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Research Report

Effects of syntactic complexity in L1 and L2; An fMRI study of Korean–English bilinguals

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ABSTRACT

The neural mechanisms underlying the syntactic processing of sentence comprehension in Korean (L1) and English (L2) by late bilinguals were investigated using functional MRI. The Korean native speakers were asked to read sentences with different levels of syntactic complexity in L1 and L2 and respond to comprehension questions concerning the sentences. The syntactic complexity was varied using a center-embedded sentence "The director that the maid introduced ignored the farmer" or a conjoined sentence "The maid introduced the director and ignored the farmer". It was found that the major areas involved in sentence processing such as the left inferior frontal gyrus (IFG), bilateral inferior parietal gyrus, and occipital lobe including cuneus, and lingual gyrus were commonly activated during the processing of both L1 and L2. However, the pattern of activation was different for L1 and L2 in the left IFG. The amount of activation was greater for embedded sentences than for conjoined sentences in L1 while no difference was found in L2. These results suggest that the cortical areas involved with syntactic processing in L1 and L2 are shared, but that the underlying neural mechanisms are different. The findings of the present study are discussed in comparison with Hasegawa et al.'s (Hasegawa, M., Carpenter, P.A., Just, M.A., 2002. An fMRI study of bilingual sentence comprehension and workload. NeuroImage 15, 647–660.) and Yokoyama et al.'s (Yokoyama, S., Okamoto, H., Miyamoto, T., Yoshimoto, K., Kim, J., Iwata, K., Jeong, H., Uchida, S., Ikuta, N., Sassa, Y., Nakamura, W., Horie, K., Sato, S., Kawashima, R., 2006. Cortical activation in the processing of passive sentences in L1 and L2: An fMRI study. NeuroImage 30, 570–579.) studies which also found common areas of activation but different patterns of activation during the processing of L1 and L2.

1. Introduction

A number of studies on bilingual subjects have investigated the neural mechanisms associated with the processing of L1 and L2, especially with the aid of modern imaging techniques such as PET (positron emission tomography) and fMRI (functional magnetic resonance imaging). The focus of most of the studies was on whether the same or different locations

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of the brain are activated during the processing of L1 and L2. Their assumption was that activation of the same site for L1 and L2 indicated that the same module was shared for the processing of both languages while the activation of distinct sites indicated otherwise. Previous studies have reported that similar sites are activated when L2 is acquired at an early age or if the proficiency level is high (Chee et al., 1999; Kim et al., 1997; Lee et al., 2004; Perani, 2000). Regarding late bilinguals who acquired L2 after puberty, the findings for shared brain areas are more varied. While more studies provide evidence for different cortical organization for L1 and L2 for late bilinguals (Kim et al., 1997; Lee et al., 2004; Luke et al., 2002; Wartenburger et al., 2003), some studies have reported similar areas of activation for both languages (Chee et al., 1999; Illes et al., 1999).

More recently, several studies, especially in the area of sentence comprehension by bilinguals extended beyond comparing the areas of activation and examined patterns of activation in different regions of interests when various factors of language comprehension came into play. They frequently found that the areas of activation overlap but that the patterns of activation were different during the processing of L1 vs. L2. For example, Hasegawa et al. (2002) investigated the relation between the neural mechanisms supporting the comprehension of L1 and L2. In their study, Japanese native speakers listened to positive and negative sentences presented in Japanese and English. They found that the areas of activation overlapped between L1 and L2. However, they found that the amount of activation for L2 was greater than that for L1, in general. There was also an interaction between the language and the type of sentence; the amount of neural activation for negative sentences was much greater than that for positive sentences in L1 but the difference was not as great for L2. Hasegawa et al. (2002) concluded that a shared network of cortical regions is involved in the processing of both L1 and L2, but the cognitive workload demanded by sentence processing determines the amount of activation, since negative sentences and L2 which presumably require more computation evoked more activation than positive sentences and L1, respectively.

Another study that examined the pattern of neural activation during sentence processing in L1 and L2 was reported by Yokoyama et al. (2006). They also used fMRI to compare brain activity during the processing of active and passive sentences in Japanese and English by Japanese native speakers. Like Hasegawa et al. (2002), they reported activation in similar language-related regions including the left IFG, superior and middle temporal, and parietal cortices for both L1 and L2. In terms of the pattern of activation, however, their results were not in agreement with the findings reported by Hasegawa et al. (2002). First, the amount of activation for L2 was not greater than that for L1. Second, the pattern of interaction between the language and sentence type differed depending on the area. They found a greater activation for passive than for active sentences in L1 in the left anterior inferior frontal cortex (near the pars triangularis) and parietal cortex but no difference in L2 in these areas. On the other hand, they found a greater activation for passive than for active sentences in L2 but no difference in L1 in the left pars orbitalis. Yokoyama et al. (2006) attributed their results to linguistic and psycholinguistic differences between Japanese and English such as morphological component and analysis of the thematic role. They pointed out that in English, passive transformation required an extra word (the verb "be") while Japanese passive transformation does not, and that is why greater activation was found for the passive than the active sentences in English in the left pars orbitalis. On the other hand, assigning a thematic role in Japanese passive sentences requires greater reanalysis compared to English passive sentences due to the fact that the patient role received nominative case which is usually assigned to agent role in Japanese, which led to greater activation for Japanese in left pars triangularis and parietal regions.

Studies reported by Hasegawa et al. (2002) and Yokoyama et al. (2006) show that the neural networks involved with sentence processing by late bilinguals may be shared by L1 and L2, but the mechanisms of how they function are different. However, the two studies do not agree with regard to how they function. The former suggests a cognitive workload interpretation, in which the processing of L1 and L2 are different in terms of computational demand as is the case with the processing of sentences with different levels of complexity. The latter suggests that factors other than computational demand such as the features of a specific language play a role in the processing of L1 and L2.

