.892 ms, FA = 11 degrees, bandwidth = 31.25 kHz, and voxel size = 1 mm isotropic. Following the settings used by Mitchell et al., we used oblique slices in the sagittal view with a tilt of -20 to -30 degrees such that the most inferior slice was above the eyes (anteriorly) and passed through the cerebellum (posteriorly).

#### 4.5. fMRI data processing and analysis

The fMRI pre-processing was performed with SPM8 (Wellcome Department of Imaging Neuroscience, UK). Corrected for motion was applied to the images, followed by co-registration of functional and anatomical images, segmentation to identify grey matter, and normalisation into standard Montreal Neurological Institute (MNI) spaces at a re-sliced voxel size of 3 × 3 × 6 mm.

The unsmoothed data were analysed with the Searchlight method. The computation for the Searchlight was made using PyMVPA2.0, a Python package intended to run

machine-learning programs applied to human neurological data. Searchlight yielded an accuracy map for classification of the stimulus language in each trial (Korean or Chinese script) with the voxels with higher accuracy indicating small local regions that are more informative. In our study, the method was applied to the entire brain, over spherical regions of radius 3. The machine-learning classifier used with Searchlight was a logistic regression with L2-norm regularisation (also termed ridge regression or Tikhonov regularisation). Consecutively, the z-statistic of the accuracy for each voxel was computed and screened out with a threshold of 3.08, corresponding to a p-value of 0.001 under the hypothesis of normal distribution. Participant-based images were visualised using the xjView toolbox (<http://www.alivelearn.net/xjview>) to produce sensitivity maps analogous to statistical maps of a GLM. xjView toolbox was also used for extracting clusters of informative voxels in which the discrimination accuracy was high.

For the GLM analysis (Friston et al., 1994 and Friston et al., 1995) the data were additionally smoothed using an 8 mm Gaussian kernel. A conventional General Linear Model contrastive analysis was performed for each individual participant. The group-averaged effects were computed using a fixed-effects model. For the group analysis, those clusters of 4 or more that were above a threshold of  $p < 0.05$  FWE (at both the cluster-level and peak-level) were considered to be significant.

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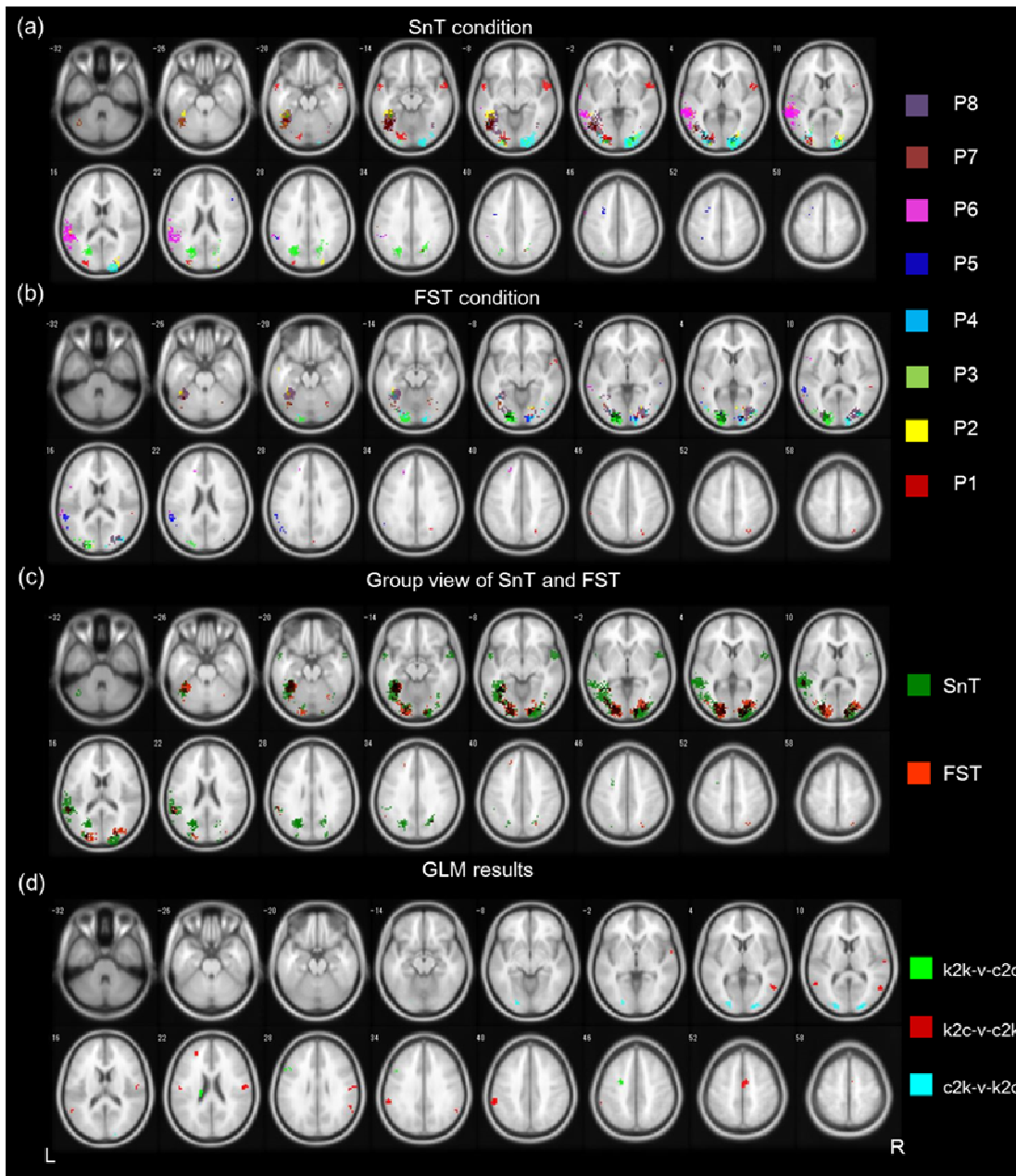


