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Chapter V

Brain Mapping of Human Language Processing

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Abstract

There is a tacit assumption in neuroscience from the genetic to the systems level, which holds that the biological foundations of humans are essentially similar to those of nonhuman primates, and that even human language can be understood by extending experiments with monkeys and apes. In accordance with this prevailing view, it has been assumed that language processing is, in principle, not entirely different from the combination of other cognitive functions commonly found in monkeys and humans. However, it has been known that human language is radically different from what is known as animal communication. The most distinct faculty of language is the property of *discrete infinity*, the ability to generate an infinite range of discrete expressions from a finite set of elements. Sentences are indeed such infinite expressions generated from a limited set of sounds, signs, or letters. Therefore, sentence comprehension characterizes human languages, and its neural basis would be uniquely human.

In this review article, I will focus on three fundamental issues concerning language processing in the human brain, and update recent advances made by brain mapping studies of language. First, I will provide the first experimental evidence that the neural basis of sentence comprehension is indeed specialized. Specifically, our recent functional magnetic resonance imaging (fMRI) and transcranial magnetic stimulation (TMS) studies have proved that the left dorsal inferior frontal gyrus (IFG) is more specialized in the syntactic processes of sentences than other general cognitive processes such as short-term memory. These results suggest that the left IFG is specialized in grammatical

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processing, which is thus referred to as the *grammar center*. Second, we have recently discovered that the activation increases of the grammar center were *positively* correlated with individual performance improvements during the early phase of second language (L2) acquisition, and that they were *negatively* correlated with individual performances during the later phase of L2 acquisition. These results further suggest that the cortical plasticity for L2 acquisition specifically involves the left IFG, observable even in adolescents. Third, we have established that the network of the subregions in the left IFG and the left lateral premotor cortex (LPM) is consistently involved in comprehension of sentences, irrespective of the modalities of signs, speech sounds, and written words. The current direction of research in systems neuroscience contributes to clarifying that the left-lateralized brain regions subserves comprehension of sentences, which is universal among any human languages.

Introduction

Linguists have provided a clear conceptualization of what distinctions need to be made between syntactic processing and other cognitive processes in order to account for linguistic competence (Chomsky, 1980). Recently, Hauser, Chomsky, and Fitch have proposed that *recursion* is the only uniquely human component of the faculty of language (Hauser et al., 2002), which is also known as the property of *discrete infinity*, the ability to generate an infinite range of discrete expressions from a finite set of elements. Sentences are indeed such infinite expressions generated from a limited set of sounds, signs, or letters. Chomsky has proposed that this property is instantiated in human languages by syntactic mechanisms (Chomsky, 2000). Our position is that sentence comprehension characterizes human languages, and that its neural basis is uniquely human. The left-dominant cortical activations observed in language tasks involving sentences suggest that sentence comprehension is predominantly controlled by the left hemisphere, whereas there is no such clear functional lateralization for the general cognitive factors commonly found in primates. The cerebral dominance may thus represent the uniqueness of human language processing, and the identification of the left cortical regions responsible for the essential properties of linguistic computation eventually leads to an understanding of how language is specialized and instantiated in the human brain.

1. The Evidence of the "Grammar Center"

The specialization of language processing in human cognitive systems is one of the central issues in systems neuroscience, and it has been highly debated from a number of perspectives including lesion studies of Broca's aphasia and functional imaging studies of the human brain (Caplan et al., 1999; Friederici, 2002; Sakai et al., 2003). The narrowest definition of Broca's area is the left pars opercularis [F3op, Brodmann's area (BA) 44] and the left pars triangularis (F3t, BA 45), a part of the third frontal convolution (F3) or the left inferior frontal gyrus (IFG). However, the syndrome referred to as permanent Broca's aphasia arises from a considerably larger brain lesion that includes the insula and subjacent white matter (Mohr, 1976), and the region *medial* to Broca's area (the left precentral gyrus of the insula) has been implicated in the motor planning of speech (Dronkers, 1996). Recent functional magnetic resonance imaging (fMRI) studies have provided accumulating evidence that the *lateral* surrounding region of Broca's area, including the left IFG (F3op/F3t) and the left lateral premotor cortex (LPM; BAs 6/8/9, mainly in BA 8), is selectively related to grammatical processing (Fig. 1) (Stromswold et al., 1996; Dapretto and Bookheimer, 1999; Kang et al., 1999; Embick et al., 2000; Friederici et al., 2000b; Suzuki and Sakai, 2003). The left LPM locates close to the left precentral sulcus (PrCS). These left frontal regions can be suggested as the most likely candidate of the "grammar center".

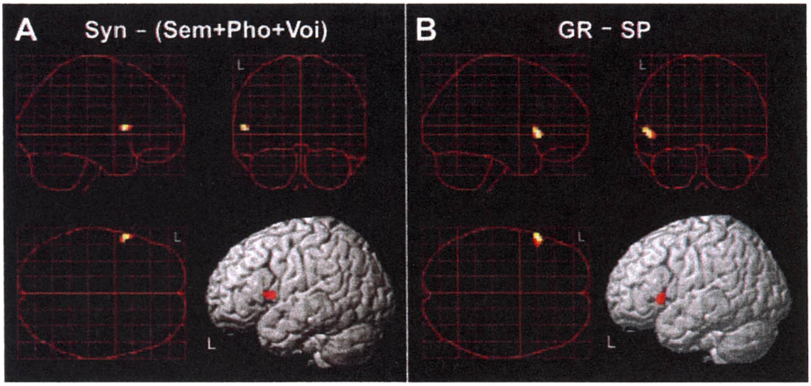

Figure 1. (**A**) Selective activation for explicit syntactic processing in the left F3op/F3t. Activated regions were identified by comparing a syntactic decision (Syn) task with other semantic decision (Sem), phonological decision (Pho), and voice-pitch comparison (Voi) tasks, combining normal and anomalous sentence conditions for each task (Suzuki and Sakai, 2003). They are projected in three orthogonal planes (sagittal, coronal, and horizontal from the top left panel) and onto a left (L) surface-rendered standard brain. (**B**) A syntactic specialization in the left F3op/F3t for detecting syntactic anomaly (Embick et al., 2000). Activation in a grammatical error-detection task (GR; explicit syntactic processing of ungrammatical sentences) was directly compared with that in a spelling error-detection task (SP; implicit syntactic processing of sentences containing spelling errors), revealing a single locus in the left F3op/F3t. The threshold was set at $p < 0.05$, corrected for multiple comparisons.

The most critical question to be addressed here is whether there exists a specialized (*domain-special*) neural system for human language processing that is separable from other *domain-general* systems. Activations of the left LPM have been attributed to the executive processes for working memory or to cognitive demands in general (Smith and Jonides, 1999; Duncan and Owen, 2000). However, there is no direct proof of one-to-one correspondence between brain functions and cortical regions, and it is possible that the left LPM is modulated primarily by domain-special factors and secondarily by domain-general factors. We recently tested this hypothesis by directly comparing the brain activations in syntactic decision tasks with those in verbal short-term memory tasks (Hashimoto and Sakai, 2002). In each trial of syntactic decision tasks, one complete sentence was presented to judge whether the subject of a verb corresponded to one of two persons, or to judge whether a pronoun was able to refer to one of two persons in the sentence. One example of a Japanese sentence used to represent the syntactic decision tasks was "*Taro-wa Saburo-ga kare-wo homeru-to omou*" ("*Taro thinks that Saburo praises him*"). These tasks explicitly required to utilize the structure-dependent rules. Using fMRI, we compared brain activation in these syntactic decision tasks with that in other two control tasks. In a short-term memory task for sentences, participants were presented with the same set of sentences as that used in the syntactic decision tasks, but were asked to memorize each phrase. Participants were then presented with a pair of phrases and judged their temporal order in the original sequence. While this judgment does not require explicit syntactic decisions, reading sentences obligatorily accompanies syntactic processes. In a short-term memory task for words, phrases of one sentence were rearranged into separate groups of nouns and verbs, so that they were syntactically unrelated. One example used in this task was "*kare-ni Taro-ni Saburo-ni omou homeru-to*" ("*him Taro Saburo thinks praises*"). A pair of phrases were then presented to judge their temporal orders in the original sequence, and this task was the most difficult one among the four tasks. The task requirements including memory encoding and retrieval are commonly involved in standard verbal short-term memory tasks. We found that the left IFG and the left LPM show selective activation for syntactic decision tasks when they were directly compared with each of the short-term memory tasks (Fig. 2; red regions). The activation of these regions is related to processes of analyzing syntactic structures, and it cannot be explained either by task difficulty or by short-term memory components such as the phonological store, the subvocal rehearsal system, and the central executive. To our knowledge, this study is the first to clarify that the left IFG and the left LPM are more specialized in the syntactic processes of sentence comprehension than other general cognitive processes.

