

An Event-related fMRI Study of Explicit Syntactic Processing of Normal/Anomalous Sentences in Contrast to Implicit Syntactic Processing

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Using event-related functional magnetic resonance imaging (fMRI), we examined activation of cortical language areas for explicit syntactic processing. In a syntactic decision (Syn) task, the participants judged whether the presented sentence was syntactically correct, where syntactic knowledge about the distinction between transitive and intransitive verbs was required. In a semantic decision (Sem) task, lexico-semantic knowledge about selectional restrictions was indispensable. In a phonological decision (Pho) task, phonological knowledge about accent patterns was required. The Sem and Pho tasks involved implicit syntactic processing, as well as explicit semantic and phonological processing, respectively. We also tested a voice-pitch comparison (Voi) task in which no explicit linguistic knowledge was required. In the direct comparison of Syn – (Sem + Pho + Voi), we found localized activation in the left inferior frontal gyrus (F3op/F3t), indicating that activation of the left F3op/F3t is more prominently enhanced in explicit syntactic processing than in implicit syntactic processing. Moreover, we determined that its activation is selective to syntactic judgments regarding both normal and anomalous sentences. These results suggest that explicit information processing in the syntactic domain critically involves the left F3op/F3t, which is functionally separable from other regions.

Introduction

How language is related to or separated from other aspects of the mind is a central question in cognitive science. Fodor postulated 'the modularity of mind', which considered language to be an input system as one of modules, such as sensory systems (Fodor, 1983). In contrast, Chomsky claimed that it is too narrow to regard the 'language module' solely as an input system and that it is, rather, a 'central system' (Chomsky, 1986), although the central system is not modular in Fodor's model of cognition. The existence of linguistic subsystems suggests that the language system itself has internal modularity (Chomsky, 1984). According to this view, there are distinct modules or subsystems inside the language module, on an assumption that a module itself can be composed of domain-specific modules (Coltheart, 1999). Possible candidates for these modules are syntax, semantics and phonology, which interact systematically with each other (Sakai *et al.*, 2001). If these linguistic modules exist in the language system, information flow among the modules, as well as the roles of their interactions, should be clarified. A further critical question is whether these modules correspond to distinct areas of the brain. Indeed, linguistic processing capacity provides an unprecedented opportunity to examine domain specificity (Goldman-Rakic, 2000).

Here, we conducted an event-related functional magnetic resonance imaging (fMRI) study involving explicit error-detection tasks, thereby addressing the following three issues. First, by devising a minimal-pair paradigm, we compared three major aspects of language processing: syntax, semantics and phonology. Secondly, we contrasted explicit and implicit

language processing using strict linguistic controls. And, thirdly, by using event-related design, we separately examined activation elicited by normal and anomalous sentences. Previous studies involving error-detection tasks have not addressed differences in cortical activation between the processing of normal sentences and that of anomalous sentences. To our knowledge, the present study is the first approach to dissociate subcomponents of language processing from the viewpoint of explicit/implicit processing of normal/anomalous sentences. A portion of this study has been reported previously in abstract form (Sakai and Suzuki, 2001).

We compared cortical activation mainly among three explicit linguistic tasks: syntactic decision (Syn), semantic decision (Sem) and phonological decision (Pho) tasks (Table 1). These tasks basically require error detection in a sentence stimulus that includes a noun phrase (a noun and a case particle) and a verb stimulus for each trial. In the Syn task, the participants judged whether the presented sentence was syntactically correct; in this case, syntactic knowledge about the distinction between transitive and intransitive verbs was required. In the Sem task, participants judged whether the presented sentence was semantically correct; in this case, lexico-semantic knowledge about selectional restrictions was indispensable. In the Pho task, the participants judged whether the presented sentence was phonologically correct; in this case, phonological knowledge about accent patterns was required. The same set of words was used to make normal (*N*) and anomalous (*A*) sentences for each task. Because *N* sentences were identical among these tasks, we tested each task in separate sessions to dissociate activation for judging whether a sentence was syntactically correct from activation for judging whether the same sentence was either semantically correct or phonologically correct. In contrast, *A* sentences had only one type of linguistic error in each task. Therefore, these stimuli formed minimal pairs for both intratask pairs (*N* and *A* sentences) and intertask pairs (e.g. *A* sentences for Syn and Sem). This task design has been already established as a minimal-pair paradigm in our recent optical topography (OT) study (Noguchi *et al.*, 2002) and in our transcranial magnetic stimulation (TMS) study (Sakai *et al.*, 2002).

In addition to these three tasks, we tested voice-pitch comparison (Voi) and pseudoword control (Con) tasks, which did not require any explicit linguistic processing. In the Voi task, the participants were instructed to detect an anomalous change in voice-pitch from a noun phrase to a following verb. Stimuli used in the Voi task were the same set of *N* sentences as used in the Syn, Sem and Pho tasks. The Voi task required no explicit linguistic knowledge and involved automatic or implicit processing of syntax, semantics and phonology (Table 2). In the Con task, the participants judged whether or not the accent patterns of each pair of pseudowords were identical. In contrast to the Voi and Con tasks, the Syn, Sem and Pho tasks required linguistic

Table 1

Examples of stimuli used in the syntactic, semantic and phonological decision tasks

Task	Normal stimuli	Anomalous stimuli
Syntactic decision (Syn)	'yuki-wo sawaru'	'yuki-wo tsumoru'
	snow-Acc touch (vt)	snow-Acc lie (vi)
	(Someone) touches snow	(Something) lies snow
	'iro-wo mazeru'	'iro-wo medatsu'
color-Acc blend (vt)	color-Acc stand out (vi)	
	(Someone) blends colors	(Something) stands out the color
Semantic decision (Sem)	'yuki-ga tsumoru'	'yuki-ga nigeru'
	snow-Nom lie (vi)	snow-Nom escape (vi)
	Snow lies (on the ground)	Snow escapes
	'iro-ga medatsu'	'iro-wo sawaru'
color-Nom stand out (vi)	color-Acc touch (vt)	
	The color stands out	(Someone) touches color
Phonological decision (Pho)	'yuki-wo sawaru'	'yuki-wo sawaru'
	(LHL) (LHH)	(LHL) (HLL)
	(Someone) touches snow	(Someone) touches snow
	'iro-ga medatsu'	'iro-ga medatsu'
(LHL) (LHL)	(LHL) (HLL)	
	The color stands out	The color stands out