Figure 1. Brain regions that showed informative and predictive clusters of voxels. (a)(b) Participant-based results, (c) group-based results of searchlight during SnT and FST conditions, (d) GLM results of significant brain activations. ( $p < 0.05$ ,  $k > 4$ , FWE corrected).

Table 1 Regions of significant brain activations. ( $p < 0.05$ ,  $k > 4$ , FWE corrected).

Regions activated	Korean to Korean vs. Chinese to Chinese		Korean to Chinese vs. Chinese to Korean		Chinese to Korean vs. Korean to Chinese	
	MNI coordinate	Z value	MNI coordinate	Z value	MNI coordinate	Z value
<b>Frontal</b>						
Left precentral	-27,-4,46	4.78				
Left middle frontal gyrus	-45,17,28	4.72	-27,44,22	4.87		
Right supplementary motor area			6,-4,52	4.82		
<b>Temporal</b>						
Left middle temporal gyrus			-57,-55,10	5.17		
Right middle temporal gyrus			54,-61,4	5.00		
<b>Parietal</b>						
Left inferior parietal gyrus			-60,-37,40	5.44		
Left postcentral			-54,-16,22	4.60		
Right postcentral			57,-13,22	5.24		
<b>Occipital</b>						
Left middle occipital gyrus					-21,-91,10	5.96
Left inferior occipital gyrus					-21,-88,-8	5.42
Right superior occipital gyrus					24,-94,10	-
<b>Other areas</b>						
Left caudate	-18,-25,-22	4.50				

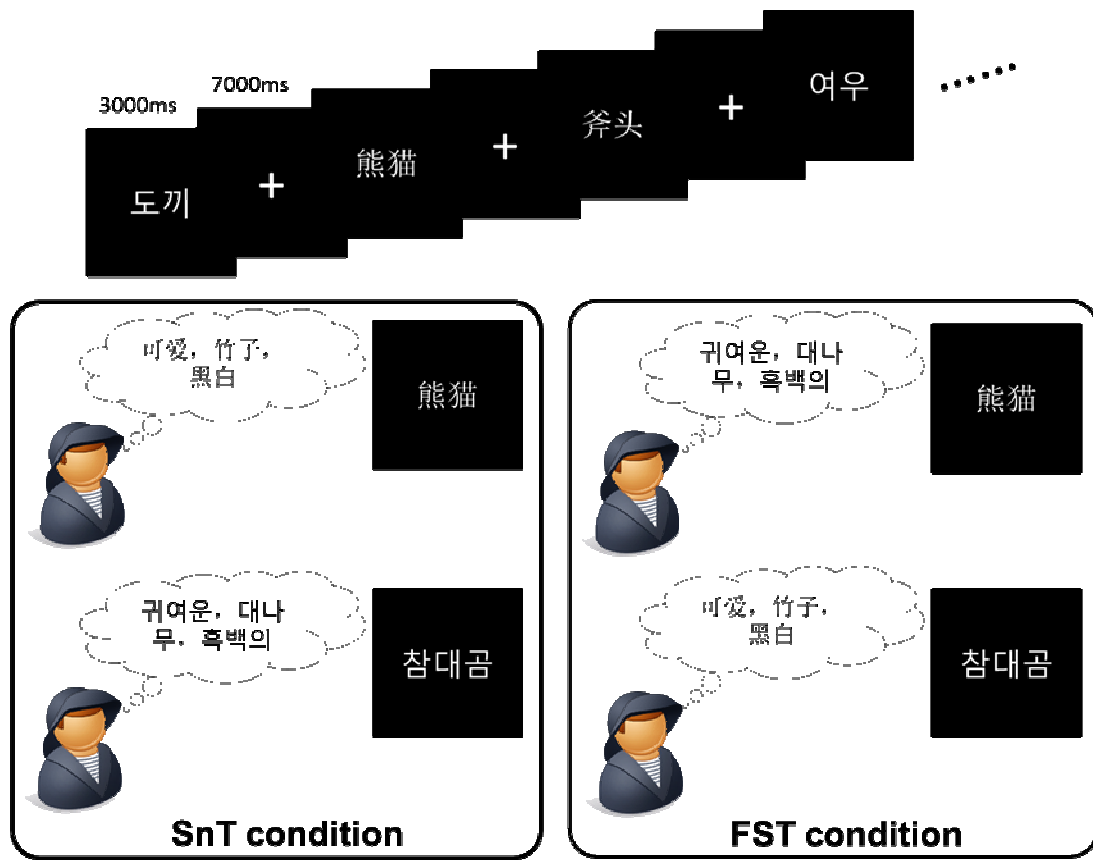


Figure 2. Depiction of the two language-switching task conditions.

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