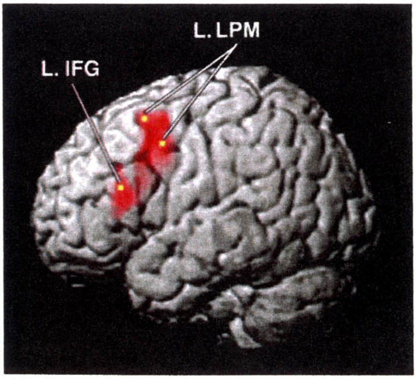

Figure 2. The grammar center in the left frontal cortex. Regions (red) identified by directly comparing syntactic decision tasks and a short-term memory task for words are projected together onto the left hemisphere of a surface-rendered standard brain.

The results of Hashimoto and Sakai (2002) have further suggested that there is a distinction between conscious, controlled sentence processing and unconscious, obligatory sentence processing. In that study, we found that the left LPM is activated when syntactic information is processed at the sentence level without explicit instructions, and that the left

IFG is additionally activated when explicit syntactic decisions are required. Consistent with these findings, our event-related fMRI study (Suzuki and Sakai, 2003) using the minimal-pair paradigm with auditory stimuli clearly established that the left F3op/F3t is involved more in *explicit* syntactic processing (as in the syntactic decision task) than in *implicit* syntactic processing (as in the semantic and phonological decision tasks) (Fig. 1A). Moreover, its activation is specific to syntactic judgments regarding both normal and anomalous sentences, which is consistent with the transcranial magnetic stimulation (TMS) (Sakai et al., 2002) and optical topography (OT) study (Noguchi et al., 2002). The left F3op/F3t activation in Suzuki and Sakai (2003) matched with that of our previous fMRI study testing an error detection in word orders (Fig. 1B) (Embick et al., 2000). The latter fMRI study contrasted explicit syntactic processing of ungrammatical sentences and implicit syntactic processing of sentences containing spelling errors, using the same lexical material across these conditions. We found that the ungrammatical sentences produced more activation in the cortical language areas than did the sentences with spelling errors, and that the difference in activation was significantly greater in the left F3op/F3t than in other language areas. Recent imaging studies from other labs have accumulated evidence of the involvement of the left LPM and the left IFG in syntactic processing (Stromswold et al., 1996; Just et al., 1996; Caplan et al., 1998; Dapretto and Bookheimer, 1999; Kang et al., 1999; Friederici et al., 2000b; Moro et al., 2001; Indefrey et al., 2001). In these studies, the syntactic knowledge of English, German, or Italian languages was tested in native speakers. Although various aspects of sentence processing are substantially different, the consistent activation of the left LPM and the left IFG in these studies and in our study using Japanese, a non-Indo-European language, suggests a universal role of the grammar center, i.e., universal grammar (UG) in the brain.

As proposed by Fodor, modular processes are by their very nature automatic and implicit (Fodor, 1983). The suggested specialization of the left LPM for implicit information processing in the syntactic domain indicates that it is a putative syntactic module. The activation of the left LPM due to non-syntactic tasks and non-automatic syntactic tasks reported in some previous studies does not necessarily contradict this hypothesis, because it is always difficult to control *automatic* syntactic factors involved in inner speech while thinking. In normal language comprehension, one does not explicitly but automatically process syntactic information. On the other hand, explicit syntactic processing is employed when sentence comprehension becomes more difficult, as in the case of garden-path or ambiguous sentences (e.g., "*The horse raced past the barn fell*"). In the presence of explicit task requirements like the syntactic task employed in our experiments, explicit syntactic processing is employed to judge the syntactic correctness of an utterance. Thus it follows that the regions activated by explicit syntactic processing involve all regions related to implicit syntactic processing as well as any additional regions. Indeed, our fMRI studies demonstrated that both the left IFG and the left LPM are activated when the explicit use of syntactic rules is required by the syntactic tasks (Hashimoto and Sakai, 2002; Suzuki and Sakai, 2003). Recent imaging studies using Jabberwocky sentences, in which all content words were replaced with pseudowords while inflections and function words were maintained to preserve grammatical structures, have indicated that the left IFG and/or the left LPM are involved in syntactic processing (Friederici et al., 2000a; Moro et al., 2001; Indefrey et al., 2001). These results support the involvement of at least two distinct frontal regions in syntactic processing.

The distinction between explicit and implicit syntactic processing raises a further question as to whether the left IFG is always dormant in implicit syntactic processing. Activation of the left F3op has been reported to occur in implicit syntactic processing (simple reading) of syntactically anomalous phrases (Kang et al., 1999). In another study, which required listening to a pair of sentences to determine whether they had the same literal meaning, the left F3op/F3t was activated for implicit syntactic processing of syntactically normal sentences (Dapretto and Bookheimer, 1999). The activation of the left F3op/F3t for syntactic processing may stem from the fact that the subjects explicitly paid attention to syntactic processing in spite of the absence of task requirements. The results of Suzuki and Sakai (2003) indicate that explicit tasks are more effective for clarifying the left F3op/F3t involvement in syntactic processing than are implicit tasks.

We further demonstrated a causal link between syntactic processing and activation in the left F3op/F3t in the above-mentioned TMS study (Sakai et al., 2002). In this study, we employed a minimal-pair paradigm of syntactic and semantic decision tasks, in which only one linguistic element differs between a stimulus pair. This TMS study has provided new findings that are striking in three ways: (1) event-related paired TMS pulses selectively reduced reaction times (RTs) in explicit syntactic decisions but not in explicit semantic decisions (Fig. 3), which is unexpected according to the known TMS effects on cognitive processes, (2) this effect was observed during syntactic decisions regarding both normal and anomalous sentences, and (3) this effect was observed when magnetic stimulation was administered to the left F3op/F3t at a specific timing (150 ms from a verb stimulus), but not to the left middle frontal gyrus. As to the first point, the temporally-restricted and syntax-selective reduction of RTs suggests the physiological effects of facilitation or priming, such that the stimulation of the left F3op/F3t at a specific timing enhances its normal function. Indeed, the mean reduction of RTs for syntactic decisions (normal sentences: 14 ms, anomalous sentences: 25 ms) were comparable to that of a previous behavioral study, in which the RTs for lexical decision were reduced when primed by a syntactically appropriate word (Goodman et al., 1981). It is possible that a TMS temporarily raises the overall excitability of neurons, thus making an alerted state of "stand-by", which leads to more effective activation when specific responses of those cells are required for syntactic decisions. With respect to the second point, the TMS effects on normal and anomalous sentences were in agreement with the left F3op/F3t activation observed in our event-related OT study using the same minimal-pair paradigm with auditory stimuli (Noguchi et al., 2002), indicating that common processes were involved both in judging a sentence to be normal and in judging it to be anomalous for each task. Therefore, explicit syntactic processing subsists not only in detecting syntactic anomalies per se, but in analyzing syntactic consistency in a sentence. This finding was achieved by utilizing event-related TMS and OT, thereby differentiating trials with normal and anomalous sentences. Even if "normal" sentences are physically identical stimuli used in both the syntactic and semantic tasks, we have demonstrated that TMS resulted in differential effects on normal sentences that paralleled the effects on anomalous sentences, depending on the types of explicit linguistic decisions being made.