In the present study, the neural mechanisms of sentence processing by late bilinguals was investigated using a framework similar to that used by Hasegawa et al. (2002) and Yokoyama et al. (2006). The patterns of neural activation were examined during the processing of L1 and L2 in order to find out how the sentence processing of L1 and L2 is different. For this purpose, the brain activations of Korean–English bilinguals were compared during the processing of sentences with different level of syntactic complexity in Korean and English. Syntactic complexity was manipulated by using two types of sentences; sentences with a center-embedded relative clause and conjoined sentences as shown in Table 1. For English, which is a head-first language, the relative clause in a center-embedded sentence modifies the subject of the sentence. In Korean, which is head-final, the relative clause modifies the object of the sentence. The conjoined sentences in English used the same words as the embedded sentences except that the relative pronoun in the embedded sentences was changed to 'and' in the conjoined sentences. The conjoined sentences in Korean were the same as the embedded sentences except that the relative clause marker was changed to a conjoining marker. Therefore, for both Korean and English, the center-embedded sentences and conjoined sentences contained the same number of words. However, center-embedded sentences are more difficult to process than conjoined sentences, leading to a longer reaction time and a lower proportion of accurate responses in behavioral data (King and Just, 1991; Kim, 1995; Gibson, 1998).

By employing conjoined and relative sentences, the results of the present study can be compared to those of Hasegawa et al. (2002) and Yokoyama et al. (2006) and it can be determined which interpretation can explain the findings of the present study. Hasegawa et al. (2002) suggested that cognitive workload determines the amount of neural activation. If it is the case, greater activation should be observed for relative

Table 1 – Examples of the embedded and conjoined sentences used in the experiment

Embedded sentence in English:
The director that the maid introduced ignored the farmer.

Conjoined sentence in English:
The maid introduced the director and ignored the farmer.

Embedded sentence in Korean:
감독이[1] 농사꾼을[2] 소개한[3] 가정부를[4] 외면했다[5].

Pronunciation : Kamdok-i[1] nongsakun-eul[2] sogaeha-n[3] kajungbu-lul[4] oemyeonhai-ss-ta[5].

Meaning : 'The director–*subj*'[1] ['the farmer–*dir obj*'[2] 'introduced']–*Rel' inflection*[3] 'the maid–*dir obj*'[4] 'ignored'[5]
(The director ignored the maid who introduced the farmer.)

Conjoined sentence in Korean:
감독이[1] 농사꾼을[2] 소개하고[3] 가정부를[4] 외면했다[5].

Pronunciation : Kamdok-i[1] nongsakun-eul[2] sogaeha-ko[3] kajungbu-lul[4] oemyeonhai-ss-ta[5].

Meaning : 'The director–*subj*'[1] 'the farmer–*dir obj*'[2] 'introduced–*and*'[3] 'the maid–*dir obj*'[4] 'ignored'[5]
(The director introduced the farmer and ignored the maid.)

sentences than for conjoined sentences and the difference between the sentences should be greater for L2 than L1. On the other hand, Yokoyama et al. (2006) suggested that morphological and thematic differences might have caused different patterns of activation. Morphologically, the extra word ('be') in English passive sentences and the need for greater reanalysis in Japanese passive sentences brought about different patterns of activation in L1 and L2 in different cortical areas, according to Yokoyama et al. (2006). In the present study the conjoined and relative sentences have the same number of words in Korean and English, respectively. The morphological devices used to change conjoined sentences into relative sentences were different in Korean vs. English in that Korean used relative marker and English used relative pronoun. It is not yet known whether relative marker and relative pronoun produce different neural activation. As for the thematic factor, Korean and English do not have the kind of difference in thematic device used to change the conjoined to relative sentences. Therefore, given the same number of words for the two types of sentences in each language and similarity between the thematic devices, the patterns of neural activation should be less different in the present study than in Yokoyama et al. (2006) if morphological or thematic factors mainly contribute to the amount of neural activation.

In a series of studies, the syntactic complexity was varied using conjoined and relative sentences, and its effects on brain activation for L1 were reported (Just et al., 1996; Caplan et al., 1998; Keller et al., 2001; Fiebach et al., 2005; Inui et al., 1998). For example, Just et al. (1996) visually presented the subjects with sentences that were different in syntactic complexity but were the same in other aspects such as the length of the sentence and the words used. Syntactic complexity was varied in three levels where the lowest complexity was represented by conjoined sentences (The reporter attacked the senator and admitted the error.), medium complexity by sentences with a subject relative clause (The reporter that attacked the senator admitted the error.), and the highest complexity by the sentences with an object relative, center-embedded clause (The reporter that the senator attacked admitted the error). They found that the volume of brain activation, as measured by functional magnetic resonance imaging, increased as the syntactic complexity of the sentences increased in four brain areas: the left laterosuperior temporal cortex (Wernicke's area), the left inferior frontal gyrus (Broca's area), and their homologous right hemisphere areas. Just et al. (1996) interpreted these results as showing that the amount of activation at the brain level was dependent upon the amount of computational demand that the task imposed at the cognitive level.

While Just et al. (1996) discussed their results in terms of a general computational process rather than a more specific process such as a syntactic or semantic one, Caplan et al. (1998) provided some evidence to suggest that neural activation due to different syntactic complexity was relevant to the syntactic process. They conducted a study in which they varied the propositional density as well as syntactic complexity to examine the effects of their variation in PET. They found that, while neural activation measured by regional cerebral blood flow (rCBF) increased as syntactic complexity and propositional density, the areas showing the increase were different for the two types of variations. rCBF increased in the left pars opercularis, and part of Broca's area when subjects processed syntactically more complex sentences while no increase in rCBF was found in that area when subjects processed sentences with two propositions, compared to those with one proposition. On the other hand, the inferoposterior brain regions showed an increased rCBF with the sentences with a larger number of propositions but not with a more complex syntactic structure. The fact that the areas showing the increased activation are variable according to the kinds of different complexity suggests that those areas are not just for general computational demand but are involved in more specific components of sentence processing.

The main purpose of the study was to compare the effects of syntactic complexity on brain activation for L1 and L2 in order to investigate whether the neural mechanism of L1 and L2 are the same or not. The issue of whether the areas of activation overlap or not for L1 and L2 was examined. Furthermore, patterns of activation as a function of syntactic complexity were compared for L1 and L2 to explore how the neural mechanisms of late bilinguals underlie syntactic processing. The patterns of activation for L1 and L2 were compared with those reported by Hasegawa et al. (2002) and Yokoyama et al. (2006) to determine which interpretation explained the results better.

