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Functional Neuroimaging of Morphological Processing in Nonnative Speakers of English

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Functional Neuroimaging of Morphological Processing in Nonnative Speakers of English

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The nature of morphological processing has been a focus of research in the cognitive neurosciences of language for decades, primarily because the systems underlying simple, word-level linguistic processes may also contribute to fundamental human cognitive capacities and brain functions (e.g., categorization, functional neural organization, and memory). To date, neuroimaging research has yet to demonstrate whether nonnative speakers of a language sort out and process morphologies in the same way that native speakers do. This study, therefore, is intended to identify neural mechanisms that have so far eluded detection. Using functional magnetic resonance imaging, this study adopts an event-related design to investigate the neural responses during English regular and irregular past tense verb generation by Korean nonnative speakers of English. A whole-brain analysis reveals that the processing of irregular verbs evoked greater neural activation than for regular verb processing, and distinctive regional differences of neural responses were found. Specifically, neural activation in regions of the middle and the superior temporal gyri in the right hemisphere was found to be relevant to regular past tense processing, whereas neural recruitment in regions of the inferior frontal gyrus, the supramarginal gyrus, the caudate, and the thalamus in the left hemisphere was found to be significant in irregular past tense processing in nonnative speakers of English. In particular, the results support claims for an inhibitory role of the caudate in prepotent responses and for a thalamic function controlling retrieval of specific items in language and memory. In addition, as reported in earlier studies with native speakers, the results showed increased activity in the frontal cortex and the cingulate cortex bilaterally during both regular and irregular past tense processing. In this study, however, the neural involvement of the cortices in both hemispheres was viewed as evidence for a more general cognitive control function induced by the experimental task rather than by their essential role in morphological processing, since the selective attention required for the rapid past tense generation task would itself entail such cognitive control. Taken together, the results shed further light on the cortical and subcortical representation of language in the human mind and brain.

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Chapter 1

Introduction

1.1 Overview

Researchers have proposed that the neural response patterns involved in processing English morphological inflection—that is, regular versus irregular past tense formation—may indicate the distinct presence of a mental grammar and a mental lexicon (e.g., Pinker & Ullman, 2002). The so-called dualist approach holds that symbolic, rule-based processing subserved by the procedure memory system exists for generating regular past tense verbs (e.g., *walk-walked*), while lexical retrieval processing from a mental storage subserved by the declarative memory system exists for irregular past tense verbs (e.g., *go-went*). Alternatively, the connectionist approach suggests that the spatial patterns of neural activation linked to the English past tense inflection may demonstrate the presence of a single integrated neural network system, consisting of simple pattern associator processing units, that is gradually affected by other factors, for examples, stem and/or word frequency, phonological properties, and semantic complexity (e.g., McClelland & Patterson, 2002). Both approaches take into account that the mechanisms underlying English past tense processing may be closely related to fundamental human cognitive capacities and brain functions (e.g., categorization, functional neural organization, and memory). That relationship explains why, for decades, research in neurolinguistics, psycholinguistics, and associated cognitive and neuroscience fields has focused on the nature of this simple, word-level linguistic process (e.g., Albright & Hayes, 2002; Baayen & Prado Martín, 2005; Babcock et al., 2012; Beretta et al., 2003; Birdsong & Flege, 2001; Burzio, 2002; Bybee & Slobin, 1982; De Diego Balaguer et al., 2005; Desai et al., 2006; Dhond et al., 2003; Eddington, 2000; Ellis & Schmidt, 1998; Embick & Marantz, 2005; Jaeger et al., 1996; Joanisse & Seidenberg, 1999; Kielar et al., 2011; Kim et al., 1991; Lambon Ralph et al., 2005; Lavric et al., 2001; Ling & Marinov, 1993; MacWhinney & Leinbach, 1991; Marcus et al., 1995; Marslen-Wilson & Tyler, 1997; Miozzo, 2003; Newman et al., 2007; Oh et al., 2011; Pinker & Prince, 1988; Plunkett & Juola, 1999; Rhee, 2001; Rumelhart & McClelland, 1986; Sach et al., 2004; Sahin et al., 2006; Sakai et al., 2004; Tyler et al., 2002; Ullman et al., 1997ab; and Weinrich et al., 1999, among many others).

To date, however, neuroimaging research has yet to demonstrate whether nonnative (L2) speakers of a language sort out and process inflectional verbs in the same way that native (L1) speakers do. The aim of this dissertation, therefore, is to investigate the neural basis of morphological processing in L2 speakers of English, in this case, native Korean speakers who have a high command of English as an L2 language. Specifically, by using event-related functional magnetic resonance imaging (fMRI), the study investigates the neural responses from those speakers as they process regular and irregular past tense forms of English verbs. The Korean language, unlike English, does not have two different inflectional morphological systems. In Korean, only a regular type of past tense form exists[1]: that is, in Korean a past tense morpheme `-ess` (or its variants `-ss/-ass/-yess`) is attached to the stem verb (Chang, 1996; Lee, 1989; Lee, 2005; Lee & Ramsey, 2000; and Sohn, 1999).

[1]See also *Note* in p. 14-15.

Thus, the imaging data from the Korean speakers could help determine whether L2 speakers use the same neural systems that L1 speakers use, despite differences in the morphological organization of Korean and English.

1.2 Previous Studies

1.2.1 L1 Studies

A number of neuroimaging studies have investigated the L1 processing of morphological inflection in the brain. For example, Jaeger et al. (1996), in a PET study on the spoken production (i.e., reading and speaking) of regular and irregular past tense forms in English, reported that the production of irregular past tense forms (i.e., "the comparison of the irregular past–read verb," which is not a direct contrast between irregular and regular past tense generation, but the irregular "*past tense* minus *read* conditions," p. 471) involved much larger and higher neural activation than did the production of regular past tense forms (i.e., "the comparison of the regular past–read verb," which is again not a direct contrast between regular and irregular generation, but the regular "*past tense* minus *read* conditions," p. 471) in terms of the area of activation and the level of significance. In particular, "in the irregular condition, the area of activation is more posterior and superior, and is contiguous with the superior parietal lobule area of activation" (p. 472). More specifically, the left lateral orbitofrontal cortex, visual associative cortex, and certain regions of the cerebellum were activated for irregular past tense forms but not for regular past tense forms. As for the activation in the left lateral orbitofrontal cortex, the authors noted that the "area is involved in inhibiting default, high-frequency responses, and is inactive during overlearned, practiced behaviors" (p. 482). As for the additional selective response area for the irregular past generation, namely, the left middle temporal gyrus, the authors took the activation as supporting evidence for the lexical retrieval from memory for the irregular past tense forms, because the temporal area was assumed to be closely linked to auditory and long-term memory. On the other hand, Jaeger et al. found that "in the regular condition, the area of activation is more anterior and inferior, involving a small portion of the supramarginal gyrus and sensory face cortex" (p. 472). Specifically, they found that the left dorsolateral prefrontal cortex, the left anterior cingulate cortex, and the left pulvinar of the thalamus were activated for regular forms but not for irregular forms. They ascribed the activation in the anterior cingulate cortex to its executive attention role in the rapid behavioral performance rate of regular past tense generation. Based on these contrastive results, the Jaeger et al. study supported the dual-route hypothesis as an explanation for the distinct differences in neural patterns between regular versus irregular past tense verb form production.

In their fMRI study of English verbal inflection, Ullman et al. (1997a) reported that the frontal cortex and the basal ganglia underwent more neuronal activation during a irregular tense generation task than they did during an regular tense generation task. In addition, Ullman et al. (1997a, p. S549) suggested that "the posterior regions (i.e., temporal and temporoparietal regions) may play a greater role in the past tense production of irregulars than of regulars." Moreover, Ullman et al. (1997b) conducted a lesion study indicating double dissociation; that is, anterior aphasics and patients with Parkinsons disease were more impaired at producing regular past tense forms, whereas posterior aphasics and patients with Alzheimers disease showed the reverse pattern. They claimed that the reversal implies that the processing of inflection morphology requires separate neural mechanisms for regular and irregular past tense verb forms (Lambon Ralph et al., 2005).

In an event-related fMRI study, Beretta et al. (2003) conducted tests on the generation of German regular versus irregular verbs and nouns, and found evidence that the brain makes a distinction between regular and irregular form generation.

Beretta et al. reported that, as in previous studies, the "total extent of cortical activation was significantly greater and wider for irregulars than for regulars" (p. 80), while they also noted that in German the irregular past tense forms are "more type-frequent" (p. 84). The authors "observed that irregulars clearly dominate in both temporal and frontal regions" (p. 86) and that the processing of irregulars activated bilateral cortical tissues, but the processing of "regulars exhibits greater lateralization to the left hemisphere than do irregulars" (p. 82). In addition, the authors interpreted the activation in the left prefrontal cortex for irregulars than for regulars as "a blocking mechanism to prevent overregularization" (p. 85) so that the application of the default past tense rule could be inhibited (p. 86).

Using Spanish language data, De Diego Balaguer et al. (2006) reported results from an event-related fMRI experiment that also supported the notion of dual processing. Their study, which compared the retrieval processes of regular and irregular past tense forms whose morphological characteristics show a more sensitive contrast between regular and irregular verbs in English (pp. 876, 886), found distinct differences in regional and neural activation within the prefrontal cortex. De Diego Balaguer et al. observed that "irregular verbs showed a more dorsolateral prefrontal pattern, whereas regular verbs were characterized by a more inferior (anterior STG[2]/insula) and hippocampal pattern of activation" (p. 882), and the main difference between the production of regular and irregular verbs lay in the activation of different areas within the prefrontal cortex (p. 885).

An event-related brain potentials (ERP) study by Newman et al. (2007) showed that there was a left anterior negativity (LAN) for violations of regular past tense forms but not for irregular violations, which could reflect the compositional aspect of morphosyntactic processing. Newman et al. used that result to support a dual-system model and suggested the existence of distinct neurocognitive substrates

[2]The superior temporal gyrus.

for the processing of the two verb types, regular and irregular past tense forms. Further, the authors suggested that regular past tense form generation depends on rule-governed processing subserved by procedural memory, and that irregular past tense form generation is retrieved from lexical memory (p. 443).

The fMRI investigations described in Joanisse & Seidenberg (2005) and Desai et al. (2006) also indicated that the generation of regular past tense forms activated regional and neural patterns that were different from those activated by the generation of irregular past tense forms. According to Joanisse & Seidenberg (2005), a cluster of significant voxels in both the left and right inferior frontal gyrus (IFG)—regions that are assumed to be related to "phonological and semantic mechanisms" (p.294)—showed greater activation for regular verb generation but not for irregular verb generation. In Desai et al. (2006), on the other hand, "frontal areas (IFG, inferior frontal sulcus, and precentral gyrus), parietal regions (dorsal supramarginal gyrus and IPS[3])" (p. 285), the right anterior insula, and "the bilateral basal ganglia, including the thalamus, caudate body, and caudate head" (p. 286) were more activated for irregular generation, and "the left dorsal STG and right ventral supramarginal gyrus" (p. 286), where there are areas closely related to the processing of phonological structures, were more activated for regulars. Additionally, Desai et al. reported that all those areas in which irregular past tense generation elicited greater activation also showed greater activation when the regular past tense generation task was contrasted in a reading task, which could reflect "domain-general processes associated with more demanding tasks" (p. 287). Thus, the regional differences between the regulars and irregulars were not viewed as mutually exclusive. Taken together, both Joanisse & Seidenberg (2005) and Desai et al. (2006) proposed an alternative interpretation for the differences that varied from the interpretations of the studies mentioned earlier. For them, the source of the regional and pattern

[3] The intraparietal sulcus.

differences was the “the higher phonological complexity of regular past tense forms” (Desai et al., 2006, p. 278), as similarly proposed in Baayen & Prado Martín, 2005). That interpretation suggested that the neuronal differences were not caused by a dual-processing system; rather, it supported a single-system explanation of past tense generation.

Using that construal, Oh et al. (2011) recently controlled the phonological complexity (i.e., high, mid, and low phonologically complex regular and irregular verbs) and tested Desai et al.'s (2006) claim by using a mixed covert and overt generation task. Oh et al. reported an effect of phonological complexity, but they also found “a main effect of regularity, demonstrating that differences over and above phonological complexity exist between the two types of verb” (p. 271). Specifically, they found that bilateral frontal gyri, Broca's area, the left inferior parietal lobe and the left caudate were more activated for regular verb inflection, while the middle temporal gyrus, the right superior temporal gyrus, the left hippocampus, the right frontal regions, and the right inferior parietal lobe were more engaged in the irregular past tense generation (p. 274). As seen in previous studies, they also reported greater overall activation for the irregular verb inflection.

Using only regularly inflected verbs and employing both covert and overt tasks, Kielar et al. (2011) have furnished new anatomical regional information regarding past tense production processing. According to them, the covert past tense generation recruited areas in the left precentral gyrus, left precuneus, and right anterior/posterior cingulate gyri, while the overt production task elicited more activation in the posterior left inferior frontal gyrus, the bilateral precentral gyri and motor cortex, the right precuneus, and the posterior cingulate (p. 188). In addition, results of their stem verb production task indicated activation in the basal ganglia, thalamus, and the cingulate gyrus.

Note that all of the studies above—except for Kielar et al.'s (2011) study with regulars only—reported that the processes for forming regular and irregular past tense were different in terms of neural activation (that is, in the area and degree of activation). On the other hand, as several authors have cautioned (e.g., Beretta et al., 2003; Bookheimer, 2002; Desai et al., 2006; Kielar et al., 2011; Oh et al., 2011; and Raichle et al., 1994), the previous studies varied in the precision with which they could identify the functions of specific brain regions. The sources of inconsistency among the studies were differences in the designs and methodologies of their experiments. Different tasks (e.g., the silent generation task, sentence completion task, overt production task, judgment task, etc.) entail different types of stimuli (e.g., word-level versus sentential-level stimuli, visual versus auditory stimuli, etc.). As a result, the participants in the different studies were asked to perform similar tasks somewhat differently, which in turn could result in different neural responses in the brain, even though all the tasks were related to morphological inflectional processing. Therefore, careful assessment of these differences would be requisite when imaging studies are compared.

Tables 1.1 and 1.2 briefly summarize L1 studies, and the following abbreviations are used: ACC (The Anterior Cingulate Cortex), A/P (Anterior/Posterior), DPFC (The Dorsolateral Prefrontal Cortex), IFG (The Inferior Frontal Gyrus), L (The Left Hemisphere), MTG (The Middle Temporal Gyrus), P (Posterior), PFC (The Prefrontal Cortex), R (The Right Hemisphere), SMG (The Supramarginal Gyrus), SPL (The Superior Parietal Lobe), and STG (The Superior Temporal Gyrus).