Three language tasks that distinguish the differences among syntactic, semantic and phonological processing in sentence comprehension. In the syntactic decision (Syn) task, participants were asked to distinguish whether a presented sentence was syntactically normal (*N*) or anomalous (*A*). In the semantic decision (Sem) task, participants were asked to distinguish whether a presented sentence was semantically *N* or *A*. In the phonological decision (Pho) task, participants were asked to distinguish whether a presented stimulus was phonologically *N* or *A*. In the Syn task, nouns with accusative (Acc) case particles can produce either *N* or *A* stimuli, depending on whether a transitive verb (*vt*) or intransitive verb (*vi*) is used. In the Sem task, nouns with Acc or nominative (Nom) case particles can produce either *N* or *A* stimuli, depending on the denotative meaning of the verb used. In the Pho task, verbs with different accent patterns can produce either *N* or *A* stimuli.

knowledge, because they could not be performed correctly by anyone who did not understand the particular language used in the present study – Japanese.

In each run, we used one of the Syn, Sem, Pho and Voi tasks as events, while the Con task was used as a baseline condition. For example, *N* or *A* sentences for Syn were interspersed among the pseudoword stimuli for the Con task. Using this event-related design, we investigated the cortical activation elicited by *N* or *A* sentences separately in each task. We then made direct comparison among the Syn, Sem, Pho and Voi tasks in order to isolate any explicit linguistic processing.

Materials and Methods

Participants

Eight male native speakers of Japanese (aged 20–31 years) participated in each task of the present study. Seven participants showed right-handedness (laterality quotients, 53–100) and one showed ambidexterity as determined by the Edinburgh inventory (Oldfield, 1971). The participants were in a supine position in the magnet with eyes closed in a dark room and their heads were immobilized with padding inside the radio-frequency coil. During the experiment, the participants wore earplugs surrounding the plastic tubes for sound delivery and scanner noise was further attenuated by insulating padding on external ears. Informed consent from each participant was obtained after the nature and possible consequences of the studies were explained. Approval for these experiments was obtained from the institutional review board of the University of Tokyo, Komaba.

Auditory Stimuli

All speech sounds were digitized (16 bit; the normal audio cut-off, 11 025 Hz) using speech synthesis software (Oshaberi-mate; Fujitsu, Tokyo) that converted Japanese written texts into digital sound waveforms. With this software, the speech stimuli faithfully replicated the natural prosody of speech in Japanese. The speech stimuli were presented binaurally to the

Table 2

A Minimal-pair paradigm for linguistic processing

Task	Syntactic processing	Semantic processing	Phonological processing
Syntactic decision (Syn)	Explicit	Implicit	Implicit
Semantic decision (Sem)	Implicit	Explicit	Implicit
Phonological decision (Pho)	Implicit	Implicit	Explicit
Voice-pitch comparison (Voi)	Implicit	Implicit	Implicit

participants through plastic tubes (inner diameter, 9 mm; length, 6.5 m) connected to silicone-cushioned headphones specifically designed to isolate the participants from scanner noise (Resonance Technology Inc., Northridge, CA). The maximum intensity of the stimuli was 84 dB SPL (sound pressure level) at the headphones and the scanning sounds were confined within the inter-stimulus interval by using a clustered volume acquisition sequence. A similar sound delivery system was used in our previous imaging study on auditory areas (Hashimoto *et al.*, 2000).

In each of the Syn, Sem, Pho and Voi tasks, one stimulus of a noun phrase (a noun and a case particle) was presented, followed by a verb stimulus for each trial. Each noun phrase and each verb was always three syllables long and presented for 350 ms in order to ensure a constant listening time. We prepared an original set of 40 pairs of noun phrase and verb. One half of the original pairs were used as *N* stimuli for each of the Syn, Sem, Pho and Voi tasks. Additional 20 pairs were made from the original set as *A* stimuli for each task. Syn *A* and Sem *A* stimuli were made by varying noun phrase–verb combinations (Table 1), whereas Pho *A* and Voi *A* stimuli were made by varying pitches of verbs. Thus, each *A* stimulus of one task had a single anomaly alone.

Words and phrases in Japanese generally have accent patterns in pitch; that is, high (H) or low (L) pitch levels are associated with each mora of a polysyllabic word and only a limited number of possible patterns are used for words (Cutler, 1999). In common Japanese (a Tokyo dialect), there are three accent patterns for three-syllable words or phrases: LHH, LHL and HLL. These sound patterns are a part of the tacit linguistic knowledge of native speakers. In the Syn, Sem and Voi tasks, we used one of the three accent patterns for noun phrases and either an LHH or LHL pattern for verbs. As anomalous stimuli in the Pho task, we used an irregular HLL pattern for verbs. In the Pho task, the participants were explicitly instructed to detect an anomaly in an accent of a noun phrase or a verb (though *A* stimuli appeared only in verbs), but they were not instructed to pay attention to the distinction among three accent patterns. We regard an anomaly in an accent pattern as a phonological error, because some Japanese words (mostly one- or two-syllable words) with different accent patterns form a minimal pair: e.g. 'hashi' (LH; gloss: bridge) and 'hashi' (HL; gloss: chopsticks). English words also have similar characteristics of accent patterns. For example, if words like 'entertain' and 'discover' are pronounced with an initial accent, they sometimes become incomprehensible (i.e. 'enter tain' and 'dis cover', respectively). In the present study, we used three-syllable stimuli, in which accent changes did not affect word meaning. Thus, Pho *A* stimuli were not semantically but phonologically anomalous. In the Con task, we made pseudowords, which had either an LHH or LHL pattern, by randomly combining three of 64 moras commonly used in Japanese.