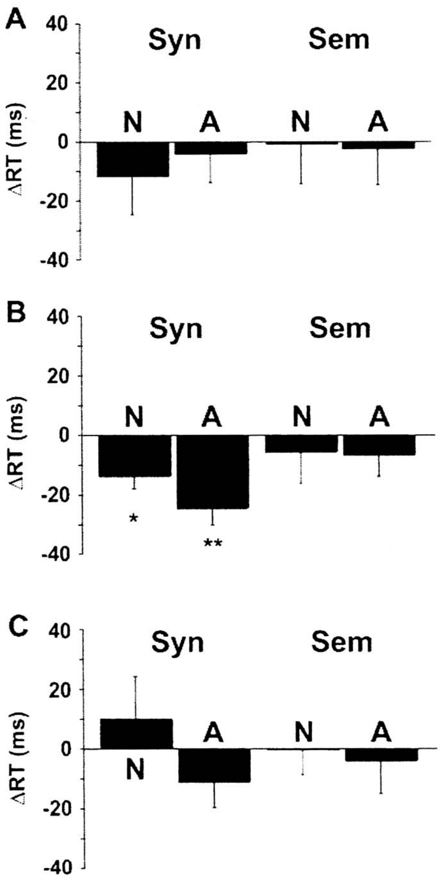

Figure 3. Selective priming effects of TMS on syntactic processing, when magnetic stimulation was administered at a specific timing over the left F3op/F3t (Sakai et al., 2002). ΔRT (mean and standard error across subjects) indicates the change of RTs (Real − Sham) elicited by the TMS. Each bar denotes ΔRT for either normal (N) or anomalous (A) sentences. TMS was delivered at one of three time points: 0 ms (**A**), 150 ms (**B**), and 350 ms (**C**) from the presentation of a verb. $*p < 0.05$, $**p < 0.01$ (t-test).

2. The Plasticity of the "Grammar Center"

The next primary challenge is how the function of the grammar center can be modified during the course of acquiring new languages. The native or first language (L1) is normally acquired in the first several years of life, during which children rapidly expand their linguistic knowledge (Gopnik et al., 1999; Boysson-Bardies, 1999). In contrast, a second language (L2) can be mastered at any time in life, though the L2 ability becomes rarely comparable to L1 if it is acquired beyond the hypothesized critical period around puberty (Lenneberg, 1967; Johnson and Newport, 1989). Whether L2 relies on the same dedicated mechanism of L1, which may critically involve the maturation of the grammar center, is thus a matter of debate (Epstein et al., 1996). It has been recently reported that L1 and L2 are represented differentially in cortical areas during discourse production or listening tasks (Kim et al., 1997; Dehaene et al., 1997). However, other imaging studies have reported common neural substrates of L1 and L2 during word generation tasks (Klein et al., 1995; Chee et al., 1999). The critical experiments thus would be to clarify brain plasticity that represents new acquisition of L2, i.e., the *dynamic* processes of L2 acquisition and associated cortical changes, rather than static states that reflect a certain level of L2 performance.

We have examined whether the learning of English past tense verbs as L2 knowledge alters brain activations for the 13-year-old students (native Japanese speakers) studying English for the first time at a secondary education school in Japan (Sakai et al., 2004). We targeted twins as subjects (six monozygotic and one dizygotic twin pairs), because it is intriguing to ask whether shared factors of twins actually influence their language abilities and neural substrates for Japanese (L1) and English (L2). For two months, the students participated in intensive training in English verbs as part of their standard classroom education. To directly evaluate the brain's changes in activation due to this training, the twins completed two sets of functional magnetic resonance imaging (fMRI) sessions, one before the training (Day 1) and one after the training (Day 2). Figure 4A illustrates the experimental paradigm with four tasks used in fMRI sessions: an English verb-matching (EM) task, an English past tense (EP) task, a Japanese verb-matching (JM) task, and a Japanese past tense (JP) task. General cognitive factors such as word recognition and response selection were controlled by the EM and JM tasks, which were directly compared with the EP and JP tasks, respectively. A particular challenge in this study was to assess the effect of an educational method used in classroom lessons *directly* in terms of brain activation.

When the EP task was contrasted with the EM task (EP – EM) in a random effects analysis for Day 2, activations were found primarily in the left IFG (Fig. 4B), which were absent in EP – EM for Day 1. Moreover, the JP – JM contrast for Day 2 revealed the left IFG activation (Fig. 4C), which was stable and remained unchanged between Days 1 and 2. It is thus striking to note that the left IFG activated for the English past tense verbs exactly match the regions activated for the Japanese past tense verbs, which is in agreement with the universal nature of grammatical processing. These results suggest that the cortical plasticity for L2 acquisition is guided toward the L1 specialization of the left IFG, at least at the age of 13, in spite of notable differences between L1 and L2 in the students' linguistic knowledge and in their performance in making past tense forms.

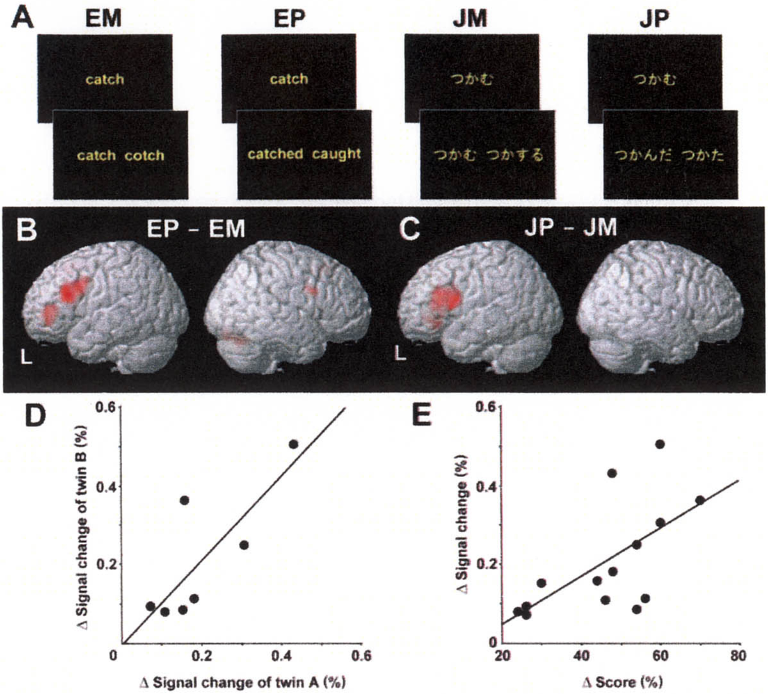

Figure 4. Correlated functional changes of the grammar center in twins (aged 13) induced by classroom education of second language (Sakai et al., 2004). (**A**) The four language tasks used to test the plasticity of the grammar center. (Left to right: English verb-matching (EM) task, English past tense (EP) task, Japanese verb-matching (JM) task, and Japanese past tense (JP) task. One example (*tsukamu*; gross: catch) is shown, and the one on the left (*tsukannda*; gross: caught) is correct. Japanese stimuli were presented in both the hiragana and kanji writing systems and were matched with English words of the same meaning. (**B**) EP – EM for Day 2. The most prominent activation change was observed in the left (L) dorsal IFG. (**C**) JP – JM for Day 2. Note the consistent activation in the left dorsal IFG. (**D**) The activation increases (ΔSignal change: Day 2 – Day 1) of the left dorsal IFG in EP – EM, plotted for each pair of twins (identified as twin A and twin B). (**E**) Significant correlation between L2 performance improvements and activation increases in the left dorsal IFG. For all individual participants, the activation increases (ΔSignal change: Day 2 – Day 1) of the left dorsal IFG in EP – EM are plotted against improvements in examination scores (ΔScore: Day 2 – Day 1). A regression line is shown.