Table 1.1: Summary of L1 Imaging Studies of Past Tense Generation

Study	Language	Type	Design	Task	REG>IRREG	IRREG>REG
Jaeger et al. (1996)	English	PET	BL	Overt	*(SMG, (L) DPFC (L) ACC (L) Pulvinar)	*((L) Orbitofrontal, Visual associative, Cerebellum, (L) MTG)
Ullman et al. (1997a)	English	fMRI	BL	Covert		(Bi) Frontal, (Bi) Basal ganglia
Beretta et al. (2003)	German	fMRI	ER	Covert		*((Bi) SPL, (Bi) Temporal, (L) PFC)
Joanisse & Seidenberg (2005)	English	fMRI	ER	Covert	(Bi) IFG	*((Bi) IFG)
De Diego Balaguer et al. (2006)	Spanish	fMRI	ER	Covert	(L) Hippocampus, (L) Insula, (L) Ant STG	(Bi) IFG, (Bi) Middle frontal, (Bi) IFG

The format of Table follows in Desai et al. (2006).

*: In Jaeger et al. (1996), the results from the contrasts of REG>control & IRREG>control; In Beretta et al. (2003), while the amplitude of IRREG>REG was greater than that of REG>IRREG, the same regions were also found in REG>IRREG; and in Joanisse & Seidenberg (2005, p. 282), the results were from the (subset of) irregular verbs that are phonologically similar to regular verbs ("e.g., *slept*, *fled*, *sold*").

Table 1.2: Summary of L1 Imaging Studies of Past Tense Generation (*cont.)*

Study	Language	Type	Design	Task	REG>IRREG	IRREG>REG
Desai et al. (2006)	English	fMRI	ER	Overt	(L) STG, (R) SMG	(Bi) IFG, (R) insula, (Bi) Basal ganglia (thalamus, caudate)
Kielar et al. (2011)	English	fMRI	ER	Covert	(L) Precentral, (L) Precuneus, (R) A/P Cingulate,	*NA (not tested)*
				Overt	(L) P IFG, (Bi) Precentral, (Bi) Motor, (R) Precuneus, (R) P Cingulate	*NA (not tested)*
Oh et al. (2011)	English	fMRI	ER	Overt	(Bi) Frontal, Broca's area, (L) Inferior parietal, (L) Caudate	(Bi) MTG, (R) STG, (L) Hippocampus, (R) Frontal, (R) Inferior parietal

1.2.2 L2 Studies

In light of the L1 observations, it is important to examine references to L2 past tense processing in the current literature. So far, compared to L1 research, considerably fewer experimental studies have investigated the processing involved in the L2 speakers knowledge of English regular and irregular past tense.

Focusing on Korean and Spanish speakers of English, Birdsong & Flege (2001) provided behavioral evidence for the dissociation of regular and irregular past tense processing, which supported the dualist approach to understanding morphological processing. Specifically, the authors found the input frequency effect in both types of L2 speakers only in the generation of irregular verbs, as predicted by the dualist approach, which posits that irregular verbs are stored in memory and are therefore influenced more by frequency than are regular verbs, which are generated by grammatical rules. For L2 morphological processing, Birdsong & Flege presented additional factors, namely, L1 influence and age of arrival, both of which interact with morphological regularity. Specifically, L1 morphological structures in L2 speakers influence their L2 morphological processing, and age at L2 acquisition inversely affects irregular verb processing, whereas regular verb processing is less sensitive to age at acquisition.

Comparing the input frequency effect on regular and irregular verb formation in L1 and L2 speakers of English, Beck (1997) also found evidence that different underlying mechanisms exist for processing regular and irregular past tenses. Her results showed the frequency effect only in irregular verb formation (for L1 speakers only but not for L2 speakers) and a significant "anti-frequency effect"[4] in regular verb formation in both L1 and L2 speakers (p. 105). In Beck's study, the L1 languages of the L2 speakers included Arabic, Bengali, Chinese, Czech, Farsi, French, German, Hungarian, Ibo, Indonesian, Italian, Japanese, Korean, Malay, Norwegian,

[4]According to Beck (p. 104), this was Pinker's term (personal communication, 1992). It refers to the condition that low frequency shows a faster reaction time than high frequency.

Russian, Spanish, Sri Lankan, Tamil, Thai, Turkish, and Urdu.

In contrast, Brovetto (2002) reported that L2 speakers of English (with Spanish and Chinese as their L1 languages) did not exhibit behavioral differences in their processing of regular and irregular verbs, but instead showed that the L2 speakers "exhibited signs of memory retrieval" (p. 334) for both types of verbs. From those findings, Brovetto argued in support of the declarative/procedural (D/P) model, which holds that L2 speakers "tend to rely on declarative memory for the computation of linguistic forms that are typically computed in the procedural system by native speakers" (p. 335), as the D/P model predicts for late L2 learners (Ullman, 2005).

Another behavioral study Basnight-Brown et al. (2007) found that L2 speakers of English (with Serbian and Chinese as L1 languages) showed more semantic "facilitation for regular as compared to irregular verbs," whereas the native speakers showed no facilitation for either regular or irregular verbs (p. 76). In addition, Basnight-Brown et al. found that, within the L2 speakers, the similarities (e.g., orthographic, phonological, and morphological similarities) between the L1 and the L2 influenced the semantic facilitation of irregular verbs (i.e., a robust facilitation was found in Serbian speakers, but no facilitation was found in Chinese speakers). The authors concluded that the L1 structures of the L2 speakers are important factors in L2 performance.

A recent behavioral study by Babcock et al. (2012) reported that, whereas both L1 and adult-learned L2 speakers (M of age of arrival = 27, range = 17-41) always stored English irregular past tense forms, they would either compose or store regular forms depending on a number of factors (i.e., gender, length of residency and age of arrival in the L2 environment). Specifically, the authors found that L2 regular forms were generally stored, that the length of residency was related negatively to reliance on mental storage but positively to reliance on composition, and that the age of arrival related positively to reliance on storage and negatively to reliance on composition[5]. In addition, L1 morphological structure did not affect L2 English past tense processing . Based on those findings, Babcock et al. concluded that L2 regular and irregular form processing "depend either on the same or on different mechanisms as in L1, and, crucially, this dependence varies as a function of multiple item- and subject-level factors" (p. 838).

Using fMRI scans from L2 Japanese speakers, Sakai et al. (2004) and Tatsuno & Sakai (2005) investigated the neural responses corresponding to the English past tense inflections. Both studies found that the neural activation was closely related to the left inferior frontal gyrus. Specifically, Tatsuno & Sakai reported that the contrast between irregular and regular past tense (i.e., IRREG>REG) resulted in an activated region in the left prefrontal gyrus ("BA 45/47," p. 1641), whereas there was no significant activation area found for the contrast between regular and irregular past tense (i.e., REG>IRREG).

Though behavioral studies in general present detailed findings on, for example, the L2 morphological processing of the English past tense, they provided little information pertinent to the development of a concrete model of morphological processing in the brain. In addition, because the two previous fMRI studies, Sakai et al. (2004) and Tatsuno & Sakai (2005), focused on learning aspects on particular regions of interest, they did not directly and specifically discuss the processing of regular and irregular past tense in L2 speakers of English. It is hoped, therefore, that the imaging data and analysis presented in this current study will help build our understanding of morphological processing in the brain.

[5]The gender differences they found are not addressed here because of their irrelevancy to the current study.

Note

An fMRI study by Yim et al. (2006) used both the terms *regular* and *irregular* for describing a Korean verbal unit, namely, *ecel*[6]. The authors noted that the unit ecel is "the specific spacing unit of a sentence which is a bigger than a word but smaller than a phrase" (p. 247) and that "irregularly inflected verbs are made by attaching an ending as regularly inflected verbs but slightly transformed based on phonological features" (p. 253). Thus, the terms *regular* and *irregular* are not used to indicate past tense verb types *per se* in Korean. Instead, the terms are phonological variations of Korean predicates (Ahn, 1985; Chang, personal communication, 2012; Choi, 2004; Doh, personal communication, 2012; and Sohn, 1999). The examples from Yim et al. (p. 248), illustrate this view:

/`mek-ta`/ 'eat'-decl.[7] → /`mek-ess-ta`/ 'eat'-past-decl.;

/`is-ta`/ 'connect'-decl. → /`i-ess-ta`/ 'connect'-past-decl.

While Yim et al. used these two items as regular and irregular past tense units, respectively, the same past tense morpheme `-ess` is attached to the stem verb in both cases, and a consonant deletion (*i.e.*, /`s`/ → ∅) is needed for the later one. For the reader reference, the following summarizes the types of such phonological variations in Korean predicates (see more examples in Sohn, 1999, p. 241, and in Yonsei[8], 1992, p. 233-235):

1. `s`-type: /`s`/ is deleted before a vowel (e.g., /`pus-ta`/ 'pour'-decl. → /`pu-ess-ta`/ 'pour'-past-decl., /`pu-ure`/ 'pour'-'in order to' ptcl.[9]; c.f., /`us-ta`/ 'laugh'-decl. → /`us-ess-ta`/ 'laugh'-past-decl., /`us-ure`/ 'laugh'-'in order to' ptcl.);

[6]The Yale romanization system was adopted for the Korean alphabet, Hankul. In Yim et al., the same verbal unit was expressed as *eojeol* for singular and *eojeols* for plural.
[7]Declarative marker.
[8]Refers to the textbook published by the Korean Language Institute at Yonsei University, Korea.
[9]Particle.

2. `t`-type: /`t`/ becomes /`l`/ before a vowel (e.g., /`ket-ta`/ 'walk'-decl. → /`kel-ess-ta`/ 'walk'-past-decl., /`kel-ure`/ 'walk'-'in order to' ptcl.; c.f., /`ket-ta`/ 'collect/uncover'-decl. → /`ket-ess-ta`/ 'collect/uncover'-past-decl., /`ket-ure`/ 'collect/uncover'-'in order to' ptcl.);

3. `h`-type: /`h`/ is deleted before a nasal or vowel (e.g., /`kuleh-ta`/ '(something/someone) is like that'-decl. → /`kule-(u)myen`/ '(something/someone) is like that'-'if' ptcl.; c.f., /`noh-ta`/ 'put'-decl. → /`noh-umyen`/ '(someone) put'-'if' ptcl.;

4. `l`-type: /`l`/ is deleted before /`n`/, /`p`/, /`s`/, and /`o`/ (e.g., /`el-ta`/ 'freeze'-decl. → /`e-nun`/ 'freezing'; c.f., /`el-ess-ta`/ 'freeze'-past-decl.);

5. `p`-type: /`p`/ becomes /`w`/ before a vowel (e.g., /`ship-ta`/ 'be easy'-decl. → /`shiw-ess-ta`/ 'be easy'-past-decl.; c.f., /`cep-ta`/ 'bend'-decl. → /`cep-ess-ta`/ 'bend'-past-decl.);

6. `u`-type: /`u`/ is deleted before a vowel (e.g., /`ssu-ta`/ 'write'-decl. → /`ss-ess-ta`/ 'write'-past-decl., /`ss-ela`/ 'write'-imperative ptcl.);

7. `lu`-type: /`lu`/ becomes /`ll`/ before /`e`/ or /`o`/ (e.g., /`kilu-ta`/ 'raise'-decl. → /`kill-ess-ta`/ 'raise'-past-decl., /`kill-ese`/ 'raise'-'by' ptcl.).

Note that those phonological variations are found not only with past tense but also with other suffixes. Therefore, the terms *regular* and *irregular* in Yim et al. should be regarded as phonological variations of Korean predicates, rather than as past tense types.

Chapter 2

Materials and Methods

The current study measured the neural response of Korean (L1) nonnative speakers of English (L2), with a focus on similarities and differences in the processing of English past tense verb form generation. The dependent variable was the fMRI blood oxygenation level dependent signal (BOLD), and the independent variable was the verb type (i.e., regular versus irregular past tense forms). An event-related design was adopted for a pseudorandom presentation of stimuli type (i.e., regular, irregular, and fixation) to prevent strategy effects caused by a blocked design (e.g., Beretta et al., 2003; Sahin et al., 2006; and Tyler et al., 2005)[1]. The study employed a modified version of the method used in Beretta et al. (2003), De Diego Balaguer et al. (2006), and Schnyer (2007). The subjects, procedure and task, MRI acquisition, and data analysis are described below.

2.1 Subjects

Sixteen right-handed, healthy Korean L2 speakers of English aged between 19 and 33 (mean age (M) = 23.96, standard deviation (SD) = 4.56) participated in

[1]Under a blocked design, participants can easily notice that trial blocks are divided by regular or irregular verbs; hence, they may tend to generate regular verbs out of habit.

the fMRI experiment. They were all male students and/or staff at The University of Texas at Austin (UT Austin), had normal or corrected-to-normal vision, and had no psychological and neurological history of impairment. The age at which the subjects had started to acquire[2] English ranged from 1 year old to 14 years (M = 8.38, SD = 3.84). Each subject was instructed to refrain from alcohol and caffeine beverages beginning the day before the experiment, and they were paid a total of $40[3] monetary compensation for their participation. All provided a written consent form, which was approved by the Institutional Review Board of UT Austin (Study Number 2012-03-0034).

Subject recruitment and selection were guided by the following criteria. Based on statistical methods exemplified in previous fMRI research (e.g., Desmond & Glover, 2002; Friston et al., 1999a & 1999; Lehr, 1992; and Murphy & Garavan, 2004), a minimal sample size of 16 subjects was set for one group. To maintain some minimal equivalence in intelligence and cognitive level across subjects, recruitment was restricted to students and staff at UT Austin. Contacts were made via group email invitations or emails to specific referrals.

Candidate participants first completed a secure online prescreening survey using REDCap[4] electronic data capture tools hosted at UT Austin (`https://redcap.prc.utexas.edu/redcap/surveys/index.php?s=o8dctF`; see Appendix A for details) establishing age, gender, handedness, L1 type, minimum English proficiency level, medical history/condition (including susceptibility to claustrophobia), and contraindications for MRI. The rationale for those criteria is the following. First, participation in the study was restricted to subjects from 18 to 35 years old. This age restriction enabled the comparison of the findings with those of a previous study by the author (Kim, 2008) that took into consideration the factor of brain-volume

[2] Including informal settings where instructions/conversations were given in English (e.g., attending a preschool, born in the United States, etc.).
[3] $10 for the pre-behavioral task, and $30 for the fMRI task.
[4] Research Electronic Data Capture.

differences by age (Salat et al., 2004). Second, to avoid possible gender-based differences in brain responses (e.g., Baxter et al., 2003; Buckner et al., 1995; Kansaku et al., 2000; Shaywitz et al., 1995; Ullman, 2005; and Babcock et al., 2012), subjects were chosen from only one gender group, male (Anderson & Lightfoot, 2002). Third, to avoid differences based on handedness (e.g., Herron, 1980; McManus, 2002; and Springer & Deutsch, 1981), only right-handed candidates were chosen. Fourth, highly proficient English L2 speakers were preferred in order to avoid factors that may confound the subjects' cognitive processes and to increase the volume size of imaging data. To reduce the rate of English errors during the performance of their experimental tasks, candidates who were taking courses in English as a second language were excluded. Fifth, candidates who had any of the following conditions were excluded: metal implants; history of significant medical illness; history of head trauma; permanent retainer or braces; any types of metal implants; history of major psychotic disorders; history of substance dependence; history of drug or alcohol abuse; any history of breathing problem or motion disorder, claustrophobia, and anemia.