Tasks

In the Syn task, the participants judged whether sentences were either syntactically *N* or *A*, while the stimuli were phonologically correct and word combinations in each sentence were semantically related. We focused on a universal aspect of syntactic operations that are common to many natural languages, including English and Japanese: a distinction between transitive verbs (*vt*) and intransitive verbs (*vi*). This distinction is critical in sentence comprehension, because the choice of *vt* or *vi* determines the syntactic structure of a sentence (Smith and Wilson, 1979). The participants were explicitly instructed to detect a syntactic anomaly, but they were not instructed to pay attention to the distinction between *vt* and *vi*. In the Sem task, the participants judged whether sentences were either semantically *N* or *A*, while the stimuli were phonologically correct and presented sentences were syntactically

correct as to the usage of *vt* and *vi*. Here we focused on the lexico-semantic relationship (selectional restrictions) between a noun and a verb. For example, 'snow' and 'lie' (Sem *N*) are semantically associated [*Snow lies (on the ground)*], whereas 'snow' and 'escape' (Sem *A*) have little association (Table 1). This distinction was sufficiently clear in Japanese, which was confirmed by high accuracy in the Sem task (Sem *N*, 95.5%; Sem *A*, 94.0%; Table 3). In the Pho task, the participants were explicitly instructed to detect an anomaly in an accent of a noun phrase or a verb, while presented sentences were syntactically correct and word combinations in each sentence were semantically related. In summary, the Syn task explicitly required syntactic processing, but it implicitly involved semantic and phonological processing (Table 2). Similarly, the Sem task explicitly required semantic processing, but it implicitly involved syntactic and phonological processing. The Pho task explicitly required phonological processing, but it implicitly involved syntactic and semantic processing.

The Syn task cannot be solved on the basis of the lexico-semantic relationship between a noun and a verb, because it is always correct for both Syn *N* and Syn *A*. In Syn *A*, there was an anomaly in the syntactic relationship between a verb and a noun phrase marked for object. Moreover, *vt* and *vi* in Japanese are clearly segregated into different words and there are a number of morphologically related verb pairs [e.g. 'tomeru' (*vt*) and 'tomaru' (*vi*); gloss: stop], which are similar to the distinction between 'raise' (*vt*) and 'rise' (*vi*) in English (Tsujimura, 1996). Although most of English verbs can be used as *vt* or *vi* without morphological changes, the *vt/vi* distinction of Japanese verbs is primarily determined by morpho-syntax. Therefore, the Syn task explicitly requires syntactic knowledge for distinguishing *vt* and *vi*.

Before scanning sessions, the participants were trained with the most difficult Con task using the same set of pseudowords presented in the scanner, so that they performed the task with the accuracy of >90%. Other tasks required no training of the subjects. During the experiments, the Syn, Sem, Pho and Voi tasks were conducted in separate runs, while the Con task served as the baseline task in all runs. In the Con task, the participants were instructed to press the green button if the both of the pair of pseudowords were of the same accent pattern; they were instructed to press the red button if they were of different accent patterns. Before each run, the participants were explicitly informed about which task they were to perform. In the Syn task, the instructions were: 'Press the green button if the presented sentence is syntactically correct; press the red button if it is syntactically incorrect.' In the Sem task, the instructions were: 'Press the green button if the presented sentence is semantically correct; press the red button if it is semantically incorrect.' In the Pho task, the instructions were: 'Press the green button if the accent of the presented sentence is correct; press the red button if it is incorrect.' In the Voi task, the instructions were: 'Press the green button if the pair is at the same voice pitch; press the red button if it is at different pitches.' Other details of the tasks were described previously (Noguchi *et al.*, 2002; Sakai *et al.*, 2002).

A single run contained 10 trial events (five *N* and five *A* sentences; 3 s each) of one task, with variable inter-trial intervals (18, 21 and 24 s, pseudorandomized within a run). Because pseudowords were presented throughout the Con task while real words were presented only in the trial events, the participants could switch from the Con task to the other task according to the stimulus types. Our event-related design corresponds to a single-event study (Friederici *et al.*, 2000b; Rao *et al.*, 2001), in which single, well-separated events were analyzed, allowing any hemodynamic changes elicited by trial events to return to the baseline level. The order of *N* and *A* stimuli was pseudorandomized in each run and the number of presentations of *N* and *A* stimuli was equated in each task. The participants did not encounter the same sentence twice during a single run. During the scanning, both accuracy and reaction time (RT) were measured on line (Hashimoto *et al.*, 2000). For all the participants, four scanning sessions were tested on separate days. Each session had two tasks in 16 runs, while the orders of tasks were counterbalanced: A-B-B-A-A-B-B-A-A-B-B-A-A-B-B-A (A, B: Syn, Sem; Sem, Syn; Pho, Voi; and Voi, Pho).

fMRI Data Acquisition and Analyses

fMRI scans were conducted on a 1.5 T scanner (Stratis II, Premium; Hitachi Medical Corporation, Tokyo, Japan). We scanned 15 horizontal

Table 3
Behavioral data for each task

Task	Sentence type	Accuracy (%)	RT (ms)
Syn	<i>N</i>	94.4 ± 1.2	536 ± 75
	<i>A</i>	94.6 ± 1.1	563 ± 78
Sem	<i>N</i>	95.5 ± 1.1	554 ± 78
	<i>A</i>	94.0 ± 1.8	599 ± 87
Pho	<i>N</i>	92.8 ± 1.5	557 ± 54
	<i>A</i>	95.5 ± 1.2	476 ± 45
Voi	<i>N</i>	90.2 ± 2.7	502 ± 58
	<i>A</i>	96.1 ± 1.4	380 ± 43
Con	<i>N</i>	91.4 ± 1.1	644 ± 62
	<i>A</i>	91.2 ± 1.7	751 ± 100

Data are shown as mean ± SE. *N*, normal; *A*, anomalous.

slices of 6 mm thickness per volume, covering the range of $z = -24$ to 66 mm from the AC-PC line, with a gradient echo echo-planar imaging sequence (repetition time = 3 s, acquisition time = 1.9 s, echo time = 50 ms, flip angle = 90°, field of view = 192 × 192 mm², resolution = 3 × 3 mm²). High-resolution structural T_1 -weighted images were also acquired from all participants in order to examine anatomical localization of activation foci (local maxima). In a single scanning session, we obtained 78 volumes following the three dummy images, which allowed for the rise of the blood oxygen level dependent (BOLD) signal. For normalizing individual brains into a standard brain, a three-dimensional structural image of each participant's whole brain was obtained using a gradient echo sequence ($T_R = 30$ ms, $T_E = 8$ ms, flip angle = 60°, field of view = 192 × 192 mm², resolution = 1.5 × 1.5 × 1.5 mm³).