We next examined whether or not shared factors of twins influence the functional changes observed here. The activation increases of the left dorsal IFG [coordinates in the standard brain, (–45, 21, 30)] across Days 1 and 2 showed a highly significant correlation within each pair of twins ($r = 0.80$) (Fig. 4D). This result suggests that the functional changes specifically observed in the left IFG are susceptible to shared genetic and environmental factors for each twin in a surprisingly predictive manner. Furthermore, the activation increases in the left IFG predicted the extent to which each individual subject improved his/her knowledge of the past tense, as shown by a significant positive correlation ($r = 0.63$) between the improvements in examination scores and the activation increases in EP – EM across Days 1 and 2 (Fig. 4E). Therefore, we conclude that the amount by which activation increases in the left dorsal IFG is a good indicator of individual improvement in acquiring L2 past tense knowledge. The present fMRI study thus successfully elucidates one type of cerebral mechanisms involving the grammar center, indicating how new linguistic knowledge is acquired and represented in individual brains. To our knowledge, the present study is the first direct demonstration that classroom education, if properly executed, can change the function of the frontal cortex.

It remains to be elucidated how cortical activations are modulated by factors of age, proficiency, and language task demands when mastering L1 and L2. Using fMRI, we tested subjects aged 19 who had studied English for six years, thereby comparing the cortical activations involved in the above-mentioned EP and EM tasks (Tatsuno and Sakai, 2005). There were two EP task blocks in a single fMRI run: one block (EPi) with seven irregular verbs and one regular verb (at a randomized position), the other (EPr) with seven regular verbs and one irregular verb. We found that the overall cortical activations in EPi – EM, as well as in EPr – EM, dramatically reduced in the higher proficiency subgroup when compared with the lower proficiency subgroup (Fig. 5A and 5B). Moreover, the activation in the left dorsal IFG [yellow dots in Fig. 5A and 5B ; coordinates in the standard brain, (–51, 24, 24)] was lower corresponding to a higher proficiency level (PL; i.e., the accuracy of irregular verbs in the EP tasks), suggesting that PL plays a major role in the activation of this region during L2 acquisition. When we considered PL as a continuous variable treating subjects as a random effect, we found a significant negative correlation between PL and the left dorsal IFG activation in EPi – EM ($r = -0.55$) (Fig. 5C). We also observed lower activation in the triangular and orbital parts of the left IFG (F3t/F3O) in EPi – EM corresponding to a higher PL, together with the nonsignificant activation in EPr – EM when its performance almost reached perfection. Indeed, the direct comparison EPi – EPr resulted in the significant activation, which was clearly localized in the left F3t/F3O [a yellow circle in Fig. 6; (–48, 21, –3)]. These results suggest that the modulation of the left F3t/F3O activation reflects language task demands for identifying correct past tense forms. On the other hand, the left F3t/F3O activation in Japanese (L1) for age 13 was significantly greater than that for age 19, despite the matched performances in L1. We conclude that these regions subserve language-specific functions that are critically required when mastering any language.

Combining these findings, we have clarified that the left dorsal IFG activation increases with PL improvements at the earlier stage of L2 acquisition, and that it is lower when a higher proficiency in L2 is attained. This latter result is consistent with a previous fMRI study reporting weaker left IFG activation for bilingual subjects with higher PLs during a semantic decision task (Chee et al., 2001). Regarding the initial increase in activation, consistent results have recently been reported showing that activation in the left F3t increases when subjects first learn the grammatical rules of L2 (Musso et al., 2003). On the other hand, another fMRI study reported that the left IFG is more activated by making grammatical judgments in L2 than in L1, but that it occurred independent of PLs in L2 (Wartenburger et al., 2003). However, the present results indicate that the left dorsal F3t may show higher, lower, or comparable activation, depending on which stages of L2 acquisition are compared. Wartenburger et al. (2003) also reported that the left IFG activation is greater for subjects at a later age of acquisition than for those at an earlier one, even when their high PLs were matched. Here, it should be noted that the subject groups' mean intervals of exposure to two languages in their study differed by 16 years, and thus the differences between those groups might have disappeared if the degree of exposure had been equated. Further research is necessary to determine whether the left IFG activation depends on exposure to the language at a particular stage of the developing brain.

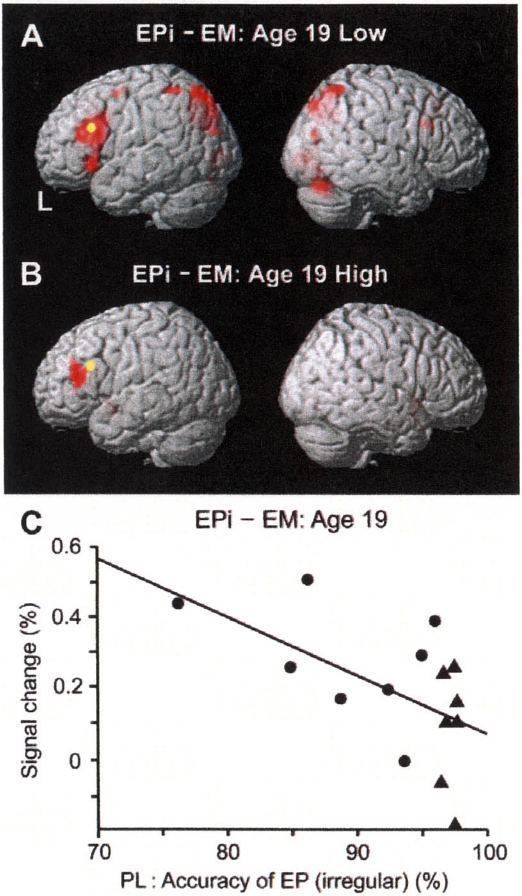

Figure 5. Past tense task-selective activations in L2 and the left dorsal IFG activation modulated by the proficiency level (PL; the accuracy of irregular verbs in the EP tasks) of the subjects aged 19. (**A**) Significant activations in the contrast of EPi – EM for the lower PL subgroup. In the EPi block, seven irregular verbs and one regular verb were presented at a randomized position. The activated regions are projected onto a surface-rendered standard brain (L, left). (**B**) Significant activations in the contrast of EPi – EM for the higher PL subgroup. Note more localized left dorsal IFG activation for this subgroup. (**C**) Significant negative correlations between PL and percent signal changes in the left dorsal IFG [yellow dots in (**A**) and (**B**)] in EPi – EM are shown for all the subjects (Tatsuno and Sakai, 2005). Circles and triangles correspond to the lower and higher PL subgroups, respectively. A regression line is shown.

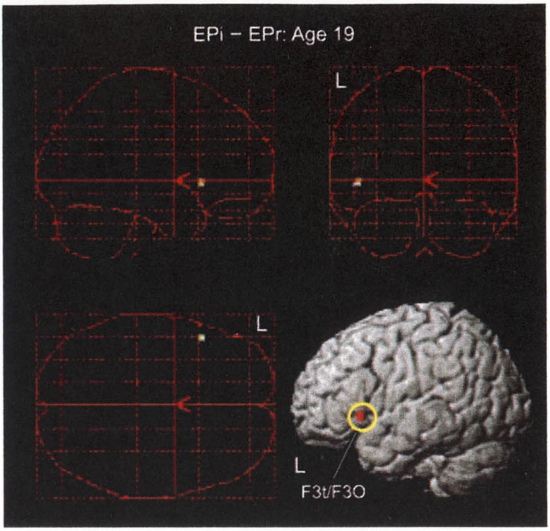

Figure 6. Left F3t/F3O activation in L2 selectively modulated by language task demands. A, a region identified by the contrast EPi – EPr for Age 19 was projected in three orthogonal planes and onto a left (L) surface-rendered standard brain. In the EPr block, seven regular verbs and one irregular verb were presented at a randomized position

3. Another Center for Processing Sentences

Sentences convey not only lexico-semantic information for each word, but sentence meaning based on syntactic structures (Caplan, 1992; Sakai et al., 2001; Townsend and Bever, 2001; Friederici, 2002). The importance of syntactic structures has been elucidated, since Chomsky's discussion of the sentence "*Colorless green ideas sleep furiously*", in that sentence structure can be understood independently of meaning (Chomsky, 1957). Although this sentence conveys no meaningful information, it is clearly different from a list of words without syntactic structures: "*Furiously sleep ideas green colorless*". Moreover, semantic processing at the sentence level differs from a simple summation of lexico-semantic processing for each word. For example, the meaning of "*John thinks that David praises his son*" clearly differs from that of "*John thinks that his son praises David*", though the lexical items involved in each of these sentences are identical. Thus, the processing of syntactic structures plays a critical role in the selective integration of lexico-semantic information into sentence meaning. In summary, syntactic analyses are performed in the service of semantics, and sentence meaning is derived from syntactic analyses of the sentence structures.