Thirty-five candidates whose responses in the prescreening survey were satisfactory were given a pre-behavioral task to test their oral and written English for accuracy in the use of the English past tense. Of the candidates who scored 90% or higher, the top 16 were chosen for the imaging study. The following is the description of the pre-behavioral task, and Table 2.1 shows the demographics for the sixteen subjects[5]: The pre-behavioral task consisted of both oral and written subtasks in which the candidate subjects were presented with a list of English verbs. The list was identical to that of the actual behavioral task, except for the number (the list for the behavioral task was four words shorter (8 words total as they were repeated)) and the order (the order was different from that of the behavioral task).

[5] AoA stands for Age of Acquisition; Place for the place that subjects began learning English; and Native L2 Teacher for whether their first English teacher was a native speaker of English.

Table 2.1: Subjects' Demographics

Subject	Age	AoA	Place	Native L2 Teacher
1	30.5	14	Korea	No
2	20.1	11	USA	Yes
3	25.2	1	Canada	Yes
4	21.6	8	Korea	No
5	20.3	5	Korea	Not recall
6	20.8	12	Korea	No
7	22.7	11	USA	Yes
8	20	6	UK	Yes
9	20.7	12	Australia	Yes
10	22.9	8	Korea	No
11	30.2	3	Canada	Yes
12	23.1	12	Korea	No
13	19.1	9	Korea	No
14	30.4	11	Korea	No
15	33.4	3	USA	Yes
16	22.5	8	UK	Yes
M	23.97	8.38		
SD	4.57	3.84		

The pre-behavioral task was conducted at the Phonetics Laboratory in the Department of Linguistics at UT Austin, and a total of 35 subjects participated in the task individually. Using DMDX, the stimuli were presented visually on a Macintosh laptop[6], and the subjects verbal responses were recorded using Audacity (Version 2.0.0.) and a MOTU microphone system. After the verbal response task, the subjects were asked to provide written responses for the same stimuli. Overall, their written responses showed higher accuracy than did their verbal responses, mainly because the candidates were given more time for their written responses.

[6]Window-based DMDX was operated on the laptop by a boot camp function on the Macintosh computer.

2.2 Procedure and Task

All subjects underwent an MRI scan. Prior to entering the scan room, the subjects were offered MR-compatible glasses if needed. Before the scan began, all subjects were asked whether they could clearly read the instruction on the screen.

During the scan, the subjects were presented a sequence of English verbs in their nonfinite forms. Upon seeing a given verb, they were asked to covertly generate the proper past tense form of that verb, and then to lie quietly until the next verb, or stimulus, appeared. The design of this silent, internal word generation task minimized head movement, which would have introduced artifacts into the neuroimaging data (e.g., Cabeza & Kingston, 2006; Huettel et al., 2004; Jezzard et al, 2001; and Kim et al., 1997). As Bookheimer (2002) and others (e.g., Barch et al., 1999; Birn et al., 1999; Palmer et al., 2001; and Wildgruber et al., 1996) reported that silent tasks were compatible with overt tasks, and that "studies comparing overt and covert speech have found differences represented primarily in magnitude of fMRI activation rather than in location, with the exception of motor areas (Palmer et al. 2001)" (p. 157). Stimuli were presented visually to prevent the subjects from mistaking any given word with a possible homonym, and, unlike for auditory stimuli, the reception of visual stimuli would not be compromised by the "masking influence of acoustic scanner noise" (Jäncke et al., 1998, p. 881; and Scarff et al., 2004). Moreover, the study employed no simultaneous behavioral task during the scan that could constitute other types of decision-making processes (e.g., a word choice), motor movement and tactile perception (e.g., pressing a button), or additional cognitive processes (Pinker, 1994). The study was thus able to collect neural responses associated strictly with the processing of morphological regularity, which can be regarded as a simple cognitive processing task that be achieved within a relatively short period. Because the task was identical to the pre-behavioral task, all subjects were already familiar with the general format of the task during the scan. The only differences from the pre-behavioral task were that the response type changed (from spoken to silent response), the order of stimuli changed, and the number of stimuli increased from 220 to 228[7]. Immediately after the scan, the subjects were asked to write down the past tense form of each test item as quickly as possible. The imaging data corresponding to incorrect response items were treated as dummy explanatory variables (i.e., separate regressors), and no contrasts were created in the imaging data analysis.

Stimuli

- Database: To compare the findings with those from previous past tense imaging studies, the author selected stimuli partially from Allen & Badecker (2002), Bird et al. (2003), Desai et al. (2006), Jaeger et al. (1996), Kielar (2008), Lavric et al. (2001), Newman et al. (2007), Okrent (2004), Stockall & Marantz (2006), Ullman (1999), and Waldron (2010)[8].

- Type: Stimuli were the nonfinite forms of regular and irregular English verbs, as well as fixation null stimuli (+) (see Appendix B for the lists).

- Number: Two sets of regular and irregular verbs were repeated twice (i.e., 2 x (114 x 2))[9]. Thus, a total of 456 (228 x 2) verb stimuli was presented, along with an additional 50% jittered null stimuli (a total of 4 runs; each run consisting of 57 regular and 57 irregular verbs[10]. The interleaved stimulus

[7]Which were matched for frequency levels between 220 and 228.

[8]To integrate the strength of each other study in its choice of stimuli words, the current study did not choose a list of words from one single study. If it had, the results would have directly been comparable.

[9] While some repetition effect might have occurred, the author believes that, because the stimuli were language data, the possible effect would not be significant. Consequently, it was possible to increase scan time for the rapid event-related fMRI task, which could otherwise be susceptible to signal-to-noise ratio (personal communication with Buckner, McCarthy, Ress, Schnyer, and Sussman, 2008 & 2012).

[10]As the verb *fit* has two past tense forms (i.e., *fit* and *fitted*), responses for this verb were excluded just as was done to incorrect responses.

presentation (i.e., jittered) was used to improve the temporal resolution of the event-related fMRI data (Song et al., 2006).

- Frequency Control: Of the several approaches to frequency control (e.g., Davies & Gardner, 2010; Francis & Kučra, 1982; Leech et al., 2001; and Medler & Binder, 2005), the current study employed the MCWord[11] method of Medler & Binder to determine the frequency of each stimulus item (available at `http://www.neuro.mcw.edu/mcword/`). To balance the frequency level within a run (i.e., between regular and irregular verb types) as well as across runs, two sets of stimuli (In Set 1, REG and IRREG: t=-.031, df=112, p=.975; In Set 2, REG and IRREG: t=-.208, df=112, p=.836) were created by using ANOVA (F (1, 12)=.00, p=.9949)[12]. Accordingly, all runs had very similar frequency levels, as seen in Table B1 through B4 in Appendix B. Note that, according to the author's previous study, input frequency (i.e., the frequency of orthographic form of stimuli), rather than the corresponding past tense frequency, had a strong effect on the subjects' accuracy rates. Thus, the frequency of stimuli was matched on the nonfinite verb form.

- Presentation and Duration: For the event-related experiment, stimuli were organized in pseudorandom order generated by optseq2[13]. Each stimulus was visually presented for 2059.96 milliseconds (msec) in lowercase white letters in Arial font (font size 79) on a black background. A DMDX display software package[14] was used on a Macintosh laptop, as seen in Figure 2.1. The spatial resolution of the screen was 1024 x 768 pixels, and the refresh rate was 16.48 ms. The stimuli were projected onto a screen located at the rear of the scanner, and a mirror, which was attached on the top of the head coil, was positioned

[11] The database is the CELEX efw.cd file. See details at `http://www.neuro.mcw.edu/mcword/`.
[12] The number of irregular past tense verbs was the limiting factor.
[13] `http://surfer.nmr.mgh.harvard.edu/optseq/`.
[14] Available at `http://www.u.arizona.edu/ kforster/dmdx/dmdx.htm`.

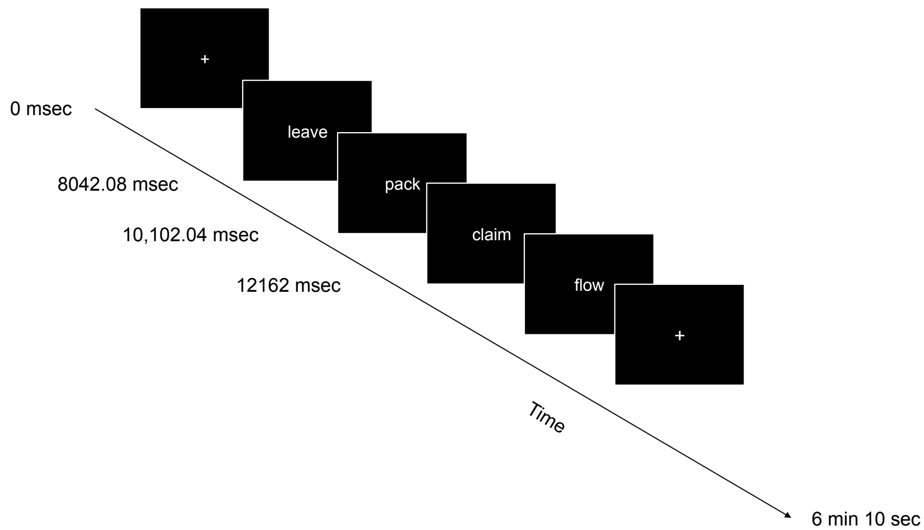


Figure 2.1: Time series of stimuli presentation

at an angle to give the subject lying inside the bore of the scanner a clear view of the screen. All subjects except one[15] participated in the four experimental runs that produced the data. Each run began with a fixation null stimulus lasting ≈ 8042.08 msec, followed by a verb stimulus for ≈ 2059.96 msec, which in turn was replaced by another ≈ 2059.96 msec verb stimulus or a $\approx 2059.96-$, $\approx 4037.52-$, or $\approx 6048.04-$ msec fixation null stimulus. The verb stimuli in each run consisted of 57 regular and 57 irregular verbs presented in random

[15]This subject was engaged in three runs.

order[16]. Each run took 6 minutes 16 seconds, which included the 6-second reference time generated by the Siemens scanner, and 5 volumes added at the end of the run to accommodate the delayed rise of the hemodynamic response. The total scanning operation for each participant lasted about an hour, which included preparation time, about 30 minutes of functional scanning, about 7 minutes of anatomical structural scan acquisition (including 13 seconds of localizer and 14 seconds of AAScout[17] scans[18]), and a brief break after each run. The presentation and timing of the stimuli were controlled by the DMDX program (Forster & Forster, 1990).

2.3 MRI Data Acquisition

Brain images were taken with a Siemens Magnetom Skyra 3.0 Tesla scanner with a 32-channel head coil in the Imaging Research Center at UT Austin. Foam padding was used to minimize the subjects head movement. To acquire T_2*-weighted[19] functional images, a multiecho GRAPPA[20] parallel imaging EPI[21] sequence was used to reduce the level of distortion typically associated with EPI scans. Functional EPI images were collected by using whole head coverage with slice orientation to reduce frontal artifacts (approximately 20 degrees off the Anterior Commissure-the Posterior Commissure (AC-PC) plane) with the following protocol: repetition time (TR)=2.000 msec., single shot, echo time (TE) = 30 msec., 45 interleaved axial slices[22], matrix size=72 x 72, field of views (FOV)=216, slice thickness=3.0 mm, acquisition voxel size=3.0 x 3.0 x 3.0 mm with a 0.3 mm inter-slice

[16] All participants were presented with the same order of randomized stimuli.
[17] AutoAlignment.
[18] Localizer information only was used for two participants with large heads.
[19] "Transverse decay time constant including magnetic field inhomogeneity effect" (Jezzard et al., 2001, p. xiii).
[20] "The generalized autocalibrating partially parallel acquisitions" (Heidemann, 2006, p. 317).
[21] "Echo-planar imaging" (Jezzard et al., 2001, p. xi).
[22] Oriented for best whole head coverage.

gap[23], flip angle= $90°$, and phase encoding direction = A/P[24]. In each run, a total of 185 EPI volumes were acquired, and the first four volumes (i.e., 8042.08 msec for the fixation null stimulus) of the time series were discarded. In addition to the EPI images during task performance, one high resolution T_1-weighted MPRAGE[25] image was taken using the T_1-weighted protocol to locate and orient the functional EPI images: TR=2530.0 msec., single shot, TE=3.37 msec., sagittal plane, matrix size=256 x 256, FOV=256, slice thickness=1.0 mm, acquisition voxel size=1.0 x 1.0 x 1.0 mm with a 0.5 mm inter-slice gap, and flip angle=$7°$.

2.4 Data Analysis

To detect the neural responses of regular and irregular past tense verb generation, a whole brain analysis was done by using the fMRI Expert Analysis Tool (FEAT) Version 5.98, which was part of FSL (FMRIBs Software Library, `http://www.fmrib.ox.ac.uk/fsl/`). In the pre-statistical process, motion correction was carried out with MCFLIRT[26] to remove the effect of subject head movement. Slice timing correction was chosen for the interleaved acquisition to adjust each voxels time series. Spatial smoothing using a Gaussian kernel of FWHM[27] 5 mm was done to reduce noise without reducing valid activation.

Finally, temporal filtering with high pass filtering was set to a 90 Hz cutoff[28] in order to remove low frequency artifacts. In the statistical process, prewhitening was done to ensure that the statistics were valid and maximally efficient. Specifically, data were "prewhitened before event-related responses were estimated using event-related convolution with an ideal hemodynamic response represented" by a

[23]Distance Factor (10% of slice thickness).
[24]Anterior to posterior.
[25]Magnetization Prepared RApid Gradient Echo.
[26]FMRIB's liner image registration tool for head motion correction.
[27]Full-width-half-maximum.
[28]Chosen by using the cutoffcalc command in FSL. This calculates the minimal period for the highpass filter that still preserves a specified amount of variance in all the design matrix regressors.

chosen gamma function and its temporal derivative (Saggar et al., 2008, p. 2312).