We performed group analyses using SPM99 statistical parametric mapping software (Wellcome Department of Cognitive Neurology, London, UK) (Friston *et al.*, 1995), on MATLAB (Math Works, Natick, MA). We realigned the functional volume data in multiple sessions and removed sessions that included data with a translation of >2 mm in one of the three directions. The acquisition timing of each slice was corrected using the first slice as reference. Each individual brain was spatially normalized to the standard brain space as defined by the Montreal Neurological Institute (MNI) and it was resampled at every 3 mm using sinc interpolation. In each participant, multiple sessions involving the same tasks were collapsed into four sessions, according to four patterns of the stimulus onset asynchrony (SOA) of the trial events. These averaged data were then smoothed by using an isotropic Gaussian kernel of 8 mm full-width at half maximum. Low-frequency noise and global changes in activity were further removed. The effects of three event types in each run (*N* and *A* sentences in one of the Syn, Sem, Pho and Voi tasks and all stimuli in the Con task) were modeled by means of canonical hemodynamic response functions. These functions were used as run-specific covariates in a general linear (fixed-effects) model (Friston *et al.*, 1998). When one condition (e.g. Syn *N*) was compared with the Con task, one covariate for that condition was evaluated, which corresponded to an event-related response from the baseline level of the Con task. For conjunction analyses [e.g. Syn *A* - (Sem *A* + Pho *A* + Voi *A*)], covariates for the subtraction were proportionally weighted [i.e. +3 for Syn *A* and -1 for each of Sem *A*, Pho *A* and Voi *A* for this example]. The significance of activation was determined by the *t*-statistics calculated on a voxel-to-voxel basis in all contrasts ($P < 0.05$, corrected for multiple comparisons), which were subsequently transformed to *Z*-values. Clusters of activation that were <10 voxels ($k = 10$) were further removed.

Results

Behavioral Data

Behavioral accuracy and RT measured from the end of a latter verb stimulus are shown in Table 3. We first analyzed the behavioral data separately between the four tasks (Syn, Sem, Pho and Voi) and the baseline Con task, because the task events and the baseline were different in frequencies within a single run. We performed an analysis of variance (ANOVA) on behavioral

data [task \times sentence type (*N* or *A*)] among the Syn, Sem, Pho and Voi tasks. As to both accuracy and RT, there was neither main effect nor interaction ($P > 0.05$), indicating that the task difficulty among these four tasks was comparable. Next, we performed an ANOVA among all five tasks and a *post hoc* test (Fisher's protected least significant difference; PLSD) revealed that Con showed significantly lower accuracy than both Syn and Sem ($P < 0.05$) and longer RT than Syn, Pho and Voi ($P < 0.05$). Because Con was shown to be the most difficult task, we can exclude the possibility that any enhanced activation in task events from the baseline Con task was due to the task difficulty.

Cortical Activation during Syntactic, Semantic, and Phonological Processing

We examined commonality and differences in cortical activation among the tasks that explicitly required particular types of linguistic processing: Syn, Sem and Pho. Any differential activation pattern should reveal a particular type of explicit linguistic processing (Table 2). We first investigated the activation patterns separately for two sentence types in each task: Syn *N*, Syn *A*, Sem *N*, Sem *A*, Pho *N* and Pho *A* (Fig. 1). The overall patterns of significant activation were similar among the three tasks, as well as between *N* and *A* types in each task. They showed

reproducibility and consistency of activation among these task conditions. We found that some regions in cortical language areas exhibited significant activation in all three tasks (Tables 4 and 5). Notable activation was found in a region along the precentral sulcus [PrCS; Brodmann's area (BA) 44/6], which was more prominent in the left hemisphere for both Syn *N* and *A* as well as Sem *N* and *A*. The other prominent activation was located in the bilateral superior temporal gyrus (STG; BA 22), which may be related to speech recognition of real words involved in all the tasks. Common activation was also observed in the posterior cingulate gyrus (BA 23/31). The left supramarginal gyrus (the posterior segment of the Sylvian fissure; BA 40) was activated in Syn *N* and *A* as well as Sem *N* and *A*.

On the other hand, we found task-specific activation in several regions. For both Syn *N* and Syn *A*, but not for other conditions, we found significant activation in the inferior frontal gyrus (IFG) of both hemispheres (Fig. 1 and Table 4). The activated region extended from the inferior part of the pars opercularis (F3op or BA 44) to the pars triangularis (F3t or BA 45), across the anterior vertical ramus of the Sylvian fissure. This region (F3op/F3t) did not extend to the pars orbitalis (F3O or BA 47). This result suggests specialization of F3op/F3t for explicit syntactic processing. Moreover, we observed more prominent