The Korean language is in marked contrast to English, both morphologically and structurally. Korean is head-final and left-branching, has an order of subject-object-verb, permits scrambling, and allows phonological null arguments and adjuncts. Typologically, Korean is classified into an agglutinative language with a rich morphology (Suh, 1994). These differences can profoundly affect the flow of information while a sentence is heard or read, and the possibility that sentences with different levels of complexity might be dealt with differently for Korean and English cannot be excluded. Therefore, it is worthwhile to determine whether the effects of syntactic complexity in brain activation are the same for these two contrasting types of languages when they are used as a native language.

Since the goal of this study was to investigate the neural mechanisms underlying syntactic processing, it is important to ensure that what is varied is the level of difficulty in syntactic structure while other factors remain constant, to the extent possible. Although other studies have attempted to control extraneous factors by using the same words, the pre-existing semantic association among the words provided different semantic or pragmatic cues for different sentences. For example, in Just et al. (1996) and Keller et al. (2001), they used sentences such as "The reporter that the senator attacked admitted the error" as the most difficult center-embedded structure and "The reporter attacked the senator and admitted the error" as the easiest conjoined structure. Although the syntactic structure is more complex for a center-embedded sentence, the pragmatic situation the sentence is describing is more familiar and clearer than that of the conjoined sentence, making the center-embedded sentence easier to understand. On the other hand, for such sentences as "The actress that the award thrilled praised the producer" as a center-embedded structure and "The award thrilled the actress that praised the producer" as an easier right-branching structure (Stromswold et al., 1996; Caplan et al., 1998), the center-embedded structure becomes even more difficult due to the fact that "the actress that the award thrilled" is an unfamiliar expression. Therefore, in the present study, care was taken to ensure that there are no lexical or semantic associations between the role and the actions of the characters in the stimulus sentences. For example, in the sentence shown in Table 1, "The director that the maid introduced ignored the farmer", the director's action of ignoring the farmer or the maid's action of introducing the director cannot be derived from the lexical, semantic, or pragmatic cues of the sentences. This way, the difference observed for each sentence type can be attributed to syntactic complexity, and not to other factors.

Findings of this study will provide a useful comparison with previous studies in the sense that the present study focused on the syntactic component among the different components of sentence processing. If the patterns of activation due to syntactic complexity are found to be different for L1 and L2, this would suggest that the neural mechanisms of syntactic processes for L1 and L2 are different for late bilinguals.

2. Results

2.1. *Behavioral results*

The results for accuracy and reaction times for the comprehension task are presented in Tables 2 and 3, respectively. These data were analyzed by an analysis of variance for the effects of sentence type, language and their interaction. Concerning accuracy, there was no significant effect of language ($F(1,15)=1.00$, $p>0.33$). As for the sentence type, the accuracy of the conjoined sentence was higher than that of the relative sentence ($F(1,15)=13.85$, $p<0.002$). There was no interaction between language and sentence type ($F(1,15)=0.41$, $p>0.53$).

Regarding reaction times, data for incorrect responses were discarded. In the analysis of variance, the reaction times were faster for Korean than for English ($F(1,15)=6.75$, $p<0.04$). The reaction times for conjoined sentences were faster than those for relative sentences ($F(1,15)=5.45$, $p<0.04$). The interaction between the two variables was not significant ($F(1,15)=0.39$, $p>0.53$).

2.2. *Functional activation results*

Table 4 shows the areas of activation for each condition of language and sentence type, which were compared to the baseline. The bilateral inferior parietal gyrus, left IFG, left middle frontal gyrus, and right lingual gyrus were found to be activated for both Korean and English. Based on the analysis of contrast with the baseline, the regions that were activated only for L1 were the left medial/superior frontal (BA 8) gyrus, the left lingual gyrus, and the right fusiform gyrus, whereas the regions of the left cingulate gyrus and left fusiform gyrus were activated for L2 only (Fig. 1).

To examine the effects of syntactic complexity on the area of activation in the processing of each language, the subtraction of the conjoined sentence conditions from the embedded sentence condition was performed. As shown in Table 5, the left middle frontal gyrus (BA 8), the left precuneus (BA 7), and the left inferior parietal gyrus (BA 40) were observed for L1. There were no areas reported after subtraction for L2 at the aforementioned threshold level. In order to observe the effect of syntactic complexity more directly, a comparison was made between the two sentence types of each language in which the embedded sentence condition was subtracted from the conjoined sentence condition.

Table 2 – Mean comprehension accuracy with standard deviations for embedded and conjoined sentences in English and Korean (%)

	English	Korean
Embedded	85.2 [14.6]	80.5 [11.2]
Conjoined	93.0 [9.1]	93.0 [11.2]

Table 3 – Mean reaction times with standard deviations for embedded and conjoined sentences in English and Korean (msec)

	English	Korean
Embedded	2062 [368]	1991 [329]
Conjoined	1882 [325]	1799 [288]

To detect language specific differences in each sentence type, the embedded and conjoined sentence conditions were compared for L1 and L2. In contrast to Korean (L1) minus English (L2) for the embedded sentence shown in Table 5, several areas of the left middle frontal (BA 10/8), the right superior/medial frontal (BA 8), and the left inferior frontal (BA 47) were activated. The left lingual gyrus or cuneus (BA 18), the right inferior parietal (BA 40), the right precentral gyrus (BA 6), and the right middle temporal gyrus (BA 21) were also activated. In contrast to English minus Korean, activation of the bilateral cuneus (BA 18/19) and the left precentral gyrus (BA 6) was observed (Fig. 2). Table 5 also shows the results of contrasts between L1 and L2 for conjoined sentences. In contrast to Korean minus English, the insula, the left lingual gyrus (BA 18), and the middle frontal gyrus (BA 8) were reported. No area was reported in the contrast of English minus Korean at the same threshold level (Fig. 3).

In the results of the signal intensity analysis of ROIs, the left IFG was the only area that showed a significant effect among the regions tested. As shown in Fig. 4, the effect of syntactic complexity was found to be significant ($F(1,15)=14.39$, $p<0.0005$), but the effect of language was not ($F(1,15)=0.02$). A significant effect of the interaction between syntactic complexity and language was found in IFG ($F(1,15)=5.24$, $p<0.05$). In order to find the source of the interaction, tests for a simple main effect were performed for sentence type and language. A significant difference due to the sentence type was found for L1 ($F(1,15)=36.66$, $p<0.0001$), but not for L2 ($F(1,15)=0.06$). For L1, the amount of activation was greater for the embedded sentence than for the conjoined sentence. There was no significant effect of language either for embedded or conjoined sentences.