Data from each subject was modeled using the General Linear Model (GLM). The statistical analysis of activation images focused on determining whether there was a contrast in the way Korean L2 speakers of English generated regular and irregular past tense verbs. Two stimulus types were set as explanatory variables (EVs): regular verb (REG) and irregular verb (IRREG). In particular, REG>IRREG contrast was modeled to show areas that were activated when regular past tense generation showed a better fit under the model set than did irregular past tense generation. The IRREG>REG was modeled to show areas that were activated when irregular past-tense generation showed a better fit under the model set than did regular past-tense generation. For each EV, a double-gamma hemodynamic response function was chosen to model the late undershoot as well. A temporal derivative was added to reduce unexplained noise, which could result in an increase in statistical significance, and temporal filtering was applied to the data as it was in the pre-statistical process since the model was designed to look like the data. On the other hand, in order to nullify the effects of timepoints from subjects' incorrect responses, dummy EVs were set with only temporal filtering applied. That approach allowed different response levels (i.e., potentially different amplitudes) to be modeled (Jenkinson & McCaren, personal communication, 2012).

In the post-statistical process, to handle the problem of multiple comparisons (i.e., to reduce the number of false positives), Z (Gaussianised T[29]) statistic images were thresholded using clusters determined by Z>2.3 and a corrected cluster significance threshold of p=.05 (Worsley, 2001). Contrast masking (Z>0) was also chosen so that the generated masks could be derived from all positive Z statistic voxels in the mask contrasts, thus avoiding the inclusion of apparently "positive" voxels resulting from differential contrasts[30].

[29]Gaussian random field theory was used to threshold the image.

[30]If both EVs were negative, the contrast could be positive.

In the registration process, a subject's low resolution functional image was first registered to his high resolution structural image by using normal search with 7 degrees of freedom (dof). The image was then registered to the standard brain image (i.e., the MNI[31] avg152 T_1-weighted template) using normal search with 12 dof.

The data from each run was given a first-level analysis. High-level (i.e., second level) analyses were then carried out that combined the results of the first-level analyses and were completed by using the fixed effects within a single subject. Finally, high level (i.e., a third level) analyses were completed by using FLAME1 (i.e., FMRIBs Local Analysis of Mixed Effects) across subjects (as one group). In this process, an automatic outlier de-weighting function was used to detect outlier datapoints.

The result cluster lists from the analysis in MNI space were first converted into Talairach coordinates by using GingerALE (Version 2.1.1). This transformed data were then searched for coordinates within a standardized Talairach space (i.e., Talairach atlas (Talairach & Tournoux, 1988)) as implemented by the Talairach Daemon (Lancaster et al., 2000; `http://www.ric.uthscsa.edu/projects/talairachdaemon.html`) to obtain Brodmann areas. In addition, the Duvernoy (1991) atlas and the Mai et al. (2004) atlas as well as the following FSL atlas tools were consulted: Harvard-Oxford cortical and subcortical structural atlases, Jülich histological (cyto- and myelo-architectonic) atlas, JHU DTI-based white-matter atlases, Oxford thalamic connectivity atlas, MNI structural atlas, and Probabilistic cerebellar atlas.

[31]Montreal Neurological Institute.

Chapter 3

Results

3.1 Imaging Results

The main results obtained in this study are the following:

1. Overall, irregular past tense processing evoked much greater activation than did regular past tense processing in terms of the extent of the affected brain and activation amplitude;

2. Regular and irregular processing engaged notably different cortical areas;

3. Regular processing predominantly engaged the right hemisphere, while irregular processing elicited bilateral activity, except for processing in the cerebellum;

4. Activity in the right cerebellum was associated almost exclusively to irregular processing;

5. Activity for regular processing was selectively associated with the activation of the temporal lobe and the occipital lobe, whereas irregular processing was extensively linked to the parietal lobe, the cerebellum, and the subcortical areas;

6. Regular processing was found more in the medial gyrus, the middle gyrus, the posterior gyrus, and the superior gyrus, whereas irregular processing was found more in the inferior gyrus and subcortical areas;

7. Regions in the anterior cingulate cortex and the medial frontal gyrus in the right hemisphere, the left precuneus, and the cingulate gyri bilateral were common areas for both regular and irregular processing.

Tables 3.1 through 3.5 list the brain locations of the activated clusters. Figures 3.1 through 3.4 display the spatial patterns in the results from L2 speakers (Cross hairs indicate the focal areas). As stated in the Data Analysis section, the voxels that were more relevant to given contrasts (i.e., REG>IRREG and IRREG>REG) were the clusters (colored) that exceeded the threshold Z>2.3 and had a corrected cluster significance threshold of p=.05, which were overlaid on the L2 speaker subjects' mean structural images.

Table 3.1: Significant Activation Clusters & Brain Regions for L2 REG>IRREG

Anatomical region	Voxels	Z-maximum	Hemisphere	x	y	z	Brodmann area
Cluster 4	1690						
Medial Frontal Gyrus		3.96	Right	2	56	-2	BA 10
Anterior Cingulate		3.56	Right	6	52	-10	BA 32
Anterior Cingulate		3.29	Right	4	50	2	BA 32
Medial Frontal Gyrus		3.2	Right	10	46	10	BA 9
Medial Frontal Gyrus		3.19	Left	-6	50	-18	BA 10
Medial Frontal Gyrus		3.17	Left	0	52	-18	BA 10
Cluster 3	1638						
Posterior Cingulate		3.59	Right	4	-48	26	BA 23
Cingulate Gyrus		3.53	Left	-2	-46	42	BA 31
Cingulate Gyrus		3.46	Right	16	-36	38	BA 31
Precuneus		3.42	Left	2	-52	56	BA 7
Posterior Cingulate		3.36	Right	6	-58	14	BA 29
Posterior Cingulate		3.34	Right	8	-56	20	BA 23

Table 3.2: Significant Activation Clusters & Brain Regions for L2 REG>IRREG (*cont.*)

Anatomical region	Voxels	Z-maximum	Hemisphere	x	y	z	Brodmann area
Cluster 2	892						
Lingual Gyrus		3.37	Right	10	-96	0	BA 17
Culmen		3.25	Right	10	-70	-6	∗(*not applicable*)
Lingual Gyrus		3.17	Right	20	-94	6	BA 17
Lingual Gyrus		3.16	Right	12	-76	-4	BA 18
Cuneus		3.16	Right	14	-92	28	BA 19
Middle Occipital Gyrus		3.12	Right	14	-94	20	BA 18
Cluster 1	815						
Middle Temporal Gyrus		4.03	Right	50	-68	24	BA 39
Middle Temporal Gyrus		3.9	Right	52	-68	30	BA 39
Superior Temporal Gyrus		3.34	Right	54	-60	22	BA 39
Superior Temporal Gyrus		3.3	Right	58	-58	16	BA 22
Superior Temporal Gyrus		3.14	Right	60	-52	12	BA 22

Table 3.3: Significant Activation Clusters & Brain Regions for L2 IRREG>REG

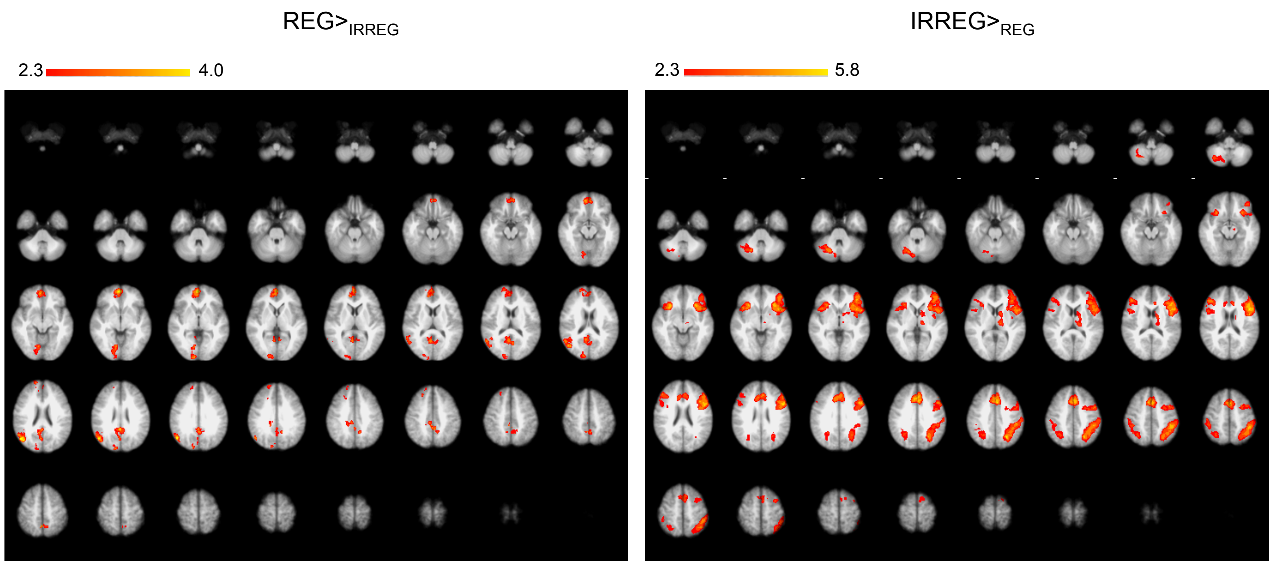
Anatomical region	Voxels	Z-maximum	Hemisphere	x	y	z	Brodmann area
Cluster 7	6541						
Inferior Frontal Gyrus		5.33	Left	-48	16	20	BA 9
Inferior Frontal Gyrus		5.3	Left	-50	12	28	BA 9
Middle Frontal Gyrus		5.15	Left	-44	22	20	BA 46
Inferior Frontal Gyrus		5.04	Left	-54	16	16	BA 45
Claustrum		4.91	Left	-30	24	-6	∗
Middle Frontal Gyrus		4.84	Left	-46	28	16	BA 46
Cluster 6	3499						
Inferior Parietal Lobule		5.89	Left	-50	-36	46	BA 40
Precuneus		5.69	Left	-26	-64	40	BA 7
Inferior Parietal Lobule		5.36	Left	-48	-34	40	BA 40
Inferior Parietal Lobule		4.94	Left	-46	-42	54	BA 40
Inferior Parietal Lobule		4.86	Left	-48	-42	50	BA 40
Superior Parietal Lobule		4.84	Left	-38	-58	58	BA 7
Cluster 5	2363						
Cingulate Gyrus		5.3	Left	-4	16	42	BA 32
Superior Frontal Gyrus		5.02	Left	0	12	50	BA 6
Cingulate Gyrus		4.93	Left	0	26	38	BA 32
Medial Frontal Gyrus		4.81	Right	6	16	44	BA 6
Cingulate Gyrus		4.75	Right	6	24	34	BA 32
Anterior Cingulate		3.68	Right	12	26	22	BA 24

Table 3.4: Significant Activation Clusters & Brain Regions for L2 IRREG>REG (*cont.*)

Anatomical region	Voxels	Z-maximum	Hemisphere	x	y	z	Brodmann area
Cluster 4	1936						
Claustrum		5.2	Right	30	24	-6	*
Middle Frontal Gyrus		4.59	Right	46	36	18	BA 46
Insula		4.22	Right	40	16	-2	*
Inferior Frontal Gyrus		3.28	Right	54	22	24	BA 9
Inferior Frontal Gyrus		3.27	Right	52	10	26	BA 9
Cluster 3	1228						
Inferior Parietal Lobule		3.77	Right	44	-36	46	BA 40
Superior Parietal Lobule		3.52	Right	34	-60	50	BA 7
Inferior Parietal Lobule		3.5	Right	52	-26	50	BA 40
Inferior Parietal Lobule		3.48	Right	48	-36	52	BA 40
Inferior Parietal Lobule		3.47	Right	28	-56	34	BA 40

Table 3.5: Significant Activation Clusters & Brain Regions for L2 IRREG>REG (*cont.*)

Anatomical region	Voxels	Z-maximum	Hemisphere	x	y	z	Brodmann area
Cluster 2	945						
Cerebellar Tonsil		4.4	Right Cerebellum	24	-66	-34	*
Inferior Semi-Lunar Lobule		3.58	Right Cerebellum	36	-68	-44	*
Cerebellar Tonsil		3.55	Right Cerebellum	22	-66	-48	*
Inferior Semi-Lunar Lobule		3.42	Right Cerebellum	28	-70	-4	*
Inferior Semi-Lunar Lobule		3.39	Right Cerebellum	20	-72	-46	*
Cluster 1	602						
Thalamus		3.89	Left	-12	-18	10	*
Caudate		3.57	Left	-14	-2	16	*
Lentiform Nucleus		3.39	Left	-14	2	8	*
Caudate		3.31	Left	-12	6	8	*
Lentiform Nucleus		3.19	Left	-10	4	2	*
Lentiform Nucleus		2.59	Left	-22	8	0	*



*Note: Images are presented in the radiological convention: the left side of the picture represents the right hemisphere.