We have recently proposed that a ventral region in the left IFG (F3t/F3O) extending from the pars triangularis (F3t, BA 45) to the pars orbitalis (F3O, BA 47) is a putative region for the selection and integration of semantic information, which are separable from simple lexico-semantic processing (Homae et al., 2002) (Fig. 7). In this fMRI study, we directly compared cortical activations in sentence comprehension tasks with those in lexical decision tasks. One sentence example translated into English is: "*May I take a picture here?*" – "*Yes, if you can break the flash*", wherein the original phrase "*do not use*" is replaced with "*can break*", to which the subjects respond by button-pressing. In the lexical decision task, the same phrases used in the sentence comprehension tasks were presented in a completely randomized order, thereby detecting pronounceable nonwords. We found sentence-processing selective activation in the left F3t/F3O, and confirmed that the left F3t/F3O is activated under both auditory and visual conditions. These results demonstrate that the sentence-related processes in this region are essentially amodal and thus beyond modality-dependent lexical processing.

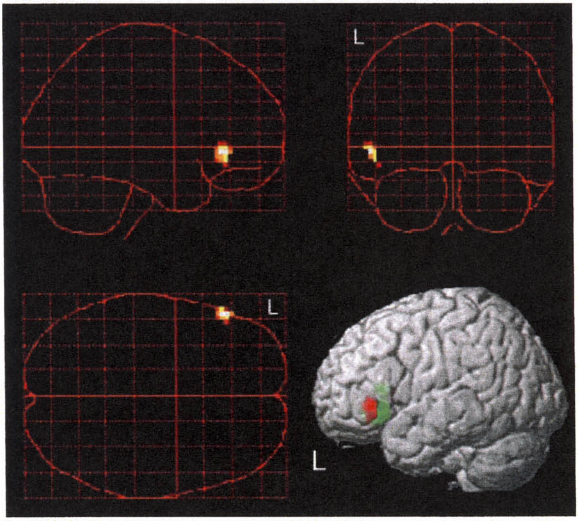

Figure 7. Sentence-processing selective activation in the left F3t/F3O. An activated region identified by comparing a sentence comprehension task and a lexical decision task under the auditory condition is projected in three orthogonal planes and onto a left (L) surface-rendered standard brain (a red region) (Homae et al., 2002). An activated region identified by comparing a sentence comprehension task and a lexical decision task under the visual condition is also rendered on the same brain (a green region). Almost all voxels of the activated region under the auditory condition, which were localized within the left F3t/F3O, coincided with those under the visual condition.

Previous neuroimaging studies have reported controversial results as to whether or not distinct cortical regions subserve the critical processes of syntax and lexico-semantics. While Röder et al. (2002) have reported that the activation of a left region of F3op/F3t reflects both syntactic and semantic effects in sentences, Dapretto and Bookheimer (1999) have claimed that F3op and F3O are differentially involved in syntactic processing and lexico-semantic processing, respectively. Regarding this controversy, we believe that the following five points should be addressed. First, each of the studies by Dapretto and Bookheimer (1999) and Röder et al. (2002) employed a single task requiring either semantic or syntactic processing under all of the contrasting conditions tested. Dapretto and Bookheimer (1999) asked the subjects to judge whether or not the meaning of two sentences differ, while Röder et al. (2002) asked the subjects to count the number of grammatical errors. It is possible that the resultant activation patterns were biased by one type of processing explicitly required in the tasks. Second, semantic processing at the sentence level is not identical to lexico-semantic processing for each word. Dapretto and Bookheimer (1999) have regarded lexico-semantic information as sentence meaning, but the two are qualitatively different, as discussed above. Röder et al. (2002) have examined sentence meaning for all-or-none conditions, in which the contribution of lexico-semantic processing cannot be separated from sentence meaning. Third, a direct comparison of syntactic versus semantic conditions, which was employed by Dapretto and Bookheimer (1999), eliminates all regions related to the syntactic processing that is involved in both conditions. Fourth, a direct comparison between normal and Jabberwocky (nonsense) sentence types, which was employed by Röder et al. (2002), does *not* cancel out all syntactic processes as they proposed, but leaves behind syntactic reanalyses required for the interpretation of sentence meaning. Indeed, they reported significant interaction between sentence types and syntactic difficulty in the left F3op/F3t. Finally, it is still possible that activations related to syntactic and semantic processing of sentences reflect domain-general cognitive factors such as task difficulty and short-term memory. It has been suggested that the left F3O is related to the maintenance of letter information (Henson et al., 2000).

In contrast to the static models of separate processes (Dapretto and Bookheimer, 1999) and overlapping processes (Röder *et al.*, 2002) for syntactic and lexico-semantic information, we propose an alternative dynamic model, such that separate processes for building syntactic structures and evaluating lexico-semantic information interact with each other in the course of processing sentences. Because semantic interpretation of sentences is clearly dependent on syntactic information, this integration process is crucial in sentence comprehension (Smith and Wilson, 1979). One theoretical model has proposed an initial stage for building syntactic structures on the basis of word-category information, and a later stage for the integration of syntactic and lexico-semantic information (Frazier, 1987a). In contrast, another model has assumed an interaction between syntactic and lexico-semantic processes from an early stage (Marslen-Wilson and Tyler, 1980). Taking either model, it is true that syntactic and lexico-semantic information is integrated in the course of sentence processing, which may subsist in the functional network of the left IFG. It would therefore be necessary to elucidate the neural mechanisms responsible for the syntactic integration of lexico-semantic information. Future studies would clarify the individual roles of the subregions in the left IFG that work in concert for human-unique sentence processing.

The neural basis of functional lateralization in language processing is also a fundamental issue in systems neuroscience. There are still many unanswered questions about brain asymmetry and functional lateralization of the two hemispheres in both basic and clinical neurosciences (Geschwind and Galaburda, 1987; Hellige, 1993; Davidson and Hugdahl, 1995; Gazzaniga, 2000; Toga and Thompson, 2003). It is generally believed that language processing is mostly lateralized to the left hemisphere, as repeatedly reported by language studies using fMRI, positron emission tomography (PET), and other neuroimaging techniques. However, recent fMRI studies by Neville and colleagues showed that the processing of American Sign Language (ASL) recruited the bilateral cortical areas of both Deaf native signers and hearing native signers of ASL, while the processing of written English was left-lateralized (Neville et al., 1998; Newman et al., 2002). It should be noted that for the Deaf signers, ASL was their first language (L1), and written English their second (L2). Another fMRI study reported bilateral cortical activation for the processing of British Sign Language (BSL), but without evidence of enhanced right-hemisphere recruitments in sign language when compared with an audio-visual speech condition (MacSweeney et al., 2002). Moreover, PET studies have reported left-lateralized activation of the inferior frontal cortex during "inner signing" of sentences or verb generation (McGuire et al., 1997; Petitto et al., 2000). It is, thus, a considerable challenge to clarify "what's right and what's left" (Paulesu and Mehler, 1998; Hickok et al., 1998). On the other hand, Bellugi and colleagues have established that sign-language aphasia is due primarily to left-hemisphere lesions (Poizner et al., 1987; Bellugi et al., 1989). It has been pointed out that language production, upon which the assessment of aphasia has largely been determined, is highly lateralized, whereas sentence comprehension is bilaterally represented in the case of sign language (Corina et al., 1998). Therefore, it remains to be clarified whether comprehension of sentences is functionally lateralized in either sign or speech.