3. Discussion

3.1. Behavioral results

In the behavioral results of the sentence comprehension tasks, significantly higher accuracies and shorter reaction times were observed for conjoined sentences compared to embedded sentences for both L1 and L2. Concerning the effect of language, accuracy and reaction times showed different patterns; L1 and L2 were different in reaction times, but not in accuracy. The subjects responded faster in L1 than in L2. The embedded sentences of L2 had a higher accuracy than that of L1 although the difference was not significant ($F(1,15)=1$, $p>0.33$).

The different patterns of accuracy and reaction times may be due to the possibility that different behavioral measures such as reaction times, accuracy, or recall are affected by different aspects of a comprehension task (Prinzmetal et al., 2005; Kim, 2005). For example, in a study in which subjects read the same content of texts in L1 and L2, Kim (2005) found

Table 4 – Activated regions in L1 and L2 for embedded and conjoined sentences compared to the baseline ($p<0.00001$ at the single voxel level)

Contrasts	Cerebral area	Brodmann area and Side	x, y, z (mm)	No. of voxels	Z-value
Korean (embedded)	Inferior parietal gyrus	40L	−38, −50, 46	415	5.41
	Middle frontal gyrus	9L	−48, 10, 36	55	5.55
	Medial/superior frontal gyrus	8L	−6, 16, 48	101	5.4
	Lingual gyrus	18R	20, −90, −12	26	5.28
	Lingual gyrus	18L	−24, −92, −14	95	5.28
	Inferior parietal gyrus	7R	34, −64, 46	78	4.83
	Inferior frontal gyrus	47L	−38, 15, −4	35	4.5
English (embedded)	Inferior frontal gyrus	46L	−44, 24, 16	77	6.57
	Cingulate gyrus	32L	−6, 24, 40	117	6.02
	Inferior parietal gyrus	7L	−34, −60, 46	92	5.7
	Fusiform gyrus	18L	−24, −94, −15	14	5.05
	Inferior parietal gyrus	7R	36, −58, 52	25	4.84
Korean (conjoined)	Lingual gyrus	17L	−16, −90, −12	266	5.75
	Inferior parietal gyrus	7L	−34, −62, 45	302	5.46
	Medial frontal gyrus	6L	−2, 10, 50	205	5.37
	Inferior frontal gyrus	44L	−50, 8, 30	109	5.27
	Fusiform gyrus	18R	24, −90, −10	75	5.16
English (conjoined)	Medial frontal gyrus	6L	−2, 10, 60	289	5.97
	Inferior parietal gyrus	7R	34, −62, 46	138	4.94
	Lingual gyrus	18R	12, −90, −10	76	4.92
Korean (embedded vs. conjoined)	Inferior parietal gyrus	40L	−38, −52, 46	130	4.55
	Precuneus	7L	−8, −70, 46	36	4.51
	Middle frontal gyrus	8L	−46, 16, 46	45	4.24

The three low lines indicate the activated regions of the contrast embedded sentence vs. conjoined sentence within L1 ($p<0.001$ at the single voxel level). There is no activation area in the case of L2.

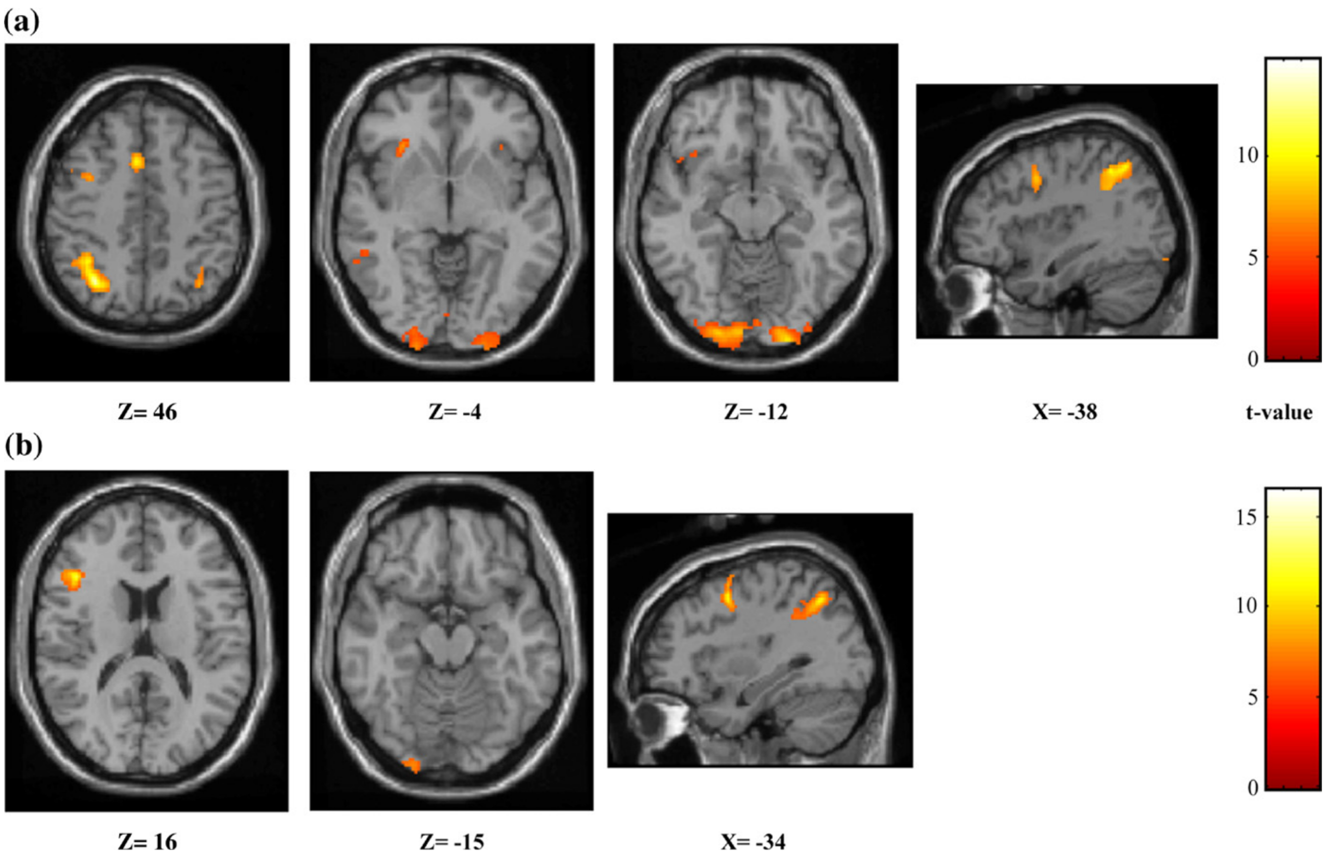

Fig. 1 – Activation map of the regions in L1 (a) and L2 (b) for embedded sentences compared to the baseline ($p<0.00001$ at the single voxel level).