Figure 3.1: Results for L2 REG>IRREG & IRREG>REG

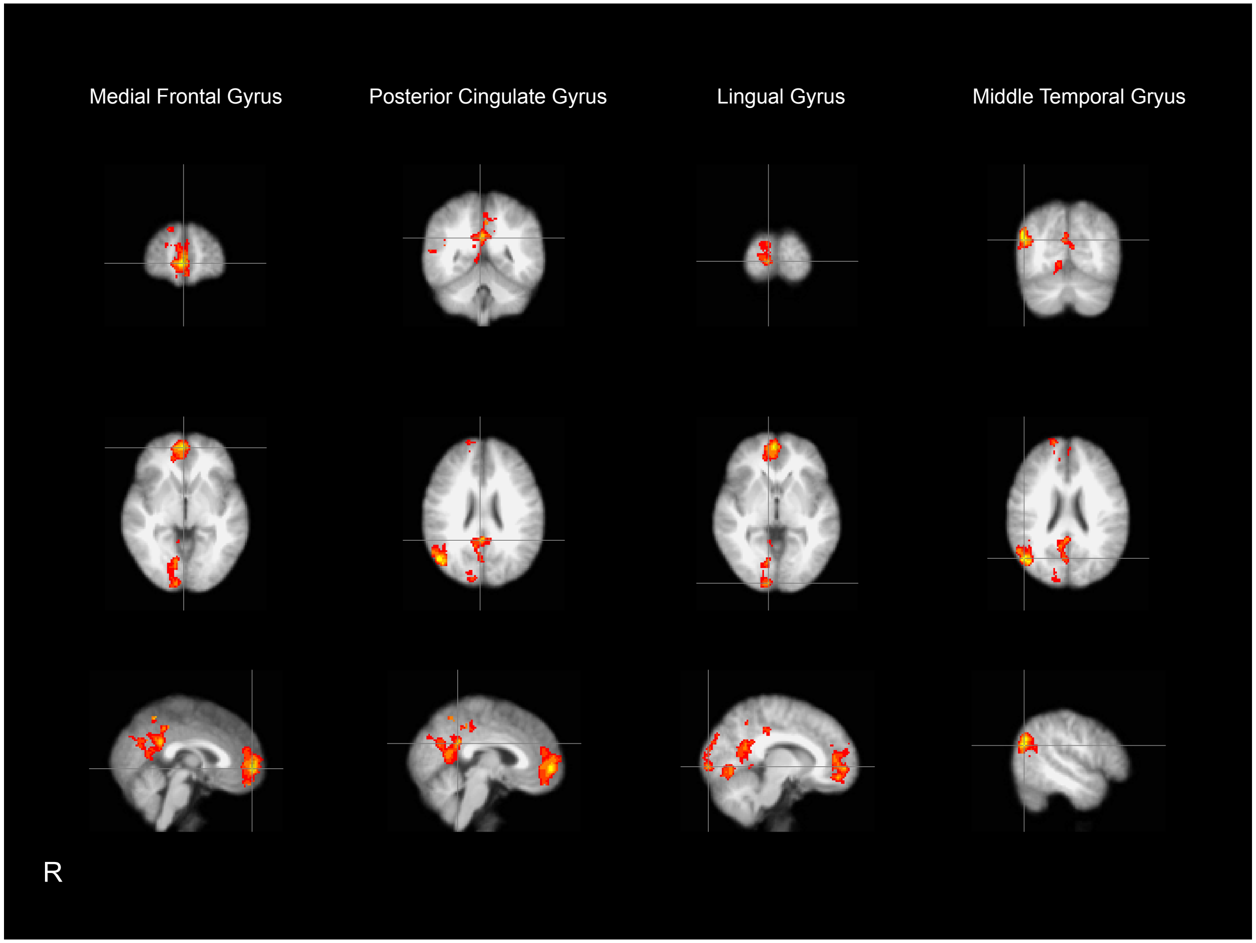


Figure 3.2: Significant Brain Regions for L2 REG>IRREG

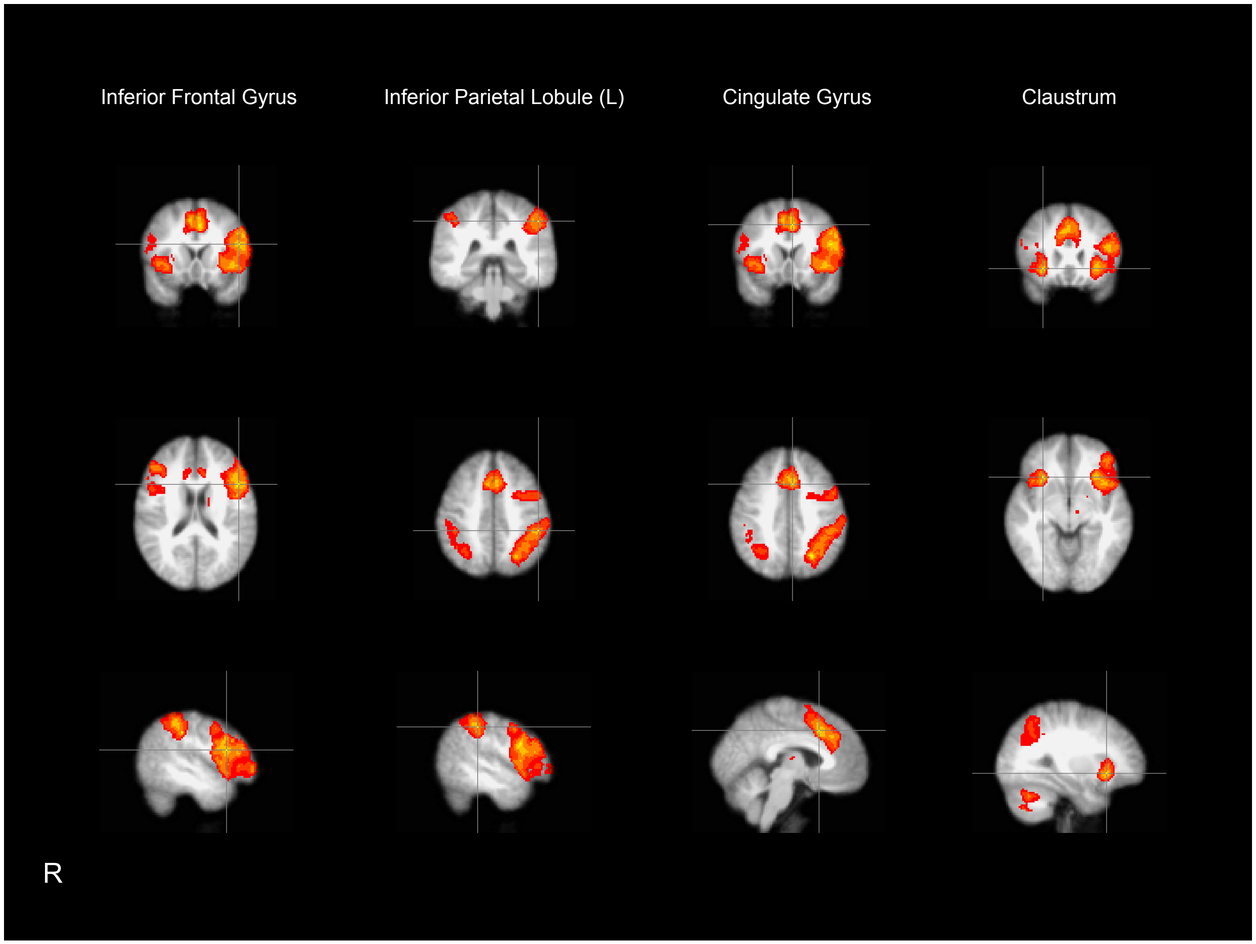


Figure 3.3: Significant Brain Regions for L2 IRREG>REG

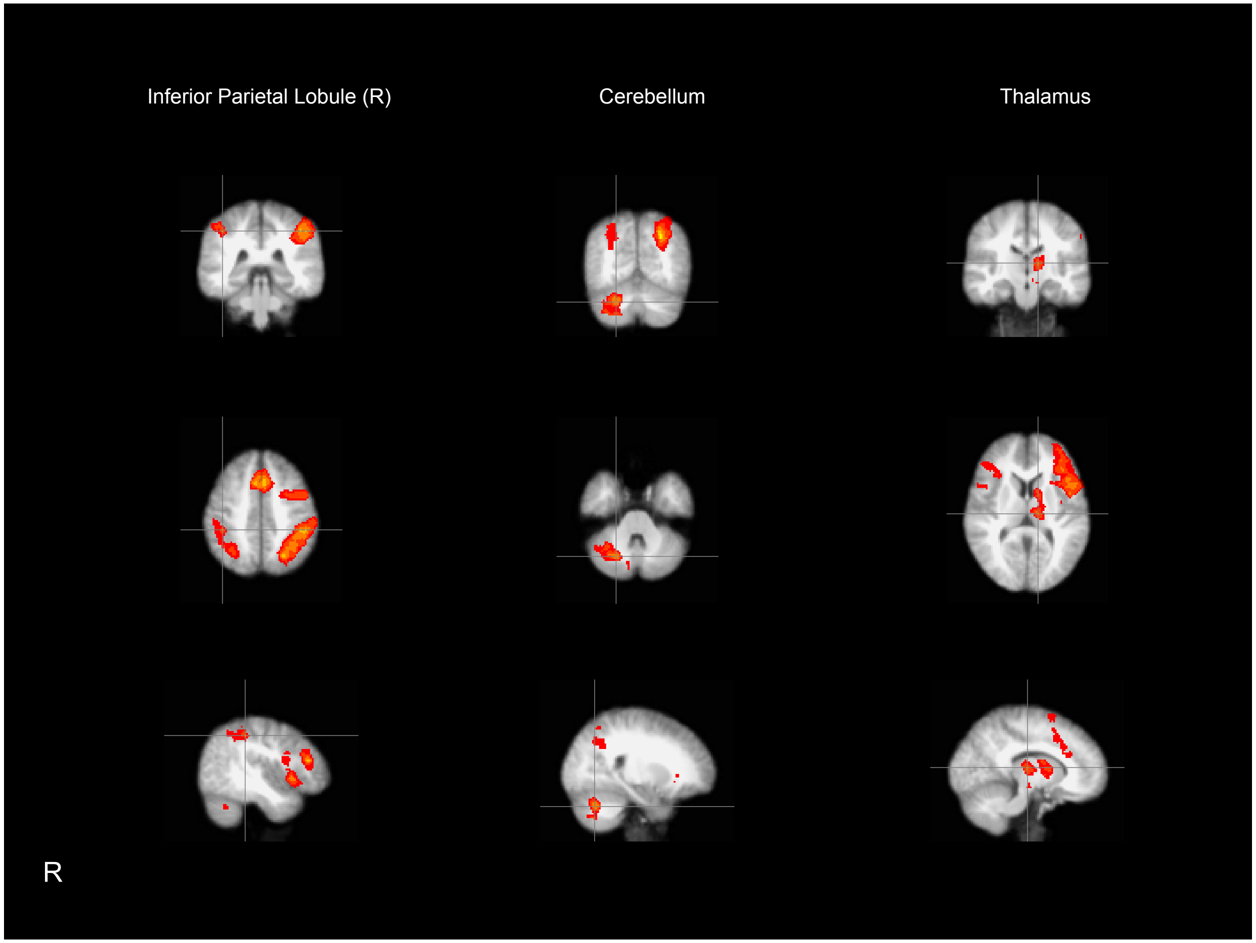


Figure 3.4: Significant Brain Regions for L2 IRREG>REG (*cont.*)

Consistent with previously reported results for L1 speakers (e.g., Jaeger et al. 1996; Ullman et al., 1997a; Beretta et al., 2003; Balaguer et al., 2006; Oh et al., 2012; and Tyler et al., 2005), the present study showed that, for L2 speakers, irregular past tense generation elicited higher neural activation and substantially larger neural clusters bilaterally than did regular past tense generation. Specifically, as illustrated in Tables 3.3 through 3.5, seven statistically significant clusters emerged in which greater activation appeared during irregular verb processing than during regular verb processing. Those areas are the inferior frontal gyrus, the middle frontal gyrus, the inferior parietal lobule (i.e., the supramarginal gyrus), and the superior parietal lobule bilaterally; the anterior cingulate cortex, (the medial frontal gyrus), the insula, and the cerebellum in the right hemisphere; the precuneus in the left hemisphere; the superior frontal gyrus, the claustrum, and the subcortical areas of the caudate, the lentiform nucleus, and the thalamus, all in the left hemisphere. Of those seven clusters, the peak intensity was found in the inferior parietal lobule in the left hemisphere.

Four clusters were more strongly activated for regular past tense generation than for irregular past tense generation in L2 speakers. The activated regions showing that contrast were the medial frontal gyrus in bilateral; the precuneus in the left hemisphere; the anterior cingulate gyrus, the posterior cingulate gyrus, the cuneus, the lingual gyrus, the middle occipital gyrus, the middle temporal gyrus, and the superior temporal gyrus in the right hemisphere; and the culmen in the right cerebellum. Of those four regions, the peak intensity occurred in the middle temporal gyrus in the right hemisphere.

In Figures 3.1 through 3.4, the thresholded Z "values describe how strongly each voxel is related to each EV" (Smith, 2001, p. 219). For example, a Z value of 5.89, as seen in the L2 IRREG>REG contrast (in Figure 3.1), is a standard deviation of 5.89 away from zero. As stated earlier, Z statistic maps were thresholded at

$Z>2.3$, and significant clusters were determined with a threshold of $p=.05$.

3.2 Behavioral Results

Tables 3.6 through 3.9, and Figure 3.5 show the results from the subjects written responses immediately after scanning. The purpose of the written task was to ensure that the subjects could generate the proper past tense forms. Because the stimuli in four runs consisted of two sets of identical verbs listed in different order, one set (i.e., runs 1 and 2) of the stimuli verbs were checked. Each timepoint corresponding to an incorrect response was set as a separate EV of no interest under the GLM model, with only temporal filtering applied (i.e., no double gamma convolution and temporal derivative were applied), and was excluded from the imaging analysis (i.e., the contrasts). That procedure effectively removed all signals related to those timepoints and prevented the introduction of unknown effects that could occur if those timepoints in the data had been simply ignored (Jenkins, 2006). Thus, the analysis was able to isolate activation associated solely with correct responses of regular and irregular past tense generation.

An ANOVA and T tests indicated that there was a significant effect in regularity with respect to accuracy and verb type: REG and IRREG, $F\ (1, 30) = 34.49$, $p<.001$; In Set 1, REG and IRREG: $t=2.585$, $df=93.365$, $p<.05$; In Set 2, REG and IRREG: $t=4.311$, $df=56$, $p<.05$).