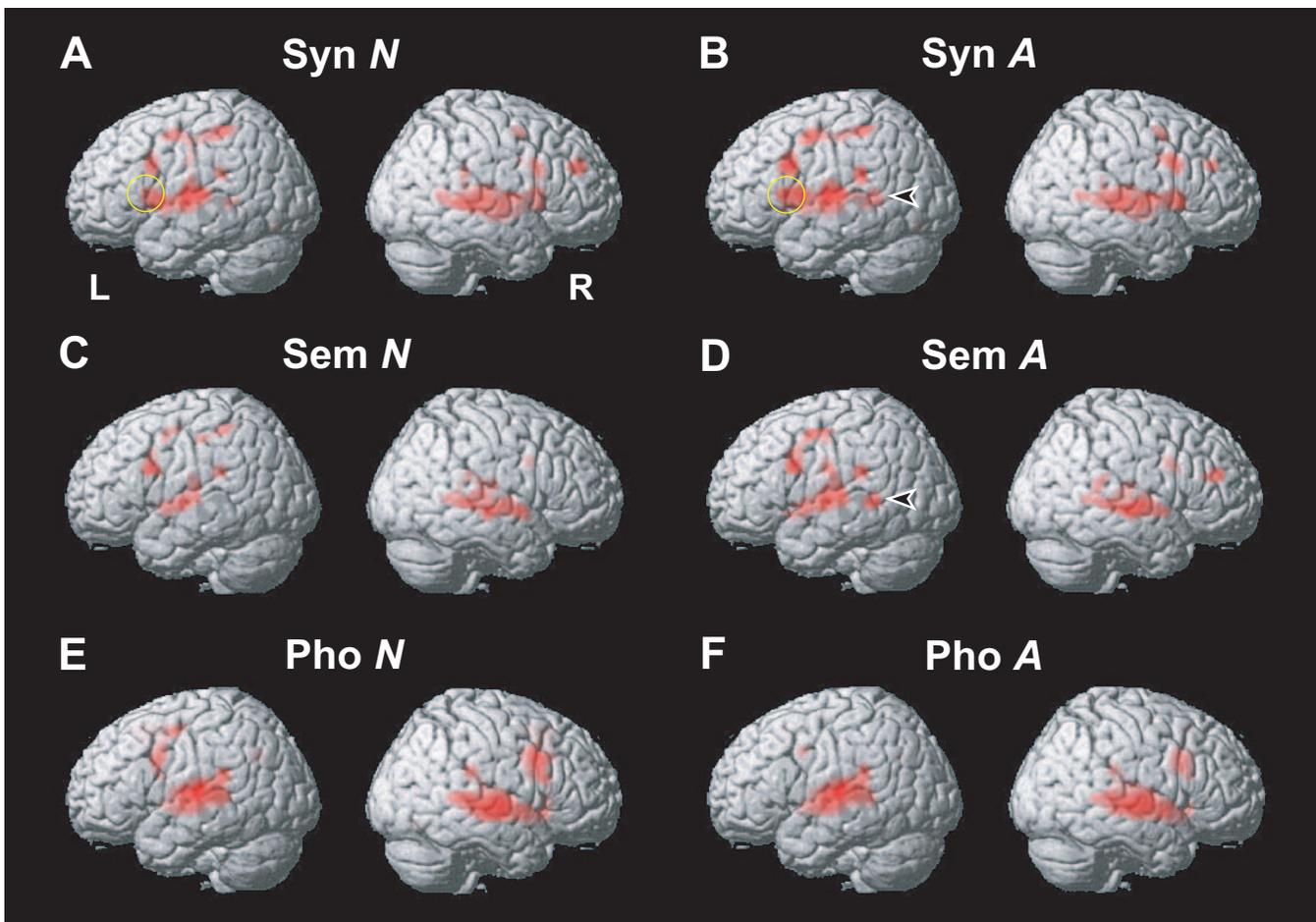


Figure 1. Activation patterns elicited by either normal (*N*) or anomalous (*A*) sentences in three explicit linguistic tasks. (A–F) Regions identified by the contrasts of Syn *N*, Syn *A*, Sem *N*, Sem *A*, Pho *N* and Pho *A*, which were projected onto a surface-rendered representative brain in normal stereotactic space. One covariate was set for each condition (e.g. Syn *N* in *A*), which corresponded to an event-related response from the baseline level of the Con task. The overall patterns of significant activation were similar among the three tasks. Note the selective activation of the left (L) F3op/F3t for both *N* and *A* sentences in the Syn task (yellow circles), as well as the activation of the left MTG for *A* sentences in the Syn and Sem tasks (arrowheads). The thresholds for all contrasts were established at $P < 0.05$, corrected for multiple comparisons.

Table 4
Cortical regions identified by the syntactic decision task

Regions	BA	Hemisphere	Sentence type							
			Normal				Anomalous			
			x	y	z	Z	x	y	z	Z
<i>Syn</i>										
Inferior frontal g. (F3op/F3t)	44/45	L	-60	6	0	>8.0	-60	15	9	7.5
		R	63	15	3	6.8	63	12	6	7.5
Precentral s.	44/6	L	-60	12	30	7.1	-57	12	30	>8.0
		R	42	0	33	5.2	42	3	33	6.4
Inferior frontal s.	45/46	R	45	33	12	5.0				
Insula	-	L					-30	18	9	5.2
		R					42	15	3	6.0
Precentral g.	6	L	-51	-3	51	7.8	-51	0	51	>8.0
		R	51	3	51	6.6	51	3	51	7.1
Postcentral g.	3/1/2	L	-63	-15	39	5.6				
Supramarginal g.	40	L	-51	-36	54	>8.0	-51	-36	54	>8.0
		L	-63	-36	24	6.4	-60	-36	24	>8.0
Superior temporal g.	22	L	-60	-15	6	>8.0	-63	-15	6	>8.0
		R	69	-27	9	>8.0	69	-27	9	>8.0
Middle temporal g.	21	L	-63	-42	0	6.2	-63	-42	3	7.7
Posterior cingulate g.	23/31	M	0	-27	33	>8.0	0	-30	33	7.2
Cerebellum	-	M	-15	-75	-15	6.0	-9	-78	-15	5.8

Stereotactic coordinates (x, y, z) in MNI space (mm) are shown for each local maximum of Z score ($P < 0.05$, corrected for multiple comparisons). BA, Brodmann's area; L, left, R, right; M, medial; g, gyrus; s, sulcus.