that the reading times were longer for L2 than for L1 but that the amount of text recalled was not different for L1 and L2 although which specific information they recalled differed. In her study, the texts were sufficiently easy for the subjects to understand and remember. In the present study, the subjects were fluent sufficiently to correctly comprehend the sentences. In the present study and Kim's (2005), it can be suggested that accuracy was not affected by the language but

Table 5 – Activated regions for direct comparison between embedded sentences in L1 and L2 ($p<0.001$ at the single voxel level)

Contrasts	Cerebral area	Brodmann area and Side	x, y, z (mm)	No. of voxels	Z-value
Korean minus English (embedded)	Middle occipital gyrus	18L	−26, −80, 2	33	3.94
	Cuneus	18R	8, −85, 14	56	3.68
	Inferior parietal gyrus	40R	50, −34, 46	22	3.52
	Precentral gyrus	6R	−60, 0, 30	19	3.21
	Lingual gyrus	18L	−16, −76, 6	14	3.13
	Middle frontal gyrus	10L	−34, 45, 8	15	3.09
	Superior/medial frontal gyrus	8R	4, 30, 48	29	3.08
	Middle frontal gyrus	8L	−40, 24, 44	12	2.97
	Inferior frontal gyrus	47L	−42, 23, −10	11	2.95
	Middle temporal gyrus	21R	62, −10, −20	12	2.88
English minus Korean (embedded)	Cuneus	19R	30, −80, 30	137	3.84
	Precentral gyrus	6L	−18, −34, 50	11	3.70
	Cuneus	18L	−18, −70, 24	11	3.23
Korean minus English (conjoined)	Insula		−38, 7, 10	56	4.02
	Lingual gyrus	18L	−30, −68, −2	21	4.0
	Middle frontal gyrus	8L	−32, 20, −18	31	3.8

The three low lines indicate the activated regions for direct comparison between conjoined sentences in L1 minus L2 ($p<0.001$ at the single voxel level). There is no activation area in the contrast of L2 minus L1.

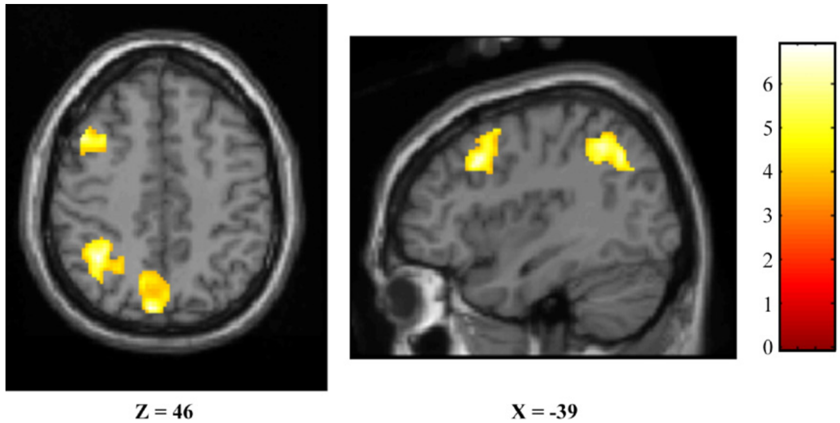

Fig. 2 – Activation map of regions in L1 for embedded sentences compared to conjoined sentences ($p < 0.001$ at the single voxel level).

reaction time was since the subjects were comfortably able to comprehend the sentences. It can be understood under the assumption that reaction times are easily affected by encoding process of stimuli which is more automatized in L1 than in L2 for late bilinguals.

There is a possibility that the behavioral results may not reflect the processing of sentences because they were obtained during the probe question task. Although the behavioral data about answering probe questions are certainly related to the processing of target sentences, they are only indirect indices for sentence processing.

3.2. Imaging results

In the results of the imaging data, the regions of the left inferior frontal, bilateral inferior parietal, and occipital (including cuneus, lingual gyrus) lobe appeared to be commonly activated in the processing of both L1 and L2. Activation of the left IFG during linguistic processing is generally well known. Specifically, the role of the anterior part of the IFG (located close to the pars triangularis) is assumed to be related to semantic processing. This region appears to be important for executive aspects of semantic processing whereas the possibility remains that this region also performs a more general function. It is perhaps involved in making comparisons or judgments among information held in the working memory that underlies the aspect of semantic processing as well as other nonlinguistic processes (Horwitz et al., 1998). Other regions of the IFG such as superior part of the IFG or Broca's area are known to be specialized for syntactic and phonological processing as well. In this sense, the IFG appears to be one of those regions where different aspects of language processing interact with each other to deliver highly complex and interactive human language processing. The activation of a large area of the IFG