Table 3.6: Verb Type & Error Rate in Set 1

	REG	*frequency*	*Error%*	IRREG	*frequency*	*Error%*
1	flop	2.67717	0	sling	2.97464	31.25
2	blink	3.86703	0	fling	4.04551	6.25
3	skip	4.46196	0	bind	4.81891	37.50
4	mend	4.81891	12.50	grind	5.7708	56.25
5	shave	6.36572	18.75	spit	6.18725	37.50
6	clutch	6.66319	0	weep	6.90116	0
7	flush	8.62645	0	creep	8.68594	25.00
8	snap	8.92391	0	freeze	8.74544	6.25
9	grab	11.1251	0	breed	11.7796	12.50
10	hire	14.4567	0	slide	14.3972	50.00
11	float	17.4314	0	bid	14.9327	43.75
12	stare	19.0972	0	swear	15.2301	0
13	knock	20.525	0	tear	18.7402	6.25
14	lock	20.763	0	bend	21.1794	0
15	solve	22.3693	0	sing	22.8452	0
16	load	24.1541	0	shoot	24.392	12.50
17	pack	27.3072	0	bet	25.2249	0
18	hook	32.1856	0	awake	25.9388	0
19	arrive	35.2197	0	wake	32.84	0
20	fill	39.7412	0	ride	36.1716	0
21	flow	41.9424	62.50	blow	41.5854	0
22	raise	45.9284	6.25	seek	45.2145	31.25
23	laugh	51.5207	0	sell	52.2346	0
24	cry	52.5321	0	fly	52.9486	12.50
25	vote	52.8891	0	feed	53.722	0
26	taste	58.7788	0	hurt	57.4105	12.50
27	snow	60.0282	6.25	draw	58.7194	0
28	pick	63.8952	0	choose	63.0623	0
29	pull	68.0597	0	shut	66.9294	6.25
30	fit	70.9154	0	build	71.1533	0
31	plant	73.1166	0	catch	72.1647	18.75
32	charge	75.5558	0	strike	78.114	18.75
33	test	79.4228	0	send	78.2925	0
34	count	80.7912	0	spend	82.338	0
35	dry	92.9872	0	drive	90.4885	0

Table 3.7: Verb Type & Error Rate in Set 1 (*cont.*)

	REG	*frequency*	*Error%*	IRREG	*frequency*	*Error%*
36	smile	98.5795	0	grow	95.4264	0
37	plan	100.364	0	break	103.696	0
38	watch	110.597	0	fall	112.025	0
39	please	115.356	0	sit	118.51	6.25
40	walk	123.091	0	speak	122.079	0
41	cause	125.589	0	drink	123.15	0
42	space	128.147	0	lead	126.244	0
43	doubt	150.636	0	meet	140.046	0
44	force	167.413	0	hold	157.537	0
45	hope	175.266	0	pay	176.575	0
46	care	179.549	0	cut	181.572	0
47	call	227.203	0	leave	241.957	0
48	live	229.761	0	read	277.355	0
49	open	304.484	0	feel	357.432	0
50	love	364.155	0	become	392.057	0
51	need	456.904	0	tell	448.337	0
52	hand	470.112	0	find	482.129	0
53	place	544.716	0	put	659.12	0
54	look	557.923	0	think	800.297	0
55	last	643.117	0	come	845.987	0
56	work	800.297	0	go	974.491	0
57	like	1884.02	0	know	1135.12	0
	M (*freq.*)	162.39			163.99	
	SD	291.17			254.21	
		M (*Error*)	1.86			7.57
		SD	8.76			14.16

Table 3.8: Verb Type & Error Rate in Set 2

	REG	*frequency*	*Error%*	IRREG	*frequency*	*Error%*
1	poise	1.90377	0	wring	1.96326	18.75
2	blush	3.86703	0	bleed	3.80754	0
3	render	4.99739	0	forbid	4.75942	37.50
4	sway	6.06826	0	flee	5.94928	6.25
5	slap	7.13913	0	shrink	6.18725	6.25
6	greet	8.09101	0	cling	7.13913	50.00
7	scrub	8.80493	0	spin	8.09101	18.75
8	breeze	11.2441	0	stride	9.57833	50.00
9	blast	11.7796	0	lend	12.3745	0
10	warn	11.8986	0	steal	13.0884	0
11	stir	17.8478	0	sweep	15.2301	0
12	fix	18.9187	0	dig	17.3124	6.25
13	boil	20.2275	0	bite	17.9073	12.50
14	strip	21.8933	0	forgive	22.1313	0
15	score	22.1908	0	string	22.9047	37.50
16	foster	22.8452	0	swim	24.0946	0
17	mix	24.392	0	shake	24.63	6.25
18	jump	27.8426	0	sink	27.3072	0
19	switch	28.497	0	swing	31.5907	6.25
20	pop	36.4691	0	hide	34.1488	0
21	treat	37.6589	0	split	38.7298	62.50
22	push	44.6196	0	teach	45.2145	0
23	cross	53.008	0	throw	49.498	0
24	store	57.589	0	cast	53.6	62.50
25	check	58.0054	0	stick	54.0789	50.00
26	tend	58.7788	0	beat	54.7928	31.25
27	guess	60.2662	0	win	60.5636	0
28	join	65.68	0	bear	63.7762	25.00
29	save	67.8217	0	ring	65.918	6.25
30	rule	68.1192	0	wear	67.6433	0
31	claim	74.6634	0	spring	73.1761	18.75
32	note	84.1228	0	forget	75.6748	0
33	wonder	85.7886	0	lose	81.1481	0
34	type	86.5025	0	rise	87.8113	0
35	follow	88.0493	0	spread	88.6442	50.00

Table 3.9: Verb Type & Error Rate in Set 2 (*cont.*)

	REG	*frequency*	*Error%*	IRREG	*frequency*	*Error%*
36	share	91.3214	0	hit	91.2619	0
37	reach	94.5935	0	fight	97.8656	0
38	wait	119.759	0	write	113.274	0
39	figure	124.578	0	begin	120.175	0
40	wish	125.47	0	buy	121.127	0
41	study	136.476	0	sleep	125.173	0
42	press	136.833	0	stand	138.499	6.25
43	fear	164.022	0	eat	139.213	0
44	stop	173.243	0	deal	165.152	0
45	move	183.238	0	bring	181.334	6.25
46	start	199.539	0	hear	183.476	0
47	seem	215.602	0	run	229.702	0
48	talk	247.549	0	mean	294.846	0
49	point	364.155	0	keep	350.055	0
50	help	375.221	0	set	377.125	6.25
51	end	458.63	0	let	392.474	0
52	use	467.494	0	give	465.947	0
53	head	476.537	0	take	745.563	0
54	house	563.932	0	say	752.94	0
55	want	604.922	0	make	856.696	0
56	own	921.007	0	get	1056.35	0
57	back	1235.84	0	see	1061.35	0
	M (*freq.*)	154.17			163.69	
	SD	233.30			254.48	
		M (*Error*)	0			10.20
		SD	0			17.86

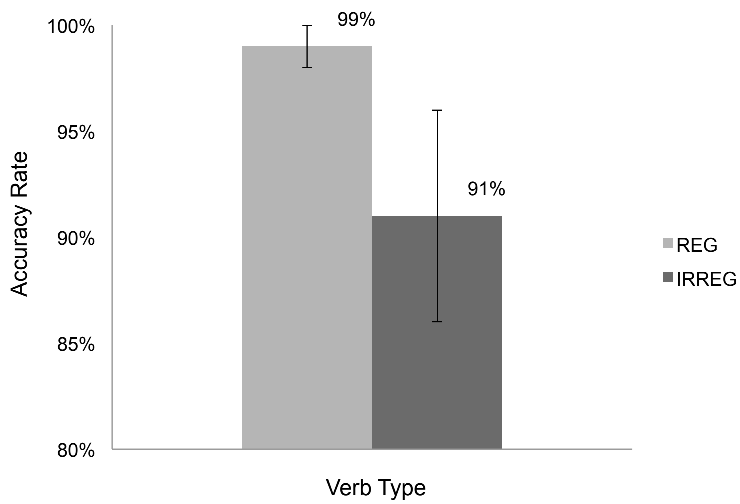


Figure 3.5: Behavioral Accuracy

Table 3.10: Subjects' Demographics & Behavioral Accuracy Rate

Subject	Age	AoA	Place	Native L2 Teacher	REG	IRREG
1	30.5	14	Korea	No	97.37	98.25
2	20.1	11	USA	Yes	99.12	85.96
3	25.2	1	Canada	Yes	99.12	87.72
4	21.6	8	Korea	No	97.37	92.11
5	20.3	5	Korea	Not recall	98.25	80.70
6	20.8	12	Korea	No	100.00	91.23
7	22.7	11	USA	Yes	99.12	94.74
8	20	6	UK	Yes	99.12	85.96
9	20.7	12	Australia	Yes	98.25	88.60
10	22.9	8	Korea	No	99.12	96.49
11	30.2	3	Canada	Yes	99.12	92.11
12	23.1	12	Korea	No	100.00	99.12
13	19.1	9	Korea	No	100.00	88.60
14	30.4	11	Korea	No	98.25	86.84
15	33.4	3	USA	Yes	99.12	94.74
16	22.5	8	UK	Yes	100.00	96.49
M	23.97	8.38			98.96	91.23
SD	4.57	3.84			0.86	5.20

Chapter 4

Discussion

This study analyzed the neural responses of highly proficienct L2 speakers of English as they generated past tense English verb forms. The specific contrasts of interest tested were REG>IRREG and IRREG>REG. The results revealed selective regional differences between two types of verb processing and showed that subcortical areas such as caudate and thalamus were disproportionally engaged in irregular verb processing.

4.1 Regions of Activation Associated Selectively with IRREG>REG Contrast

4.1.1 The Inferior Frontal Gyrus and the Claustrum

Consistent with Desai et al. (2006), this study showed that the inferior frontal gyrus, particularly in the left hemisphere, was extensively involved in irregular processing in the L2 speakers. This finding contradicts the dual-route mechanism claim that the left inferior frontal gyrus is crucial for processing of regularly inflected words (Miceli et al., 1989; Novoa & Ardila, 1987; Shapiro & Caramazza, 2003; Tyler et al., 2002; Ullman et al., 1997; Ullman, 2001, cited in Marangolo & Piras, 2008,

p. 197), and even considering their D/P model prediction that highly proficient L2 speakers would use more L1-like processing (that is greater reliance on left-frontal and basal-ganglia structures for regular processing). The result is consistent with a more general view that the inferior frontal gyrus has a key involvement in syntactic processing and L2 learning (including artificial language learning as the L2. See in details in Friederici et al., 2002) (e.g., Chee et al., 1999; Dapretto & Bookheimer, 1999; Dehaene et al., 1997; Friederici et al., 2002; Klein et al., 1999; Opitz & Friederici, 2003, Price et al., 1999; Stein et al., 2009; and Vingerhoets et al., 2003). Even though the subjects' incorrect responses were excluded from the analysis, for the high proficiency L2 speakers, activation in the left frontal gyrus could still reflect task difficulty, as indicated by the error rates for irregular past tense items (e.g., Gabrieli et al., 1998).

Another salient activation in the frontal lobe was in the claustrum in bilateral. Indeed, as seen in the regions of activation listed in Tables 3.4 through 3.5, over forty areas were engaged in the L2 processing of the irregular past tense. The bilateral claustrum may play an essential role, as Crick & Koch (2005) claim below:

> "*We suggested that the claustrum may contain specialized mechanisms that permit information to travel widely within its anterior-posterior and ventral-dorsal extent to synchronize different perceptual, cognitive and motor modalities* (p. 1266). *The neuroanatomy of the claustrum is compatible with a global role in integrating information at the fast time-scale*" (p. 1277).

4.1.2 The Parietal Lobe

As similarly reported in previous studies (Beretta et al., 1985; Desai et al., 2006; Friederici, 2012; Hernandez et al., 2007; and Ullman, 2001a & 2004), the parietal lobe, namely, the supramaginal gyrus in bilateral, was also significantly activated when the L2 speakers processed irregular verbs. For both L1 and L2 processing, the parietal lobe, along with the temporal lobe, is deeply associated with lexical search and retrieval (For L1: Damasio, Grabowski, Tranel, Hichwa, & Damasio, 1996; Goodglass, 1993; Martin, Wiggs, Ungeleider, & Haxby, 1996; Mazoyer et al., 1993; Wise, Chollet, Hadar, Friston, & Hoffner, 1991, cited in Beretta et al., 1985, p. 85.; For L2: Klein et al., 1999; and Stein et al., 2009).

4.1.3 The Insula

Inside the same cluster as that of the right claustrum, the right insula exhibited a strong response to L2 irregular processing. According to Xue et al. (2008), the insula has an inhibitory role on speech, and Ackermann & Riecker (2004) and Christoffels et al. (2007) suggested that the insula is involved in speech-motor control. In particular regard to the right insula, Christensen et al. (2008) reported its "involvement during top-down, attention-modulated processing of normal human speech" (p. 1105). In addition, Guenther (2006) and Wager et al. (2005) found that the insula is one of the cognitive functional locations for the selection and inhibition of speech movement and for response selection, respectively. For the L2 speakers in this study, the activation of the insula might reflect its participation in suppressing the default regular past tense generation in English and in controlling overt (natural) responses under the covert task simultaneously.

4.1.4 The Cerebellum

Since Petersen et al. (1988) reported the involvement of the cerebellum in generating verbs, research has further established that the cerebellum contributes to language processing (e.g., Ackermann et al., 2007; Booth et al., 2006, Chen & Desmond, 2005; Desmond & Fiez, 1998; Doron et al., 2010; Gebhart et al., 2002; Jager et al., 1996; Justus, 2004; Price, 2012; Stoodley, 2012; Stoodley et al., 2012; and Stowe et al., 2005). A series of studies, in fact, has proposed its roles: creating a (pre)verbal code in both overt and covert speech (Ackermann et al., 2007), articulatory control and phonological working memory (Booth et al., 2006; Chen & Desmond, 2005), amplification and refinement as well as processing orthographic representations (Booth et al., 2006), and so forth. In line with those studies, the current study found neural activation in the right cerebellum of the L2 speakers. The question immediately arises as to why only irregular processing would elicit activation in the right cerebellum, as it did in this study. In light of the greater recruitment of the right hemisphere in regular processing, and considering the contralateral nature of the cerebellar hemisphere (i.e., its right lateralization), the engagement of the cerebellum almost exclusively with irregular processing (with its greater recruitment of the left hemisphere) in this study seems to be reasonable given the extensive neural responses in the left inferior frontal gyrus.

4.1.5 The Caudate

In this study, irregular past tense generation was associated with activation in the left caudate of L2 speakers. A number of studies have suggested that the left caudate plays a crucial role in verbal inhibition and in the suppression of habitual or overlearned actions (Abutalebi et al., 2007 & 2008; Chee, 2006; Crinion et al., 2006; Gil Robles et al., 2005; Li, Yan, Sinha, & Lee, 2008; Parsons, Harrington, & Rao, 2005; Shadmehr & Holcomb, 1999; van Heuven et al., 2008; and Vink et al., 2005, cited in Ali et al., 2009, p. 2369, 2380, & 2381). According to Ali et al. (2009), the left caudate "helps to ensure context-appropriate behavior," and the authors proposed that the "head of caudate activation inhibits a plan triggered by the incongruent word rather than inhibiting the actual vocal response itself" (p. 2380). Packard & Knowlton (2002) provided a slightly different view of the role of the caudate. For them, the caudate "mediates a form of learning and memory in which S-R associations or habits are incrementally acquired" (p. 567). Here, Packard & Knowlton introduced their notion of a mnemonic function for the caudate, which is "organized based on the nature of the topographical cortical input this structure receives" (p. 571). Packard & Knowlton further proposed that the mnemonic function enables caudate-dependent response learning and hippocampus-dependent place learning in the memory system. That idea was supported by an imaging study in which "neuronal activity in the human caudate nucleus shows a similar phenomenon while the subject is performing a declarative memory task" (p. 582). Packard & Knowlton also noted the role of the caudate as "a potential site of storage of learned habits or procedures" (p. 583). Since irregular verb learning could be regarded as incremental and because no hippocampal areas related to activation in the temporal lobe was observed in the current study (i.e., in both contrasts: REG>IRREG and IRREG>REG), the memorization of irregular verbs and the generation/search of those lexical items may rely on the caudate-dependent response learning in the L2 speakers memory system. On the other hand, the caudate might instead contribute directly to the suppression of a prepotent cognitive action (i.e., the English past tense rule: attaching an -ed morpheme) in L2 speakers.