One possible factor for right frontal activation is prosody, which marks syntactic boundaries and adds certain semantic or emotional information to sentences. It has been indicated that sign movements operate as the most basic prosodic units of the language (Brentari, 1999). Lesion studies have reported that patients with right frontoparietal damage spoke essentially in a monotone voice, without prosody (Ross and Mesulam, 1979), and a recent fMRI study has shown enhanced right frontal activation during an explicit task for evaluating the prosody of spoken sentences (Plante et al., 2002). Another factor for the right hemispheric activations might be expressing or encoding spatial relations with signs (Hickok et al., 1996), but, according to a recent PET study of expressing spatial relations in ASL, neither left nor right frontal regions showed positive activation (Emmorey et al., 2002).

If the basic neural mechanisms of sentence comprehension are universal between signed and spoken languages, left-lateralized activations should be consistently observed. To our knowledge, however, no previous research directly comparing sign language comprehension in deaf signers with auditory speech comprehension in hearing non-signers has been conducted. Therefore, we targeted comprehension of sentences which requires processing of linguistic information not only at the word and phrase levels, but at the sentence and discourse levels, so that highly structured and highly productive processes of language could be examined. Using fMRI, we explored the extent to which sign language comprehension and speech comprehension activate similar brain regions, when the task is perceiving sparsely occurring anomalies in discourse compared with perceiving lexical anomalies (Sakai et al., 2005). This study was also designed to minimize emotional or other non-linguistic factors that might affect cortical activations. Video-taped images showing the full frontal profile of each signer were presented as signed stimuli, whereas synthesized speech sounds were used as spoken stimuli. These stimuli contained linguistic information that was necessary and sufficient to comprehend dialogue sentences. We have already established that synthesized speech stimuli elicit activations in bilateral early auditory areas and left-lateralized language areas (Hashimoto et al., 2000; Homae et al., 2002; Suzuki and Sakai, 2003). Here we hypothesized that comprehension of sentences in sign language is realized in the brain in the same manner as comprehension of sentences is in the English and Japanese languages. The commonality among the modalities with regard to the left-dominant activation patterns could be properly elucidated if the language tasks given to subjects were thoroughly controlled, and if hemispheric comparisons were strictly executed.

By using tasks involving comprehension of sentences (Sc) and sentential non-word detection (Sn), we compared different groups and stimulus conditions. Under the Sign condition with sentence stimuli in Japanese Sign Language (JSL), we tested two groups of subjects: Deaf signers (Deaf) of JSL, and hearing bilinguals (children of Deaf adults, CODA) of JSL and Japanese (JPN). Under the Speech condition, we tested hearing monolinguals (Mono) of JPN with auditory JPN stimuli alone (AUD), or with an audiovisual presentation of JPN and JSL stimuli (A&V). We found that the overall bilateral activation patterns under the four experimental conditions of Deaf, CODA, AUD, and A&V were almost identical, despite differences in stimuli (JSL and JPN) and groups (Deaf, CODA, and Mono). Moreover, consistently left-dominant activations involving frontal and temporo-parietal regions were observed across all four conditions. Furthermore, irrespective of the modalities of sign and speech, the main effects of task (Sc – Sn) were found primarily in the left regions: the ventral part of the inferior frontal gyrus (F3t/F3O), the precentral sulcus, the superior frontal gyrus, the middle temporal gyrus, the angular gyrus, and the inferior parietal gyrus (Fig. 8). Among these regions, only the left F3t/F3O showed no main effects of modality condition. These results demonstrate amodal commonality in the functional dominance of the left cortical regions for comprehension of sentences, as well as the essential and universal role of the left F3t/F3O in processing linguistic information from both signed and spoken sentences. Therefore, the left F3t/F3O would subserve another center for processing sentences.

Even though automatic sentence processing probably occurs in both Sc and Sn tasks, the Sc task explicitly requires selection and integration of semantic information across sentences for understanding and tracking the contextual information within the dialogues. As stated above, our previous study directly contrasted a sentence (S) task, which is similar to the Sc task, with a phrase (P) task, in which phrases taken from dialogues were presented in a completely randomized order and subjects were asked to detect non-words among them (Homae et al., 2002). In spite of the general impression that discourse processing requires bilateral regions of the brain, we have already established that the left-lateralized activation in F3t/F3O is selective to processing sentences at the discourse level, irrespective of the modalities of speech sounds and written words. Furthermore, we recently reported that the reciprocal connectivity between the left F3t/F3O and the left PrCS is significantly enhanced during the S task, but not during the P task (Homae et al., 2003). In the study of Sakai et al. (2005), we successfully observed significant activation of the left F3t/F3O with the more highly stringent comparison of Sc – Sn, where sentence stimuli were presented in both conditions, than with the previous comparison of S – P. Combining these results, we have established that the network of the left F3t/F3O and the left PrCS is consistently involved in comprehension of sentences, irrespective of the modalities of signs, speech sounds, and written words. Moreover, this is true for monolingual or bilingual subjects, even if some research on spoken language bilingualism has argued that there is always dominance of one language over another (Perani *et al.*, 1998).

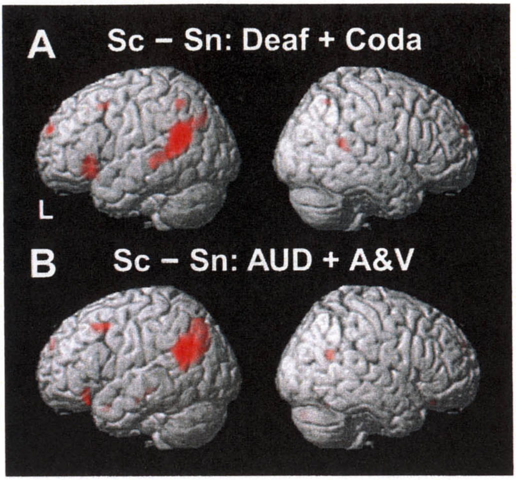

Figure 8. Consistently enhanced activations for comprehension of sentences in sign and speech. Activations were directly compared between comprehension of sentences (Sc) task and sentential non-word detection (Sn) task. (**A**) Activated regions in Sc – Sn are shown for sign conditions, where data from deaf signers (Deaf) and hearing bilinguals (CODA, children of Deaf adults) with Japanese Sign Language (JSL) stimuli were combined. (**B**) Activated regions in Sc – Sn are shown for speech conditions, where data from hearing monolinguals with auditory Japanese stimuli alone (AUD) and with audiovisual presentation of Japanese and JSL stimuli (A&V) were combined. Note that the left-lateralized activations are equivalent for the sign and speech conditions

On the issues of functional lateralization of the two hemispheres, we propose that functional lateralization is not an all-or-none phenomenon (e.g., left but not right), but that it reflects *dominance* of one hemisphere over the other, the salience of which can be parametrically modulated by task demands. In the present study, left-dominant activations were clearly exhibited in the Sc task, even if bilateral activations existed under the same conditions, as confirmed by the comparison with a lowest-level repetition detection task (Sakai *et al.*, 2005). Moreover, we clarified that this dominance is related to specific linguistic factors in the Sc task, as demonstrated by the comparison with the Sn task (Fig. 8). Therefore, it turns out that the choice of task is critical in determining and comparing cerebral dominance. The left F3t/F3O activation in our study is consistent with the activations in sign production tasks for Deaf subjects reported by Petitto *et al.* (Petitto et al., 2000). However, it is difficult to interpret, from the results of that study, why the *right* F3t/F3O was significantly activated when the verb-generation task was compared to an imitation task, but *not* when the same verb-generation task was compared to a less stringent fixation task. In contrast, we observed the right F3t/F3O activation under all four conditions only when the Sc task was compared to the R task, but *not* when it was compared to the more stringent Sn task. Thus, it was crucial to employ appropriate task comparisons for properly evaluating the weaker activations in the right hemisphere.