Table 5
Cortical regions identified by the semantic and phonological decision tasks

Regions	BA	Hemisphere	Sentence type							
			Normal				Anomalous			
			x	y	z	Z	x	y	z	Z
<i>Sem</i>										
Precentral s.	44/6	L	-60	12	30	6.6	-60	12	30	6.6
		R	45	6	30	5.6	45	6	30	6.2
Middle frontal g.	46	R	45	39	21	6.2	45	39	21	6.2
Precentral g.	6	L	-51	0	51	5.6	-48	-3	54	7.0
Supramarginal g.	40	L	-48	-42	57	7.0	-51	-24	45	5.2
		L	-63	-36	24	6.3	-63	-36	24	7.3
Superior temporal g.	22	L	-60	-9	0	7.0	-60	-12	3	>8.0
		R	69	-9	0	7.6	69	-9	0	>8.0
Middle temporal g.	21	L	-63	-45	0	6.8	-63	-45	0	6.8
Posterior cingulate g.	23/31	M	3	-33	30	5.5	0	-36	24	5.0
Caudate Nucleus	-	L	-18	-9	21	5.3	-18	-9	21	5.3
<i>Pho</i>										
Precentral s.	44/6	L	-57	6	36	7.5	-57	6	36	5.7
		R	48	12	30	>8.0	48	9	27	6.7
Insula	-	R	39	21	3	5.5				
Precentral g.	6	L	-48	-3	54	6.6				
Intraparietal s.	7	L	-24	-63	36	6.4	-27	-63	33	5.4
Superior temporal g.	22	L	-66	-18	9	>8.0	-66	-18	9	>8.0
		R	66	-12	0	>8.0	66	-12	0	>8.0
Anterior cingulate g.	32	M	3	18	51	>8.0	3	18	51	5.8
Posterior cingulate g.	23/31	M	0	-30	30	>8.0	3	-30	30	>8.0
Cerebellum	-	M	12	-75	-12	5.7				
Thalamus	-	M	12	-12	12	5.1				

Stereotactic coordinates (x, y, z) in MNI space (mm) are shown for each local maximum of Z score ($P < 0.05$, corrected).

activations for Pho in the bilateral STG than in other tasks (Fig. 1E,F). Task-specific activation was also found in the medial cerebellum for Syn and in the thalamus for Pho. Other regions with activations in a single task as shown in Tables 4 and 5 were not significantly activated when direct comparisons among the Syn, Sem and Pho tasks were made.

Direct Comparison of Explicit and Implicit Processing

Syntactic Processing

To further assess the selectivity of F3op/F3t for syntactic processing, we performed conjunction analyses by directly comparing the Syn and the other tasks. Any differential

activation pattern in the subtraction would reveal explicit syntactic processing in contrast to implicit syntactic processing involved in other tasks (Table 2). In the contrast Syn - (Sem + Pho + Voi) combining *N* and *A* conditions for each task, we found a single locus of activation for syntactic processing in the left F3op/F3t [local maximum: $(x, y, z) = (-57, 9, 6)$, $Z = 5.6$; Fig. 2A]. The contrast Syn *A* - (Sem *A* + Pho *A* + Voi *A*) also revealed a similar focus in the left F3op/F3t [$(-57, 9, 9)$, $Z = 5.5$; Fig. 2B], while Syn *N* - (Sem *N* + Pho *N* + Voi *N*) resulted in weaker activation in the bilateral F3op/F3t (three voxels each). The maximum amplitudes of fitted hemodynamic responses at the local maximum $(-57, 9, 6)$ clearly revealed selective responses to the Syn task (Fig. 2C). An ANOVA on these amplitudes [task \times sentence type (*N* or *A*)] among the Syn, Sem, Pho and Voi tasks showed a significant main effect of task ($P < 0.0005$), without the main effect of sentence type and their interaction. A *post hoc* test also revealed that Syn showed significantly larger response than each of other tasks ($P < 0.001$). The contrast Syn *A* - (Sem *A* + Pho *A* + Voi *A*) further resulted in significant activation of the medial cerebellum (vermal lobule VI) [$(-9, -78, -12)$, $Z = 5.8$].

Semantic Processing

In contrast to the syntax-related regions, we observed no significant activation in Sem - (Syn + Pho + Voi) combining *N* and *A* conditions for each task, or in Sem *A* - (Syn *A* + Pho *A* + Voi *A*). Thus no regions were specifically involved in explicit semantic processing for the framework of our current tasks. We conclude that explicit syntactic processing recruited the left F3op/F3t more than implicit syntactic processing did and that its activation cannot be explained by semantic processing implicitly involved in the Syn task.

Phonological Processing

As shown in Figures 1E,F, we observed enhanced activation of the bilateral STG in Pho. However, we observed no significant activation in Pho - (Syn + Sem + Voi) combining *N* and *A* conditions for each task, or in Pho *A* - (Syn *A* + Sem *A* + Voi *A*). The apparent absence of STG activation in these contrasts was due to the fact that STG was activated in both Pho and Voi. Indeed, (Pho + Voi) - (Syn + Sem) combining *N* and *A* conditions for each task clearly revealed activation of the bilateral STG (Fig. 3A). The most robust activation was observed in the left STG [$(-66, -24, 12)$, $Z = 7.4$], at which the maximum amplitudes of fitted hemodynamic responses clearly revealed selective responses to the Pho and Voi tasks for both *N* and *A* sentence types (Fig. 3B). An ANOVA on these amplitudes [task \times sentence type (*N* or *A*)] among the Syn, Sem, Pho and Voi tasks showed a significant main effect of task ($P < 0.005$), without the main effect of sentence type and their interaction. A *post hoc* test also revealed that both Pho and Voi showed significantly larger responses than Syn and Sem ($P < 0.01$). The contrast (Pho + Voi) - (Syn + Sem) further resulted in significant activation of another region in the left STG [$(-57, -18, 0)$, $Z = 5.2$], the right STG [$(60, -15, 0)$, $Z = 5.9$; $(51, -21, 3)$, $Z = 5.3$; and $(57, -36, 6)$, $Z = 5.8$] and the thalamus [$(12, -12, 9)$, $Z = 5.4$]. Because the Pho task required detection of pitch changes in syllables while the Voi task required detection of pitch changes in phrases, these two tasks commonly involved pitch discrimination. Although the medial superior frontal gyrus [$(0, 39, 42)$, $Z = 5.3$; $(12, 42, 45)$, $Z = 4.7$] also showed significant activation in the contrast, these regions showed deactivation for both Syn and Sem with little activation in Voi. Finally, Voi - (Syn + Sem + Pho) combining *N* and *A* conditions for each task showed significant activation in the right supramarginal gyrus [$(69, -30, 27)$, $Z = 6.1$], in which Voi showed significantly larger