4.1.6 The Thalamus

The direct comparison of the IRREG>REG contrast identified the involvement of the thalamus in irregular past tense generation in the L2 speakers. Indeed, a variety of evidence has suggested that the thalamus plays a specific role in language processing (e.g., Aglioti, 1997; Bechtereva et al., 1992; Crosson et al., 2003; Gogolitsin & Nechaev, 1989; Guillery, 1995; Johnson & Ojemann, 2000; Ketteler et al., 2008; Mestres-Misse et al., 2012; Metz-Lutz et al., 2010; Nadeau & Crosson, 1997; Ullman, 2001 & 2006; Wahl et al., 2008; Wallesch & Papagno, 1988; and Whelan et al., 2002). For example, by using implanted electrodes, Gogolitsin & Nechaev

(1989) reported “a considerably high degree of selectivity and specificity in reactions of thalamic neuronal populations to lexical processing” (p. 167). Comparing left and right thalamotomy patients, Whelan et al. (2002) found a laterality effect in that the left thalamotomy patient evinced significantly different linguistic behaviors. Similarly, Metz-Lutz et al. (2000) used fMRI data from a thalamic aphasic patient to obtain direct evidence for the involvement of the left thalamus in language function. From EEG data, Wahl et al. (2008) reported that thalamic structures were systematically engaged in syntactic and semantic analysis for sentential stimuli. Finally, Ketteler et al. (2008), also using fMRI, found that the thalamus, along with other cortical and subcortical foci, was engaged in ambiguity resolution during the semantic search of homonym data.

Models of thalamic functions in language have also emerged in the research. For example, according to the D/P model, implicit rule-based grammatical processing involves a fronto-striatal procedural memory system (i.e., the basal ganglia), whereas explicit memory retrieval is subserved by temporo-thalamic networks (Longworth et al., 2005; and Wahl et al., 2008). Alternatively, both the lexical selection model and selective engagement model provide fronto-cortical networks (i.e., the basal ganglia) and cortico-thalamic networks to explain nonlinguistic functions of the basal ganglia and the key role of the thalamus in language processing, as reviewed in Wahl et al. (2008). More specifically, Johnson & Ojemann (2000) proposed that “regions of the thalamus operate as a specific alerting response, increasing the input to memory of category-specific material while simultaneously inhibiting retrieval from memory” (p. 218). In addition, in proposing “a left pre-SMA[1]dorsal caudate–ventral anterior thalamic loop” for lexical retrieval, Crosson et al. (2003) “hypothesized that activity in this loop was related to maintaining a bias toward the retrieval of one lexical item versus competing alternatives for each response dur-

[1]Supplementary motor area.

ing word generation blocks" (p.1075). Whereas two aspects of the thalamus in the subcortical areas (i.e., the types of neurotransmitter, excitatory (i.e., glutamate) and inhibitory (i.e., GABA[2]), and the poststimulus excitation of the thalamus and the caudate) should be acknowledged, and in consideration of Occams razor, the findings of this study seem to conform to those of Johnson & Ojemann (2000) and Crosson et al. (2003). In those studies, the authors state that past tense generation could be efficiently achieved by "a gating mechanism that controls the input and retrieval of specific items" (Johnson & Ojemann, 2000, p. 227). Moreover, the maintenance mechanism is biased; that is, irregular verbs are taken as "category-specific material" and their verbatim past tense can be searched, while at the same time highly automated regular type processing can be inhibited. Notably, as Crosson et al. (2003) reported, it seems that activity in the subcortical areas is usually not strong enough to be captured by direct task-to-task comparisons; yet, the present study succeeded in showing activation in those areas. Taken together, therefore, the results of this study were compatible with the position that the subcortical areas of the thalamus and the caudate have specific effects on L2 language processing.

4.2 Regions of Activation Associated Selectively with REG>IRREG Contrast

4.2.1 The Medial Frontal Gyrus (The Anterior Prefrontal Cortex)

The largest area of activation observed in this contrast was in the medial frontal gyrus in the right hemisphere. In neurocognitive science, the left side of this frontal gyrus is well-known to be the area for the top-down processing of selective attention as well as for learning, memory, and language processing (e.g., Desimone & Duncan, 1995; Friederici, 2012; Miller & Cohen, 2001; and Opitz & Friederici, 2003).

[2] Gamma(γ)-amino butyric acid.

More specifically, in the L1 literature (see Marangolo & Piras, 2008), the left inferior frontal gyrus has found to be a central location for processing inflected words, which is in keeping with the frontal/basal ganglia rule system of the dual-route mechanism. In addition, Poldrack & Gabrieli (2001) suggested that the involvement of the left prefrontal region may indicate "increased engagement of lexical search" (p. 79). On the other hand, according to Goel et al. (2009), "the right prefrontal cortex has critical roles to play in reasoning processes" (p. 2796), and Poldrack et al. (1999) reported that "right frontal lesions impair performance on reasoning tasks" (p. 570). In a similar vein, Brownell et al. (1986) reported that a right hemisphere-damaged patient had more trouble making inferences. In their L2 research, Dehaene et al. (1997) and Hernandex (2009) observed greater activation in the right hemisphere of L2 speakers, and Ullman (2005) noted that "strategy-dependent compensatory right-hemisphere processes" (p. 162) were involved in L2 processing. All in all, activation in the right hemisphere could indicate that highly proficient L2 speakers utilize L1-like rule-based past tense generation for regular verbs, but within the realm of general reasoning processes.

4.2.2 The Temporal Gyrus

As reported in the Results section, both the middle and the superior temporal gyri in the right hemisphere were selectively engaged with regular past tense processing in L2 speakers. In the L1 literature, a series of past tense studies have reported the involvement of the left temporal region in the processing of the irregular past tense. In their comprehension experiment, however, Stamatakis et al. (2005) found that, in L1 speakers, the "bilateral superior temporal gyrus and the middle temporal gyrus were preferentially activated for regularly inflected words" (p. 115). Such cortical responses in the temporal lobe were predicted for L2 regular processing by the D/P model, which posited that L2 grammatical processing would rely strongly on the declarative memory system, that is, the temporal lobe regions. That argument is supported by evidence that a temporal lobe lesion had a more severe impact on L2 grammatical processing than on L1 grammatical processing (Ullman, 2005). Similarly, Dehaene et al. (1997) observed greater activation in the temporal regions of the right hemisphere in L2 speakers than in L1 speakers, which the authors interpreted as a sign of a retrieval process from declarative memory. Dehaene et al. also noted that the engagement of the left temporal lobe was significantly less in L2 speakers. Although the D/P model predicts that, as L2 speakers become highly proficient, their brains shift their processing mechanism from the declarative to the procedural system, apparently the highly proficient L2 speakers in this study still showed reliance on the temporal lobe regions, but only those in the right hemisphere.

4.3 Common Cortical Regions for Both REG>IRREG & IRREG>REG

4.3.1 The Anterior Cingulate Gyrus, the Medial Frontal Gyrus (The Dorsolateral Prefrontal Cortex), and the Precuneus

Whereas language embraces the most natural of human behavior, almost all cognitive tasks used in experimental conditions require subjects to perform certain discrete action.[3] Such action, in turn, forces the subjects to maintain or shift particular mental states over the course of the task. In the present study, the subjects attentional control process was indispensable. Of the cortical regions commonly involved in both contrast conditions in this study, the anterior cingulate gyrus, the medial frontal gyrus (the dorsolateral prefrontal cortex), and the precuneus possibly exhibited task-induced responses. Justification for that contention is as follows:

[3]When language stimuli were used.

1. Anatomical Location: As numerous studies have reported (e.g., Adler et al., 2001; Botvinick et al., 1999, 2001, 2004; D'Esposito et al., 1995; Desimone & Duncan, 1995; Dosenbach et al., 2006, 2007, 2008; Friederici, 2012; Miller & Cohen, 2001; Narayanan et al., 2005; Petersen & Posner, 2012; and Posner & Dehaene, 1994), the anterior/frontal regions, the anterior cingulate gyrus, and the precuneus are widely assumed to be engaged in attentional processes. As for the L2 perspective, Dehaene et al. (1997) reported that the anterior cingulate gyrus was related to the attentional resources of L2 processing. In addition, Abutalebi (2008) reported that both the (pre)frontal cortex and the anterior cingulate cortex were involved in language control.

2. Task: In the past tense generation task, subjects performed top-down processing; that is, their task outcome was delimited to a verb category, and they were required to control their responses to conform to that internal goal or intention. In addition, to promptly respond to the stimuli, the subjects were expected to retain task-relevant information, grammar, and/or memory items necessary to satisfy the rules[4] for task accomplishment. All these required the subjects' attention;

3. Accuracy Rate: Based on their accuracy rates (i.e., 99% for REG and 91% for IRREG), it is certain that the subjects were highly advanced, as well as attentive, L2 speakers. Though the difference between accuracy rate in respect to verb type (i.e., REG vs. IRREG) was statistically significant, any error rate less than 10% can be considered high performance (c.f., Babcock et al., 2012; Brovetto, 2002).

As Mestres-Misse et al. (2012) noted, "Language lies in high automaticity" (p. 42). In addition, compared to many other types of cognitive tasks, language

[4]Which includes all types of rules (e.g., pattern recognition).

tasks are often assumed to elicit relatively few neural responses (Poldrack, personal communication, 2010). Whereas a word generation task has been thought to be "superior" to a word reading task (Gabrieli et al., 1998, p. 907), the activation of the attention loci, the anterior cingulate gyrus, the medial frontal gyrus, and the precuneus seems to indicate the presence of a general control function above and beyond the tense morphological process *per se*.

4.4 A Comparison Between L1 and L2 Produced by Korean Speakers

Taking a Korean verbal unit *ecel* as a basis of regularity[5], Yim et al. (2008) found that both regular and irregular *ecel* units were associated with the temporal lobe. In addition, the authors found that regular *ecel* units did not evoke activation in the left inferior frontal lobe, a result that the authors viewed as common among English- and German-based studies as well. Tables 4.1 and 4.2 show the results[6] of their study.

Because the terms *regular* and *irregular* indicate different linguistic units (i.e., verb vs. *ecel*), their salient difference lies in the tasks they impose (i.e., lexical decision vs. silent generation), and, crucially, the subtractions were made by the control condition (i.e., REG>control & IRREG>control), a direct comparison between Yim et al.'s results and those of the current study may not be appropriate. However, if regularity is taken as a broader[7] linguistic or cognitive unit, there was a notable hemispheric difference between the L1 and L2 data of Korean speakers;

[5]As mentioned in the Introduction, in their study the terms regular and irregular were not used to indicate past tense verb types *per se*. Instead, they referred to phonological variations in Korean predicates expressed by the *ecel* unit, which is "bigger than a word but smaller than a phrase (p. 247).

[6]Based on their Talairach coordinates, the lists were reproduced by the author. These tables contain the same information as that in Yim et al. (p.252).

[7]Which is bigger than a word level.

namely, in L1, the majority of the REG>control contrast elicited activation in the left hemisphere, whereas the majority of IRREG>control contrast was observed in the right hemisphere (including the peak intensity sites in both REG>control and IRREG>control). These activations are counter to the patterns of the current L2 study. Based on the hemispheric differences, it may be inferred that a contralateral processing mechanism may underlie the L1 and L2 regularity processing of Korean speakers. In other words, because they recruit a less L1 dominant hemisphere for L2, regularity processing of L1 and L2 do not interfere with each other. Alternatively, the right hemisphere dominance in L2 REG>IRREG may simply reflect that the right hemisphere was more "involved in the processing of automatic-non-propositional speech" (Code, 1987, p. 85). Further study is required in this area.

Table 4.1: Brain Regions for Korean L1 REG>Control (from Yim et al., 2008)

Anatomical region	Voxels	Z-score	Hemisphere	x	y	z	Brodmann area
Medial Frontal Gyrus	89	4.6	Left	-8	-14	54	BA 6
Inferior Occipital Gyrus	24	4.05	Left	-40	-90	-4	BA 18
Postcentral Gyrus	112	3.86	Left	-40	-28	60	BA 3
Precentral Gyrus	23	3.41	Left	-38	-14	44	BA 4
Paracentral Lobule	79	3.58	Left	-12	-34	52	BA 5
Superior Temporal Gyrus	31	3.98	Left	-64	-30	8	BA 42
Transverse Temporal Gyrus	23	3.68	Left	-58	-16	12	BA 42
Middle Temporal Gyrus	35	3.5	Left	-58	-2	-10	BA 21
Medial Frontal Gyrus	113	3.8	Right	8	-24	58	BA 6
Parahippocampal Gyrus	30	3.85	Right	18	-32	-8	BA 35
Insula	61	3.79	Right	44	-4	2	BA 13
Lingual Gyrus	49	3.52	Right	14	-78	-4	BA 18

Table 4.2: Brain Regions for Korean L1 IRREG>Control (from Yim et al., 2008)

Anatomical region	Voxels	Z-score	Hemisphere	x	y	z	Brodmann area
Insula	308	4.82	Left	-38	-14	14	BA 13
Middle Temporal Gyrus	91	3.7	Left	-56	-32	2	BA 22
Postcentral Gyrus	24	3.46	Left	-14	-42	64	BA 5
Insula	97	4.63	Right	40	-8	22	BA 13
Insula	40	4.37	Right	44	-2	-4	BA 13
Insula	31	4.03	Right	42	-20	0	BA 13
Middle Temporal Gyrus	134	3.97	Right	58	-28	-6	BA 21
Middle Temporal Gyrus	47	3.68	Right	58	-60	8	BA 39
Superior Temporal Gyrus	24	3.6	Right	68	-36	20	BA 22
Sub-Gyral	24	3.7	Right	36	-30	-6	Hippocampus
Sub-Gyral	29	3.56	Right	38	-10	-20	BA 20
Middle Frontal Gyrus	20	3.53	Right	22	26	-14	BA 11
Inferior Frontal Gyrus	27	3.45	Right	44	26	0	BA 47

4.5 A Comparison Within L2 Korean Speakers

Further imaging analyses were conducted to determine whether the effects of AoA and Proficiency (i.e., the accuracy rates) of L2 speakers could be found in this study. Specifically, analyses of single-group averages (for both REG>IRREG and IRREG>REG contrasts) with additional covariates, namely, AoA or Proficiency (both orthogonalized[8] in relation to the group mean) were first conducted. Second, the Korean L2 group was divided into subgroups as follows: Early Acquisition (EA) and Late Acquisition (LA) groups for AoA, and Lower Proficiency (LP) and Higher Proficiency (HP) groups for Proficiency. Those subgroups were then contrasted. No activation was found in any of the tests. The subgroup membership information is shown in Tables 4.3 & 4.4:

[8] Which refers to demeaned or centered means.