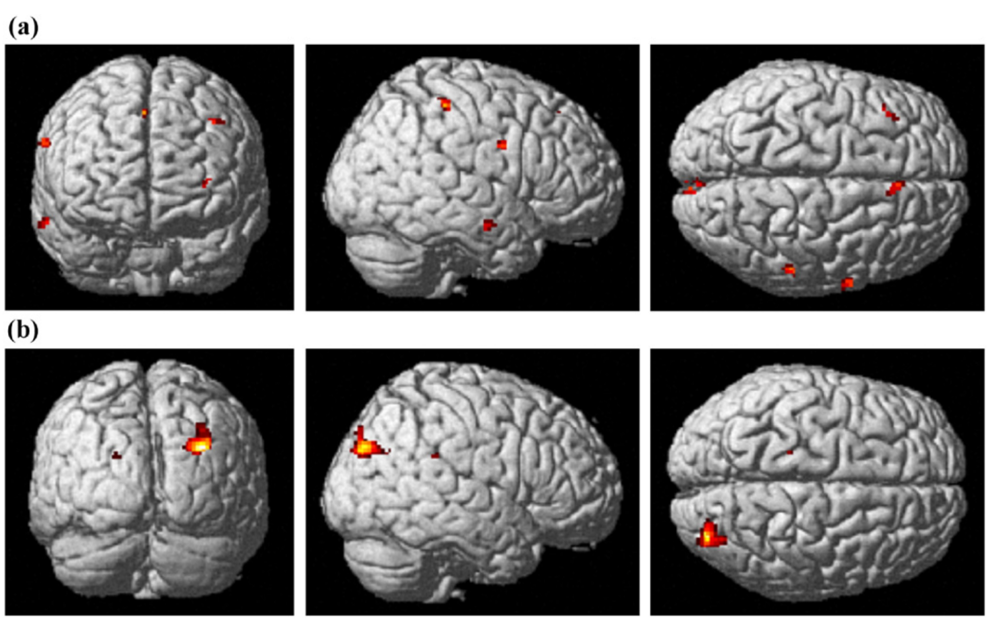

Fig. 3 – Activation map of regions for the direct comparison between embedded sentences in L1 and L2 ($p < 0.001$ at the single voxel level).

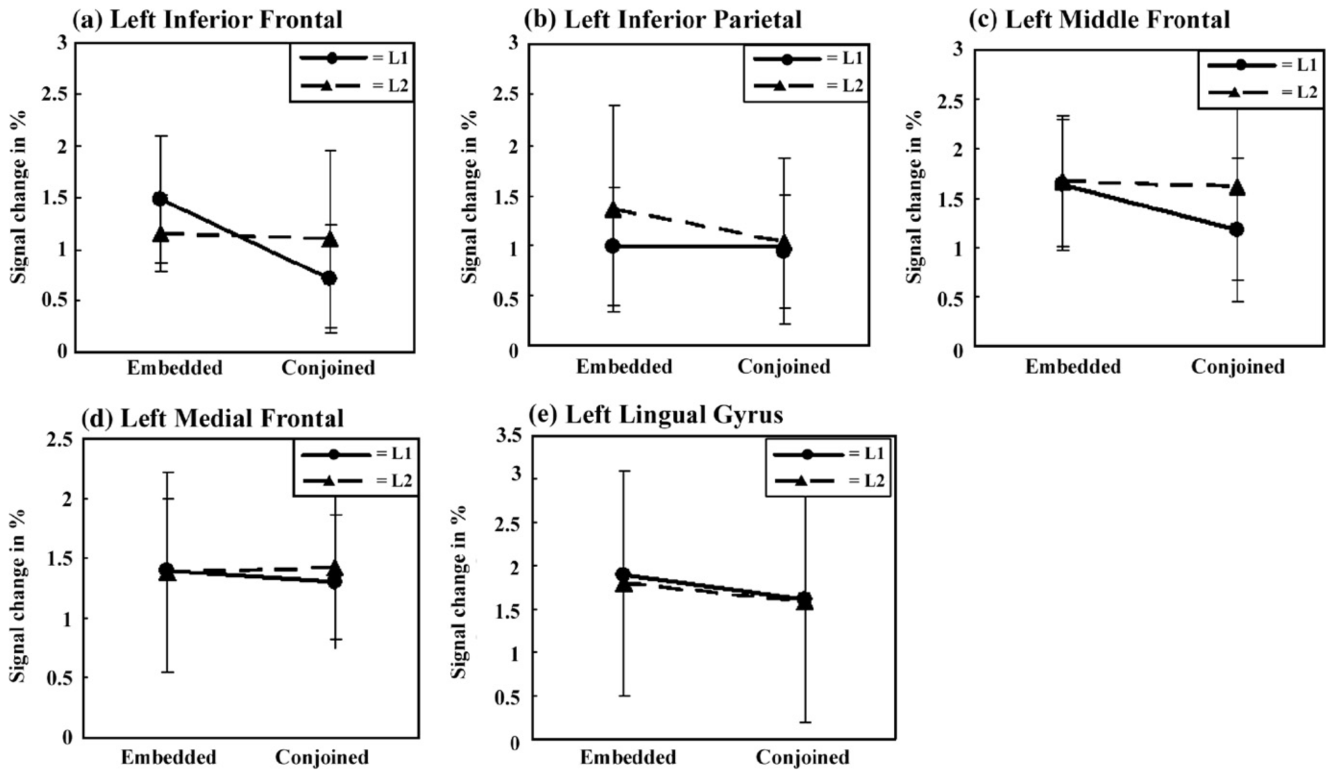

Fig. 4 – Signal intensity analysis of areas of interest. The detection of a signal is based on a comparison to baseline conditions of both languages and sentence types. Significant difference was detected only in the region of the left inferior frontal gyrus in the case of L1 (details in the text).

both for L1 and L2 in the present study agrees with the findings of the previous studies concerning IFG (Bookheimer, 2002; Nakai et al., 1999).

Activation of the inferior parietal region is generally known to be associated with the semantic or orthographic processing of a single word (Demonet et al., 1992) and the implication of developmental dyslexia (Horwitz et al., 1998). However, Keller et al. (2001) interpreted the activation of this area as possibly reflecting a larger role for the maintenance of phonological representations of surface structures of a sentence and some minor role related to recording visual information into a phonological form. Such an interpretation is consistent with the present study since the stimuli were presented visually and the subjects were required to transform orthographic representations possibly into phonological representations in order to maintain the surface structure of the sentences during comprehension. Since we presented sentences as visual stimuli, the activation of this parietal region (probably together with the frontal eye field region, nearby middle frontal) might be also reflected due to the subjects' eye movement (Pierrot-Deseilligny et al., 2004; Yoon et al., 2005).

While the activation of the occipital area has not been interpreted as directly involved with sentence comprehension, some studies provided evidence that extrastriate temporal/occipital region has a role in both orthographic and semantic processes that are related to lexical access (Keller et al., 2001). Therefore, the activation of this area in the present study might be related to lexical processing of words that were visually presented.