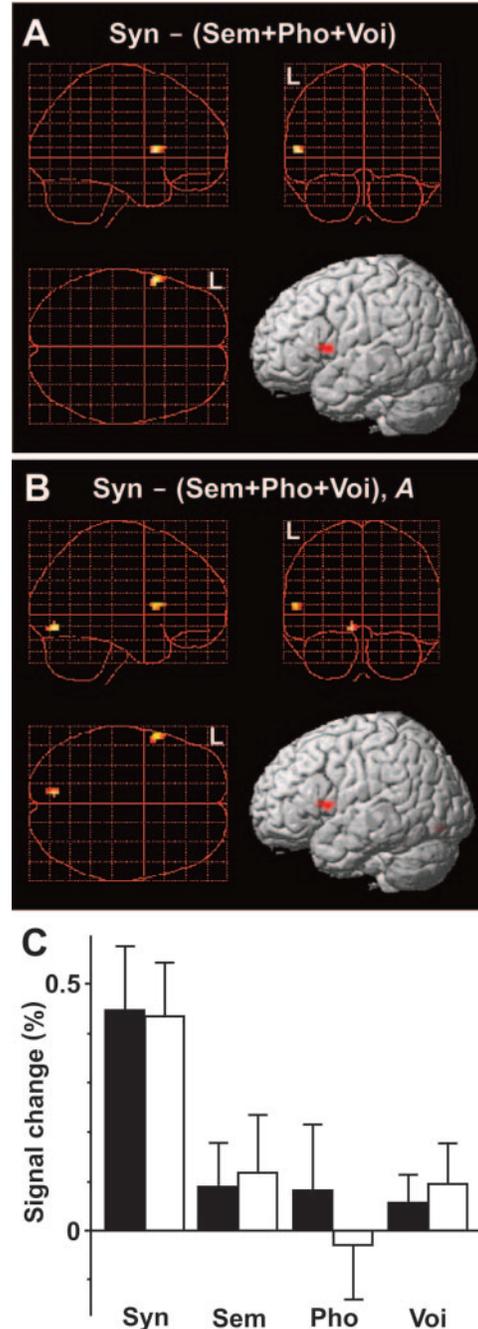


Figure 2. Selective activation for syntactic processing in the left F3op/F3t. (A) Regions identified by the contrast Syn - (Sem + Pho + Voi), combining *N* and *A* conditions for each task. They were projected in three orthogonal planes and onto a left surface-rendered representative brain. Note a single activated region in the left F3op/F3t. The threshold was established at $P < 0.05$, corrected for multiple comparisons. (B) Regions identified by the contrast Syn - (Sem + Pho + Voi), with *A* conditions alone. Note the activation in the left F3op/F3t as well as in the medial cerebellum. (C) Histograms for averaged maximum amplitudes of fitted hemodynamic responses at the local maximum in the left F3op/F3t (mean \pm SE, $n = 8$). Filled and open bars denote signal changes for *N* and *A* sentences, respectively. Signal changes in Syn were significantly larger than those in Sem, Pho and Voi for both *N* and *A* sentences.

response than Syn, Sem and Pho ($P < 0.05$). Voi *A* - (Syn *A* + Sem *A* + Pho *A*) also revealed activation in the same region, as well as in the left STG [$(-66, -33, 12)$, $Z = 5.8$].

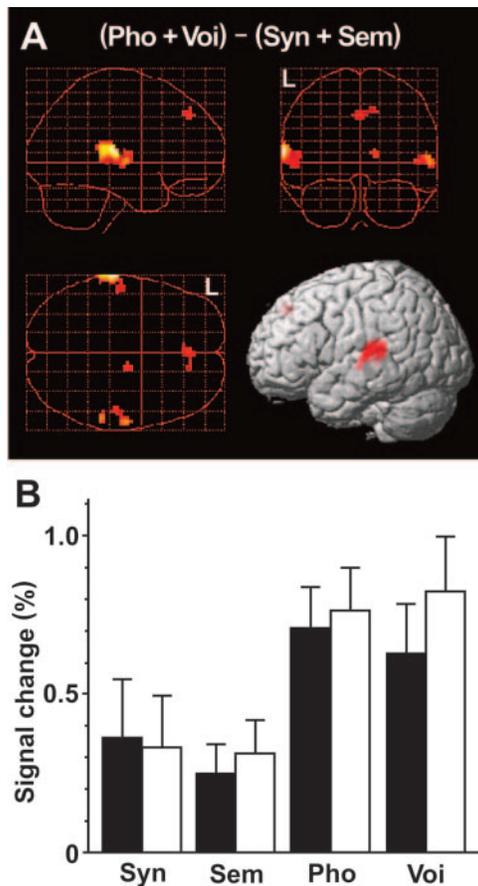


Figure 3. Selective activation for pitch discrimination in the left STG. (A) Regions identified by $(\text{Pho} + \text{Voi}) - (\text{Syn} + \text{Sem})$ combining N and A conditions for each task. This contrast showed significant activation of the bilateral STG and the thalamus. The threshold was established at $P < 0.05$, corrected for multiple comparisons. (B) Histograms for averaged maximum amplitudes of fitted hemodynamic responses at the local maxima in the left STG (mean \pm SE, $n = 8$). Filled and open bars denote signal changes for N and A sentences, respectively. Signal changes in Pho and Voi were significantly larger than those in Syn and Sem for both N and A sentences.