Conclusion

The functional lateralization of F3t/F3O observed under both sign and speech conditions further establishes that the recruitment of this region for comprehension of sentences is universal among natural languages. It is consistent with the accumulating evidence that aphasia in signed language is primarily due to left-hemisphere lesions, just like aphasia in spoken language (Poizner et al., 1987; Bellugi et al., 1989). Moreover, theoretical models of sentence comprehension, even though they are either rule-governed or habit-based models, do not depend explicitly on the constraints of modality (Frazier, 1987b; McClelland *et al.*, 1989; Mitchell, 1994; Townsend and Bever, 2001). The results reported here thus contribute to resolving the on-going debate about lateralization of sign-language processing by clarifying, for the first time, that the left F3t/F3O subserves comprehension of sentences, irrespective of the language modalities. Future studies would further clarify how individual subregions of the left frontal cortex (i.e., the left LPM, the left F3op/F3t, the left dorsal IFG, and the left F3t/F3O), including the grammar center, work in concert for human-unique sentence processing.

References

Bellugi, U., Poizner, H., Klima, E. S., 1989. Language, modality and the brain. *Trends Neurosci.* 12, 380-388.

Boysson-Bardies, B., 1999. How Language Comes to Children: From Birth to Two Years. *The MIT Press,* Cambridge, MA.

Brentari, D., 1999. A Prosodic Model of Sign Language Phonology. *The MIT Press,* Cambridge, MA.

Caplan, D., 1992. Language: Structure, Processing, and Disorders. *The MIT Press,* Cambridge, MA.

Caplan, D., Alpert, N., Waters, G., 1998. Effects of syntactic structure and propositional number on patterns of regional cerebral blood flow. *J. Cognit. Neurosci.* 10, 541-552.

Caplan, D., Alpert, N., Waters, G., 1999. PET studies of syntactic processing with auditory sentence presentation. *Neuroimage* 9, 343-351.

Chee, M. W. L., Hon, N., Lee, H. L., Soon, C. S., 2001. Relative language proficiency modulates BOLD signal change when bilinguals perform semantic judgments. *Neuroimage* 13, 1155-1163.

Chee, M. W. L., Tan, E. W. L., Thiel, T., 1999. Mandarin and English single word processing studied with functional magnetic resonance imaging. *J. Neurosci.* 19, 3050-3056.

Chomsky, N., 1980. Rules and Representations. Columbia University Press, New York, NY.

Chomsky, N., 1957. *Syntactic Structures.* Mouton Publishers, The Hague.

Chomsky, N., 2000. New Horizons in the Study of Language and Mind. Cambridge University Press, Cambridge, UK.

Corina, D. P., Neville, H. J., Bavelier, D., 1998. What's Right about the neural organization of sign language? - *Reply. Trends Cognit. Sci.* 2, 468-470.

Dapretto, M., Bookheimer, S. Y., 1999. Form and content: Dissociating syntax and semantics in sentence comprehension. *Neuron* 24, 427-432.

Davidson, R. J., Hugdahl, K., 1995. Brain Asymmetry. *The MIT Press,* Cambridge, MA.

Dehaene, S., Dupoux, E., Mehler, J., Cohen, L., Paulesu, E., Perani, D., Van de Moortele, P.-F., Lehéricy, S., Le Bihan, D., 1997. Anatomical variability in the cortical representation of first and second language. *NeuroReport* 8, 3809-3815.

Dronkers, N. F., 1996. A new brain region for coordinating speech articulation. *Nature* 384, 159-161.

Duncan, J., Owen, A. M., 2000. Common regions of the human frontal lobe recruited by diverse cognitive demands. *Trends Neurosci.* 23, 475-483.

Embick, D., Marantz, A., Miyashita, Y., O'Neil, W., Sakai, K. L., 2000. A syntactic specialization for Broca's area. *Proc. Natl. Acad. Sci.* USA 97, 6150-6154.

Emmorey, K., Damasio, H., McCullough, S., Grabowski, T., Ponto, L. L. B., Hichwa, R. D., Bellugi, U., 2002. Neural systems underlying spatial language in American Sign Language. *Neuroimage* 17, 812-824.

Epstein, S. D., Flynn, S., Martohardjono, G., 1996. Second language acquisition: Theoretical and experimental issues in contemporary research. *Behav. Brain Sci.* 19, 677-714.

Fodor, J. A., 1983. The Modularity of Mind. *The MIT Press,* Cambridge, MA.

Frazier, L., 1987a. Sentence processing: A tutorial review, In: Coltheart, M. (Ed.), Attention and Performance XII - The Psychology of Reading. Lawrence Erlbaum Associates, Publishers, London, pp. 559-586.

Frazier, L., 1987b. Theories of sentence processing, In: Garfield, J. L. (Ed.), Modularity in Knowledge Representation and Natural-Language Understanding. *The MIT Press,* Cambridge, MA, pp. 291-307.

Friederici, A. D., 2002. Towards a neural basis of auditory sentence processing. *Trends Cognit. Sci.* 6, 78-84.

Friederici, A. D., Meyer, M., von Cramon, D. Y., 2000a. Auditory language comprehension: An event-related fMRI study on the processing of syntactic and lexical information. *Brain Lang.* 74, 289-300.

Friederici, A. D., Opitz, B., von Cramon, D. Y., 2000b. Segregating semantic and syntactic aspects of processing in the human brain: An fMRI investigation of different word types. *Cereb. Cortex* 10, 698-705.

Gazzaniga, M. S., 2000. Cerebral specialization and interhemispheric communication - Does the corpus callosum enable the human condition? *Brain* 123, 1293-1326.

Geschwind, N., Galaburda, A. M., 1987. Cerebral Lateralization: Biological Mechanisms, Associations, and Pathology. *The MIT Press,* Cambridge, MA.

Goodman, G. O., McClelland, J. L., Gibbs, R. W. Jr., 1981. The role of syntactic context in word recognition. *Mem. Cognit.* 9, 580-586.

Gopnik, A., Meltzoff, A. N., Kuhl, P. K., 1999. The Scientist in the Crib: Mind, Brains, and How Children Learn. William Morrow and Co., Inc., New York.

Hashimoto, R., Homae, F., Nakajima, K., Miyashita, Y., Sakai, K. L., 2000. Functional differentiation in the human auditory and language areas revealed by a dichotic listening task. *Neuroimage* 12, 147-158.

Hashimoto, R., Sakai, K. L., 2002. Specialization in the left prefrontal cortex for sentence comprehension. *Neuron* 35, 589-597.

Hauser, M. D., Chomsky, N., Fitch, W. T., 2002. The faculty of language: What is it, who has it, and how did it evolve? *Science* 298, 1569-1579.

Hellige, J. B., 1993. Hemispheric Asymmetry: What's Right and What's Left. Harvard University Press, Cambridge, MA.

Henson, R. N. A., Burgess, N., Frith, C. D., 2000. Recoding, storage, rehearsal and grouping in verbal short-term memory: an fMRI study. *Neuropsychologia* 38, 426-440.

Hickok, G., Bellugi, U., Klima, E. S., 1998. What's Right about the neural organization of sign language? - A perspective on recent neuroimaging results. *Trends Cognit. Sci.* 2, 465-468.

Hickok, G., Bellugi, U., Klima, E. S., 1996. The neurobiology of sign language and its implications for the neural basis of language. *Nature* 381, 699-702.

Homae, F., Hashimoto, R., Nakajima, K., Miyashita, Y., Sakai, K. L., 2002. From perception to sentence comprehension: The convergence of auditory and visual information of language in the left inferior frontal cortex. *Neuroimage* 16, 883-900.