In conclusion, the areas of activation during the processing of L1 and L2 overlap considerably especially in the areas of the left IFG, the bilateral inferior parietal, and occipital lobe. Although there were some areas of activation specific to either L1 or L2, most of the major areas that are known to be involved with language processing showed activation for both languages. These results are consistent with finding reported by Hasegawa et al. (2002) and Yokoyama et al. (2006) in which they also found a significant overlap between the areas of activation during L1 and L2 processing.

As mentioned in the results section, a direct comparison was made between the two sentence types of each language in which the embedded sentence condition was subtracted from the conjoined sentence condition. According to this analysis, a different level of syntactic complexity resulted in the differential activation of brain areas for L1, especially around the left middle frontal gyrus (MFG). However, this differential activation was not observed for L2 at least at the aforementioned threshold level. This result is discussed in conjunction with that of a signal intensity analysis as follows.

3.3. *Signal intensity analysis in regions of interest*

The patterns of activation were examined through a signal intensity analysis. The language did not have a significant effect on the amount of activation. Although L2 is often expected to invoke a greater amount of activation than L1 on the grounds that L2 requires more computation (Yoon et al., 2006; Chee et al., 2001), it was not confirmed in the present study. This result is in agreement with that of Yokoyama et al. (2006) but is in contrast with Hasegawa et al.'s (2002) findings. Yokoyama et al. (2006) attributed this inconsistency to the fact that their stimuli sentences were easy. While the level of difficulty of the stimuli can be a factor for Yokoyama et al.'s (2006) study, the stimuli in the present study were not easy. In fact, embedded sentences are regarded to be considerably difficult not only for L2 but also for L1 since semantic and pragmatic cues were eliminated to the extent possible.

One of the factors that could contribute to the difference of L1 vs. L2 in the amount of activation is the manner in which the material was presented in the experiments. The present study and Yokoyama et al.'s (2006) presented the stimuli visually while Hasegawa et al. (2002) presented them auditorily. Studies have shown that listening and reading comprehension are affected differently by different factors such as linguistic or the background knowledge of the comprehender and the characteristics of the material (Rubin, 1994). More specifically for L2 comprehension, Park (2000) found that top-down factors such as background knowledge affected listening comprehension more than reading comprehension in L2, while linguistic knowledge affected both types of comprehension to a similar degree. Considering the fact that people resort to top-down processes when the encoding of a stimulus is more ambiguous, the greater activation in L2 may, in general, be attributed to the encoding processes of listening comprehension. In addition, all the participants of these studies, including the present study, were late bilinguals who were advanced in their education and familiar with reading comprehension in L2 which was English. For these participants, auditory input is likely to be more ambiguous and difficult to decode than visual input.

Another important result of the signal intensity analysis is that a significant interaction between language and syntactic complexity was found in the left IFG. The amount of activation was greater for embedded sentences than for conjoined sentences in L1 but no difference was found in L2 (Fig. 4). This effect of interaction was not found in any other regions of interest. These results provide several points for discussion.

First, regarding the effect of syntactic complexity in L1, the present study replicated the results of the previous studies, in which the left IFG showed an increased activation for more complex sentence structures. While the locations of increased activation in the previous studies using syntactic complexity varied from the left inferior frontal gyrus or the pars opercularis of Broca's area, the left medial frontal gyrus, the left laterosuperior temporal cortex (Wernicke's area) to the right homologous areas of Broca's and Wernicke's, it should be noted that the activated area common to all these studies was the IFG (a part of Broca's area), where this study found an increased activation. This suggests that the IFG is the area that is most reliably affected by syntactic complexity processing.

On the other hand, all the other studies found that areas other than the IFG were affected by syntactic complexity although they did not agree on which specific areas were affected. Since the studies were different in sentence structures (two vs. three levels of syntactic complexity), tasks (comprehension probe vs. plausibility judgment), and data analysis (fMRI vs. PET), it is understandable that there were differences in the exact locations of activation and at the same time, it was difficult to pinpoint which factors caused certain areas to be affected. As mentioned earlier, one of the characteristics of the present study is that the possible influence of other factors rather than syntactic complexity was eliminated from the stimulus sentences. The reason for why only the IFG area was found to show increased activation could be attributed to this exclusive role of syntactic cues used in this study. This interpretation is consistent with the view that the left IFG is strongly involved with syntactic processing.

Second, the fact that the effect of syntactic complexity found in L1 was not observed in L2 suggests that the neural mechanisms of L1 and L2 processing are not identical, at least in their neural response to different levels of syntactic complexity. As mentioned earlier in the discussion of imaging results, additional activation was reported for embedded than conjoined sentences around the MFG area in L1 but no such difference was found in L2. However, the areas of differentiation in L1 were different in the intensity analysis vs. the area analysis; the IFG for the case of the intensity analysis and the MFG for the area analysis. Based on previous studies using syntactic complexity in L1, the IFG seems to be the area responding as a function of syntactic complexity. As for the left MFG, previous research suggests that the area may be involved with working memory (Leung et al., 2002; Zhang et al., 2003). The differential activation of the left MFG may reflect the differential working memory load of the two sentence types in L1 since the difficulty in processing the embedded sentences arises, in part, from the demand to retain the relative clause in working memory until its syntactic structure is parsed. The reason why the subtraction analysis and ROI analysis produced different results is not clear at this point and requires further investigation.

This finding is different from that reported by Hasegawa et al. (2002) where the difference in the amount of activation due to sentence complexity was more pronounced in L2 than in L1. Hasegawa et al. interpreted their results by assuming that one source of difficulty (e.g. syntactic complexity) in processing adds an extra load for another source of difficulty (e.g. second language). Their interpretation cannot explain the results of the present study since the difference of activation was found for L1 but not for L2 in this study. Yokoyama et al.'s (2006) interpretation, which attributed the effect to morphological or thematic differences in languages, cannot be readily applied. There may be morphological or thematic differences between two types of sentences, but such differences appear similarly in each language.

While the reasons for these findings need to be investigated in future studies, some suggestions can be made. The difference between L1 and L2 could be due to the fact that certain syntactic processes are automatized in L1 but not in L2. That is, for L1, easier syntactic structures such as conjoined sentences are exposed frequently and thus their processes are automatized. For more difficult structures such as embedded sentences, however, their processing is not automatized even for L1. Such differences in processing strategies might result in differences in activation patterns in L1. On the other hand, the processing of sentences in L2 is not likely to be automatized regardless of the difficulty level, which is why no difference between two sentence structures was observed.