Table 4.3: AoA Group

Subject	**AoA**	Sub-Group
3	1	EA
11	3	EA
15	3	EA
5	5	EA
8	6	EA
4	8	EA
10	8	EA
16	8	EA
13	9	LA
2	11	LA
7	11	LA
14	11	LA
6	12	LA
9	12	LA
12	12	LA
1	14	LA

Table 4.4: Proficiency Group

Subject	**Accuracy%**	Sub-Group
12	99.6	HP
16	98.2	HP
1	97.8	HP
10	97.8	HP
7	96.9	HP
15	96.9	HP
6	95.6	HP
11	95.6	HP
4	94.7	LP
13	94.3	LP
3	93.4	LP
9	93.4	LP
2	92.5	LP
8	92.5	LP
14	92.5	LP
5	89.5	LP

4.6 Summary

The aim of this study was to explore the neural responses of L2 speakers of English as they processed the English past tense inflection. Through a whole-brain analysis of event-related fMRI data, the study found distinct cortical differences between regular versus irregular past tense verb generation in the L2 speakers. Regular verb processing was more positively associated with activation in the temporal lobe and the occipital lobe, whereas irregular verb processing was extensively associated with activity in the parietal lobe, the posterior lobe, and the sub-lobar regions. These findings are in keeping with those of studies that have shown that distinctions in linguistic morphology correlate with areas of brain morphology and with learning and memory functions. This study extends the earlier research by employing a comparative approach that relates morphological processing functions to regions in the L2 speakers' brain. The results of the study could lead to new interpretations of existing data and suggest new models of L1 processing, because its findings underscore the plasticity of the brain[9]. More generally, the study may deepen our understanding of morphological processing in general.

Note

Whereas the study showed that regions of the brain were selectively engaged in the two morphologically different categories, it is important to note that, in neuroimaging, regional contrasts in the brain are relative, not absolute. As Bookheimer (2002) states, "MRI signal intensity changes are comparative by nature" (p.154). In addition, the choice of contrast could affect the results significantly (e.g., task condition 1>task condition 2, task condition>rest condition, etc.) (e.g., Hund-Georgiadis et al., 2001). Therefore, any worthwhile review of study results should also carefully

[9] The same brain regions seemed to be involved with different functions between L1 and L2.

examine the methodology and the comparison setup.

4.7 Future Work

- First, further statistical analyses on the behavioral data will be conducted to test whether, for example, a mixed regression including both item- (e.g., frequency) and subject-level (e.g., AoA) covariates in the same model provide finer accounts.

- Second, a re-analysis of the imaging data will be performed to better model the data. Specifically, dummy EVs for the subjects' incorrect responses will be modeled as was performed on the two EVs (i.e., REG & IRREG), which include a double-gamma hemodynamic response function, a temporal derivative, and temporal filtering.

- Third, based on the previous imaging studies, region of interest (ROI) analyses will be conducted to effectively measure time course signal changes, which in turn will show significant contrast effects.

- Fourth, in the future, a control task should be added to provide a basis for claiming dissociation between the contrasts, namely, (REG>control)>(IRREG >control) and (IRREG>control)>(REG>control).

- Fifth, whereas REG>IRREG and IRREG>REG generation involved selective spatial patterns, the precise functions in the brain need to be further elucidated. In particular, the role of the left hemisphere in irregular past tense generation and that of the right hemisphere in regular past generation will be addressed.

- Sixth, if funding is available, three experiments will be carried out: (1) with a monolingual native control group, to directly compare L1 and L2 results; (2)

with the same Korean L2 group, to examine their L1processing mechanism and to draw a direct comparison between L1 and L2 processing system within a group; (3) with a Chinese L2 group, to investigate how learner's L1 may affect L2 development[10].

- Seventh, in the future experiments, a proficiency test currently used in behavioral L2 studies will be administered to acquire an independent measure describing L2 groups, and to facilitate comparisons across L2 research[11].

[10] Korean and Chinese speakers have morphological structures either gradually or vastly different, respectively, from those of English: English (both REG & IRREG), Korean (REG), and Chinese (no morphological REG & IRREG).

[11] Input from an anonymous reviewer of the National Science Foundation is acknowledged for this direction and writing.

Appendix A

Prescreening Survey

Your answers in this survey will help us determine whether you qualify for participation in a neuroimaging study in the Department of Linguistics at The University of Texas at Austin (UT Austin). You will need to qualify for both a behavioral task and a functional magnetic resonance imaging (fMRI) task. Both tasks involve the same type of simple linguistic processing. Those qualified will be notified by e-mail when enrollment begins.

The study procedure is as follows: You will first participate in a 30-minute behavioral task ($10 compensation). If your performance on the behavioral task meets research selection criteria, you will be asked to participate in an hour-long fMRI task ($30 compensation). In the fMRI task, you will perform the same behavioral task while researchers collect images of your brain using MRI. The remaining time will be used for the fMRI task preparations and for the acquisition of the structural MR images of your brain.

Both the behavioral and the fMRI tasks will be conducted at UT Austin, normally after 5 pm on weekdays and/or weekends.

Please feel free to contact the principal investigator, So-Hee Kim (skim32@utexas.edu) if you have any questions or need further information about the study. This study has been approved by the UT Austin Institutional Review Board.

Thanks for your time!

Note: We gratefully acknowledge research funding from UT Austin to Dr. Sussman and from POSCO Graduate Research Fellowship to So-Hee Kim. We also thank Dr. Poldrack for sharing the survey format, and Dr. Banks for providing reformatting assistance.

Section 1: This section should take 1 minute at most.

- Please enter the date you are completing the survey. (CLICK THE " TODAY" BUTTON.)
- Birth Date (Use the calendar icon to add your birthdate or type it in using numbers in the Year-Month-Day (YYYY-MM-DD) format.)
- Our system will record your age, in years, as:
- Gender (Female; Male)
- Are you left handed, right handed, or ambidextrous? (Left; Right; Ambidextrous)
- Are you a native speaker of Korean? (Yes; No)
- Are you currently enrolled as an ESL student or taking an ESL course? (Yes; No)

- Are you currently taking or have you recently taken any medication or drug? This includes: -antidepressants, -antianxiety drugs, -drugs to treat ADD or ADHD (Yes; No)

Section 2:

For office use only (This field is automatically calculated for office use only.)

- Section 2: Would you like to complete more questions to see if you qualify for this study that involves using MRI to capture images of your brain? (Yes; No)
- Do you have a history of significant medical illness? This can include any: -Cardiovascular disease, -Cancer, -Immunodeficiency disorders (including HIV infection), -Diabetes, -Unstable endocrine disorders, -Neurological disorders, -Blood dyscrasias (Yes; No)
- Do have a history of head trauma with ANY of the following? -Loss of consciousness, -Cerebrovascular accident, -Seizures, -Neurosurgical intervention (Yes; No)
- Do you have a permanent retainer or braces? (Yes; No)
- Do you have any of the following in your body? -Aneurysm clip, -Cardiac pacemaker, -Implanted cardioverter defibrillator, -Electronic implant or device, -Magnetically-activated implant or device, -Neurostimulation system, -Spinal cord stimulator, -Internal electrodes or wires, -Bone growth/bone fusion stimulator, -Cochlear, otologic, or other ear implant (Yes; No)
- Do you have any of the following in your body? -Insulin or other infusion pump, -Implanted drug infusion device, -Any type of prosthesis, -Artificial or prosthetic limb, -Heart valve prosthesis, -Eyelid spring or wire, -Metallic stent, filter, or coil, -Shunt, -Vascular access port or catheter, -Radiation seeds or

implants, -Wire mesh implant, -Tissue expander, -Dentures or partial plates (Yes; No)

- Do you have any of the following in your body? -Swan-Ganz or thermodilution catheter, -Surgical staples, clips, or sutures, -Joint replacement, -Bone/joint pin, screw, nail, wire, plate, etc., -Any other implant or any metallic fragment or foreign body (Yes; No)

- Do you have any of the following? -A hearing aid that, when removed, will make it impossible for you to hear our researchers give instructions, -A medication patch that cannot be removed (Yes; No)

- Do you have a history of major psychotic disorders? This can include: -Schizophrenia, -Biopolar disorder (Yes; No)

- Do you have a history of substance dependence? (Yes; No)

- Do you have a history of drug or alcohol abuse? (Yes; No)

- Do you have either of the following? -A metal body piercing, -A tattoo or permanent makeup (Yes; No)

- Do you have any history of: -Breathing problem or motion disorder? -Claustrophobia? -Anemia or disease that affects your blood? (Yes; No)

Section 3:

For office use only

I'm sorry, you do not qualify for the study at this time. Please close your browser window. Do NOT click the submit button. SIMPLY CLOSE YOUR BROWSER WINDOW.

Congratulations - your screening information is now complete! You qualify for the

following tasks:
Behavioral Task: This task involves sitting at a computer to do a simple linguistic task.
fMRI Task: This task involves doing the same type of linguistic task as the behavioral task while researchers collect images of your brain using MRI.

The researcher who contacts you will give you more details when they contact you for this study.

By providing us with the following information, you are giving us permission to contact you about your participation in this study. You can always remove your name from our list by sending a request to skim32@utexas.edu. If you are still interested in this study, please enter your information below and a researcher will get in touch with you when the study opens up!

- First Name:
- Last Name:
- E-mail Address: (Please note that e-mail will be the primary method for communicating with participants. All participants are asked to check their e-mails frequently and respond in a timely manner.)
- Phone Number:
- At what age did you begin learning English?
- Where did you begin learning English?
- Was your first English teacher a native speaker of English?

Appendix B

Lists of Word Sets

Table B.1: A List of Words in Set 1

	REG	*frequency*	IRREG	*frequency*
1	like	1884.02	know	1135.12
2	work	800.297	go	974.491
3	last	643.117	come	845.98
4	look	557.923	think	800.297
5	place	544.716	put	659.12
6	hand	470.112	find	482.129
7	need	456.904	tell	448.337
8	open	304.484	become	392.057
9	love	364.155	feel	357.432
10	live	229.761	read	277.355
11	call	227.203	leave	241.957
12	care	179.549	cut	181.572
13	hope	175.266	pay	176.575
14	force	167.413	hold	157.537
15	doubt	150.636	meet	140.046
16	cause	125.589	lead	126.244
17	space	128.147	drink	123.15
18	please	115.356	speak	122.079

Table B.2: A List of Words in Set 1(*cont.*)

	REG	*frequency*	IRREG	*frequency*
19	walk	123.091	sit	118.51
20	watch	110.597	fall	112.025
21	plan	100.364	break	103.696
22	dry	92.9872	grow	95.4264
23	smile	98.5795	drive	90.4885
24	plant	73.1166	spend	82.338
25	test	79.4228	send	78.2925
26	count	80.7912	strike	78.114
27	fit	70.9154	catch	72.1647
28	charge	75.5558	build	71.1533
29	pull	68.0597	shut	66.9294
30	pick	63.8952	choose	63.0623
31	snow	60.0282	draw	58.7194
32	taste	58.7788	hurt	57.4105
33	vote	52.8891	feed	53.722
34	cry	52.5321	fly	52.9486
35	laugh	51.5207	sell	52.2346
36	raise	45.9284	seek	45.2145
37	flow	41.9424	blow	41.5854
38	fill	39.7412	ride	36.1716
39	hook	32.1856	wake	32.84
40	arrive	35.2197	awake	25.9388
41	pack	27.3072	bet	25.2249
42	load	24.1541	shoot	24.392
43	lock	20.763	sing	22.8452
44	solve	22.3693	bend	21.1794
45	knock	20.525	tear	18.7402
46	stare	19.0972	swear	15.2301
47	hire	14.4567	bid	14.9327
48	float	17.4314	slide	14.3972
49	grab	11.1251	breed	11.7796
50	snap	8.92391	freeze	8.74544
51	flush	8.62645	creep	8.68594
52	shave	6.36572	weep	6.90116
53	clutch	6.66319	spit	6.18725

Table B.3: A List of Words in Set 1(*cont.*)

	REG	*frequency*	IRREG	*frequency*
54	blink	3.86703	grind	5.7708
55	mend	4.81891	bind	4.81891
56	skip	4.46196	fling	4.04551
57	flop	2.67717	sling	2.97464
	M	162.39		163.99
	SD	291.17		254.21

Table B.4: A List of Words in Set 2

	REG	*frequency*	IRREG	*frequency*
1	back	1235.84	see	1061.35
2	own	921.007	get	1056.35
3	want	604.922	make	856.696
4	house	563.932	say	752.94
5	head	476.537	take	745.563
6	use	467.494	give	465.947
7	end	458.63	let	392.474
8	help	375.221	set	377.125
9	point	364.155	keep	350.055
10	talk	247.549	mean	294.846
11	seem	215.602	run	229.702
12	move	183.238	hear	183.476
13	stop	173.243	bring	181.334
14	fear	164.022	deal	165.152
15	study	136.476	eat	139.213
16	start	199.539	stand	138.499
17	press	136.833	sleep	125.173
18	wish	125.47	buy	121.127

Table B.5: A List of Words in Set 2 (*cont.*)

	REG	*frequency*	IRREG	*frequency*
19	figure	124.578	begin	120.175
20	wait	119.759	write	113.274
21	reach	94.5935	fight	97.8656
22	share	91.3214	hit	91.2619
23	follow	88.0493	spread	88.6442
24	type	86.5025	rise	87.8113
25	note	84.1228	lose	81.1481
26	wonder	85.7886	forget	75.6748
27	claim	74.6634	spring	73.1761
28	rule	68.1192	wear	67.6433
29	save	67.8217	ring	65.918
30	join	65.68	bear	63.7762
31	guess	60.2662	win	60.5636
32	check	58.0054	beat	54.7928
33	store	57.589	stick	54.0789
34	tend	58.7788	cast	53.6
35	cross	53.008	throw	49.498
36	push	44.6196	teach	45.2145
37	treat	37.6589	split	38.7298
38	pop	36.4691	hide	34.1488
39	switch	28.497	swing	31.5907
40	jump	27.8426	sink	27.3072
41	mix	24.392	shake	24.63
42	score	22.1908	swim	24.0946
43	strip	21.8933	string	22.9047
44	foster	22.8452	forgive	22.1313
45	boil	20.2275	bite	17.9073
46	fix	18.9187	dig	17.3124
47	stir	17.8478	sweep	15.2301
48	breeze	11.2441	steal	13.0884
49	warn	11.8986	lend	12.3745
50	scrub	8.80493	stride	9.57833
51	greet	8.09101	spin	8.09101
52	slap	7.13913	cling	7.13913
53	blast	11.7796	shrink	6.18725

Table B.6: A List of Words in Set 2 (*cont.*)

	REG	*frequency*	IRREG	*frequency*
54	sway	6.06826	flee	5.94928
55	render	4.99739	forbid	4.75942
56	blush	3.86703	bleed	3.80754
57	poise	1.90377	wring	1.96326
	M	154.17		163.69
	SD	233.30		254.48

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