Homae, F., Yahata, N., Sakai, K. L., 2003. Selective enhancement of functional connectivity in the left prefrontal cortex during sentence processing. *Neuroimage* 20, 578-586.

Indefrey, P., Hagoort, P., Herzog, H., Seitz, R. J., Brown, C. M., 2001. Syntactic processing in left prefrontal cortex is independent of lexical meaning. *Neuroimage* 14, 546-555.

Johnson, J. S., Newport, E. L., 1989. Critical period effects in second language learning: The influence of maturational state on the acquisition of English as a second language. *Cognit. Psychol.* 21, 60-99.

Just, M. A., Carpenter, P. A., Keller, T. A., Eddy, W. F., Thulborn, K. R., 1996. Brain activation modulated by sentence comprehension. *Science* 274, 114-116.

Kang, A. M., Constable, R. T., Gore, J. C., Avrutin, S., 1999. An event-related fMRI study of implicit phrase-level syntactic and semantic processing. *Neuroimage* 10, 555-561.

Kim, K. H. S., Relkin, N. R., Lee, K. M., Hirsch, J., 1997. Distinct cortical areas associated with native and second languages. *Nature* 388, 171-174.

Klein, D., Milner, B., Zatorre, R. J., Meyer, E., Evans, A. C., 1995. The neural substrates underlying word generation: A bilingual functional-imaging study. *Proc. Natl. Acad. Sci.* USA 92, 2899-2903.

Lenneberg, E. H., 1967. Biological Foundations of Language. John Wiley and Sons, Inc., New York.

MacSweeney, M., Woll, B., Campbell, R., McGuire, P. K., David, A. S., Williams, S. C. R., Suckling, J., Calvert, G. A., Brammer, M. J., 2002. Neural systems underlying British Sign Language and audio-visual English processing in native users. *Brain* 125, 1583-1593.

Marslen-Wilson, W., Tyler, L. K., 1980. The temporal structure of spoken language understanding. *Cognition* 8, 1-71.

McClelland, J. L., St.John, M., Taraban, R., 1989. Sentence comprehension: A parallel distributed processing approach. *Lang. Cognit. Processes* 4, 287-335.

McGuire, P. K., Robertson, D., Thacker, A., David, A. S., Kitson, N., Frackowiak, R. S. J., Frith, C. D., 1997. Neural correlates of thinking in sign language. *NeuroReport* 8, 695-698.

Mitchell, D. C., 1994. Sentence parsing, In: Gernsbacher, M. A. (Ed.), Handbook of Psycholinguistics. *Academic Press,* San Diego, pp. 375-409.

Mohr, J. P., 1976. Broca's area and Broca's aphasia, In: Whitaker, H., Whitaker, H. A. (Eds.), Studies in Neurolinguistics. *Academic Press,* New York, pp. 201-235.

Moro, A., Tettamanti, M., Perani, D., Donati, C., Cappa, S. F., Fazio, F., 2001. Syntax and the brain: Disentangling grammar by selective anomalies. *Neuroimage* 13, 110-118.

Musso, M., Moro, A., Glauche, V., Rijntjes, M., Reichenbach, J., Büchel, C., Weiller, C., 2003. Broca's area and the language instinct. *Nat. Neurosci.* 6, 774-781.

Neville, H. J., Bavelier, D., Corina, D., Rauschecker, J., Karni, A., Lalwani, A., Braun, A., Clark, V., Jezzard, P., Turner, R., 1998. Cerebral organization for language in deaf and hearing subjects: Biological constraints and effects of experience. *Proc. Natl. Acad. Sci.* USA 95, 922-929.

Newman, A. J., Bevelier, D., Corina, D., Jezzard, P., Neville, H. J., 2002. A critical period for right hemisphere recruitment in American Sign Language processing. *Nat. Neurosci.* 5, 76-80.

Noguchi, Y., Takeuchi, T., Sakai, K. L., 2002. Localized activation in the inferior frontal cortex during syntactic processing: An event-related optical topography study. *Hum. Brain Mapp.* 17, 89-99.

Paulesu, E., Mehler, J., 1998. Right on in sign language. *Nature* 392, 233-234.

Perani, D., Paulesu, E., Galles, N. S., Dupoux, E., Dehaene, S., Bettinardi, V., Cappa, S. F., Fazio, F., Mehler, J., 1998. The bilingual brain - Proficiency and age of acquisition of the second language. *Brain* 121, 1841-1852.

Petitto, L. A., Zatorre, R. J., Gauna, K., Nikelski, E. J., Dostie, D., Evans, A. C., 2000. Speech-like cerebral activity in profoundly deaf people processing signed languages: Implications for the neural basis of human language. *Proc. Natl. Acad. Sci.* USA 97, 13961-13966.

Plante, E., Creusere, M., Sabin, C., 2002. Dissociating sentential prosody from sentence processing: Activation interacts with task demands. *Neuroimage* 17, 401-410.

Poizner, H., Klima, E. S., Bellugi, U., 1987. What the Hands Reveal about the Brain. *The MIT Press,* Cambridge, MA.

Röder, B., Stock, O., Neville, H., Bien, S., Rösler, F., 2002. Brain activation modulated by the comprehension of normal and pseudo-word sentences of different processing demands: A functional magnetic resonance Imaging study. *Neuroimage* 15, 1003-1014.

Ross, E. D., Mesulam, M.-M., 1979. Dominant language functions of the right hemisphere? - Prosody and emotional gesturing. *Arch. Neurol.* 36, 144-148.

Sakai, K. L., Hashimoto, R., Homae, F., 2001. Sentence processing in the cerebral cortex. *Neurosci. Res.* 39, 1-10.

Sakai, K. L., Homae, F., Hashimoto, R., 2003. Sentence processing is uniquely human. *Neurosci. Res.* 46, 273-279.

Sakai, K. L., Miura, K., Narafu, N., Muraishi, M., 2004. Correlated functional changes of the prefrontal cortex in twins induced by classroom education of second language. *Cereb. Cortex* 14, 1233-1239.

Sakai, K. L., Noguchi, Y., Takeuchi, T., Watanabe, E., 2002. Selective priming of syntactic processing by event-related transcranial magnetic stimulation of Broca's area. *Neuron* 35, 1177-1182.

Sakai, K. L., Tatsuno, Y., Suzuki, K., Kimura, H., Ichida, Y., 2005. Sign and speech: Amodal commonality in left hemisphere dominance for comprehension of sentences. *Brain in press.*

Smith, E. E., Jonides, J., 1999. Storage and executive processes in the frontal lobes. *Science* 283, 1657-1661.

Smith, N., Wilson, D., 1979. Modern Linguistics: The Results of Chomsky's Revolution. Indiana University Press, Bloomington.

Stromswold, K., Caplan, D., Alpert, N., Rauch, S., 1996. Localization of syntactic comprehension by positron emission tomography. *Brain Lang.* 52, 452-473.

Suzuki, K., Sakai, K. L., 2003. An event-related fMRI study of explicit syntactic processing of normal/anomalous sentences in contrast to implicit syntactic processing. *Cereb. Cortex* 13, 517-526.

Tatsuno, Y., Sakai, K. L., 2005. Language-related activations in the left prefrontal regions are differentially modulated by age, proficiency, and task demands. *J NEUROSCI* 25, 1637-1644.

Toga, A. W., Thompson, R. M., 2003. Mapping brain asymmetry. *Nat. Rev. Neurosci.* 4, 37-48.

Townsend, D. J., Bever, T. G., 2001. Sentence Comprehension: The Integration of Habits and Rules. *The MIT Press,* Cambridge, MA.

Wartenburger, I., Heekeren, H. R., Abutalebi, J., Cappa, S. F., Villringer, A., Perani, D., 2003. Early setting of grammatical processing in the bilingual brain. *Neuron* 37, 159-170.