In conclusion, a large proportion of areas was commonly activated for the processing of L1 and L2 in the present study. The left inferior frontal, bilateral inferior parietal, and occipital (including cuneus and lingual gyrus) lobe were activated for both L1 and L2 processing. This activation is in agreement with other studies of language processing. In addition, the present study found that the neural mechanisms responding to the different levels of syntactic complexity were different for the processing of L1 and L2. The location for responding to different levels of syntactic structure was shown to reside in the IFG area for L1. Regarding L2, such a location was not clear. It can be speculated that the manner of processing different syntactic structures are similar for L2 while they are different for L1. It is also possible that the intensity of neural activation is not necessarily greater for L2 than for L1 when the stimuli were visually presented.

The results of the present study and those of other previous studies relevant to the issue indicate the complexity of the neural and cognitive mechanisms underlying sentence comprehension. When it comes to the issue of a bilingual's language processing, it becomes even more complex due to interactions among the factors such as the age of acquisition, mode of input, and phonological, syntactic, or semantic features of a specific language.

4. Experimental procedures

4.1. *Participants*

Sixteen subjects (14 male and 2 female) aged between the ages 19 and 29 (average=22.9) participated in the experiment. All were native speakers of Korean and started to learn English as a foreign language in junior high school. The level of English proficiency, as measured by the TOEFL (CBT) test, was between 230 and 283 (average=249). The subjects had no history of any medical, neurological, or psychiatric illness, past or present, and were not taking any medication. All of the subjects consented to the protocol.

4.2. *Materials*

Sixteen sentences as shown in Table 1 were created for each of four conditions (two sentence types for two languages). All of the subjects and objects of the sentences were nouns referring to occupations of people. The sentences were constructed so that there were no predictable semantic relations among the subjects, objects, and verbs of the sentences. For the comprehension task, a proposition from the stimulus sentence (relative or conjoined) was used. For example, for the stimulus sentence of "The director that the maid introduced ignored the farmer", the correct comprehension sentences are "The maid introduced the director" and "The director ignored the farmer".

4.3. *Experimental design*

Before the fMRI experiments, the subjects participated in a practice session where they were given instructions and were exposed to the practice material. Once the fMRI session began, each subject participated in 8 epochs in which he or she responded to 16 sentence stimuli. The sentences were presented in one of the two languages (Korean or English) in the first four epochs and the sentences in the other language were presented in the second four. Each epoch consisted of two trials and lasted approximately 24 s. In each trial, a sentence stimulus either in a relative clause type or a conjoined type was presented for 5.5 s. The presentation time of 5.5 s was decided based on a pilot study and a previous study by Kim (1995). The pilot study found an average reading time of 5.04 for the sentences used in the study. In Kim (1995) 's study which used similar material, the average reading time for relative sentences was 5.56. Therefore, it was decided that the sentences were to be presented for 5.5 s. The sentences were presented all at once in two lines. With a 500-ms interval after the stimulus presentation, a comprehension task, which was presented at the same fashion, was given in order to ensure that the participants understood the sentences they read. For this task, a comprehension sentence was presented and the subject was asked to decide whether the sentence was correct or not based on the stimulus sentence. The same type of sentences was used in both trials of an epoch. The order of language, the type of sentences, and the question type were all counterbalanced. After each epoch, an 18 s of rest period was given before the next epoch.

4.4. *Data acquisition and analysis*

Visual sentences were produced using E-prime (Psychology Software Tools Inc., Pittsburgh). Images were acquired using a 3-T MRI scanner (ISOL Technology, Korea). Following a T1-weighted scout image, high-resolution anatomic images were acquired using an MPRAGE (Magnetization-Prepared RApid Gradient Echo) sequence with TE=3.7 ms, TR=8.1 ms, flip angle=8°, and an image size of 256×256. T2*-weighted functional data were acquired using echo planar imaging (EPI) with a TE of 37 ms, a flip angle of 80°, a TR of 3000 ms, and an image size of 64×64. The FOV was 220×220 mm. We obtained 30 slices of EPI images with a slice thickness of 5 mm, with no gaps between the slices for the entire brain. Image data were analyzed using SPM 2 (Wellcome Department of Cognitive Neurology, London). The images for each subject were corrected for motion and realigned using the first scan of the block as a reference. T1-weighted images were coregistered with the mean of the functional scans, then aligned to the SPM T1 template in the MNI (Montreal Neurological Institute) space and realigned to the Talairach space (Talairach and Tournoux, 1988). A calculated nonlinear transformation was applied to all images for spatial normalization. Finally, the images were smoothed using a 7-mm full-width at half-maximum (FWHM) Gaussian filter. In order to calculate contrasts, the SOA (stimulus onset asynchrony) from the protocol was defined as epochs and convolved with the hemodynamic response function (HRF) to specify the appropriate design matrix. Condition and subject effects were estimated using the general linear model at each voxel in the brain. Significant changes in the hemodynamic response for each subject and condition were assessed using *t*-statistics. For the group analysis, single subject contrast images were analyzed using a random effect model. Activations were reported if they exceeded a threshold $p<0.00001$ (uncorrected) on the single voxel level for the task of the all sentence types and languages vs. baseline. This means that the aforementioned p-value is chosen, if the presentation tasks are contrasted to the baseline condition. The threshold $p<0.001$ (uncorrected) at the single voxel level was chosen for the direct comparison of the language and sentence conditions. This p-value is valid if the experimental tasks (sentence types of both languages) are compared with each other. Activations are based on the extent of ten voxels.

In order to determine the effects of syntactic complexity and language of each activated area, the ROI analysis was performed. For the comparison of the intensity of activation, we selected the significantly activated clusters if each sentence types and languages (four different types of conditions) were contrasted with the control baseline task. Mean signal changes were calculated in each ROI for each subject in each condition. ANOVAs were conducted for all conditions, and a post hoc comparison was performed. The regions of interest (ROI) encompass most of the regions that are known to be involved in sentence comprehension including the bilateral inferior frontal, inferior parietal, middle frontal, lingual gyrus, medial/superior frontal gyrus, and the superior/middle temporal gyrus. These regions include all of the areas that showed the effects of different syntactic complexity and languages in other studies.

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