Selectivity of Sentence Types in the Left MTG

As shown in Figure 1, N and A sentences generally resulted in similar activation patterns. Nevertheless, we found a significant difference between sentence types in the contrast of $(\text{Syn } A + \text{Sem } A) - (\text{Syn } N + \text{Sem } N)$ at a single region in the left middle temporal gyrus [MTG; $(-54, -42, 3)$, $Z = 4.7$; Fig. 4A]. For each task, we estimated maximum amplitudes of fitted hemodynamic responses at the local maximum (Fig. 4B). According to paired t -tests performed separately for each task, signal changes in response to A sentences were significantly greater than those to N sentences in both Syn [$t(7) = 2.5$, $P < 0.05$] and Sem [$t(7) = 5.9$, $P < 0.001$], but in neither Pho nor Voi ($P > 0.1$). These results suggest that the left MTG is more sensitive to differences between A and N sentences when analyzing the form and content of sentences.

Discussion

Consistent with earlier research, the present study using the minimal-pair paradigm clearly established that the left F3op/F3t (IFG) is selectively involved in syntactic processing, in contrast to other linguistic processing. Our study further provides new findings that are striking in two ways: (i) activation of the left F3op/F3t is more prominently enhanced in explicit syntactic

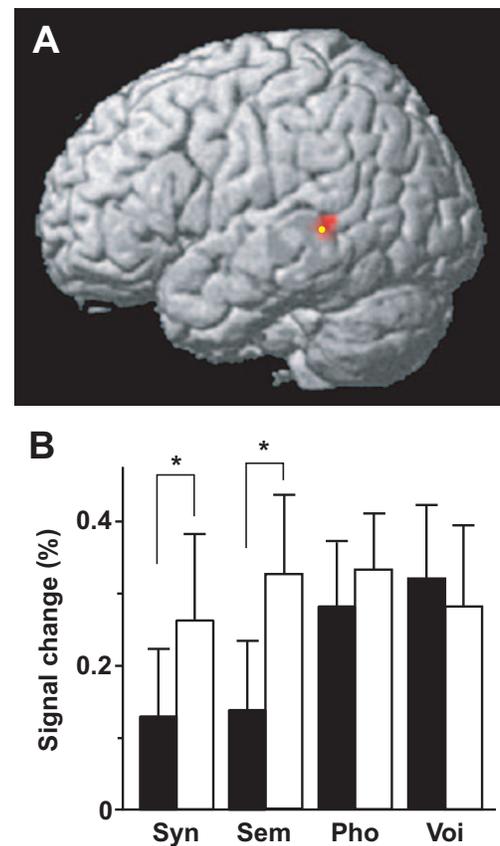


Figure 4. Selective activation for anomalous sentences in the left MTG. (A) Regions identified by the contrast of $(\text{Syn } A + \text{Sem } A) - (\text{Syn } N + \text{Sem } N)$. For display purposes, the threshold was established at $P < 0.0001$, uncorrected. The local maximum in the left MTG showed significant activation ($P < 0.05$, corrected at both voxel- and cluster-levels). (B) Histograms for maximum amplitudes of fitted hemodynamic responses at the local maximum in the left MTG (mean \pm SE, $n = 8$). Filled and open bars denote signal changes for N and A sentences, respectively. Asterisks denote that A sentences elicited significantly larger signal changes than did N sentences both in Syn and in Sem (paired t -tests, $P < 0.05$).

processing than in implicit syntactic processing and (ii) its activation is selective to syntactic judgments regarding both N and A sentences. These results suggest that explicit information processing in the syntactic domain involves the left F3op/F3t, which may be functionally separable from other regions.

The left F3op/F3t activation in the present study matched with that of our previous study using a block design (Embick *et al.*, 2000). In that fMRI study, we used an explicit error-detection paradigm that contrasted sentences containing grammatical errors with sentences containing spelling errors, using the same lexical material across these conditions. We found that the ungrammatical sentences produced more activation in 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. Reanalysis of the direct comparison between these two conditions with SPM99 revealed a single locus of the left F3op/F3t at the local maximum of $[(-57, 18, 0)$, $Z = 6.1$; Fig. 5]. This locus is very close to the local maximum for Syn - (Sem + Pho + Voi) at $(-57, 9, 6)$. Recent imaging studies from other laboratories have accumulated evidence of the involvement of the left IFG in syntactic processing (Just *et al.*, 1996; Stromswold *et al.*, 1996; Caplan *et al.*, 1998; Dapretto and Bookheimer, 1999; Kang *et al.*, 1999;

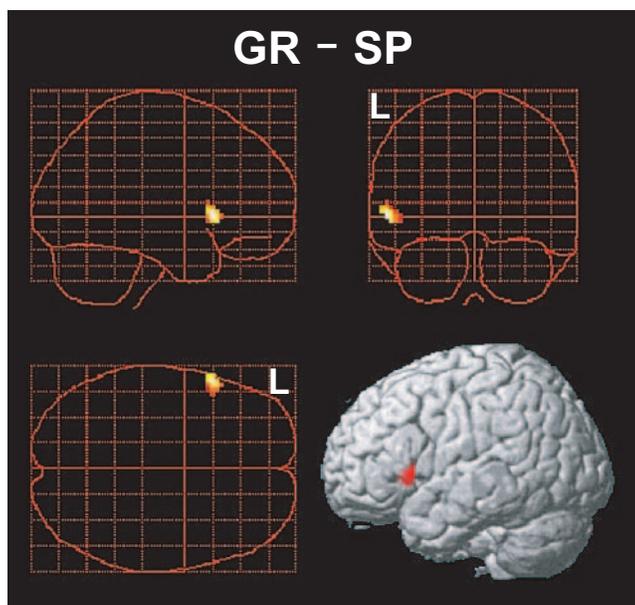


Figure 5. A reanalysis of a syntactic specialization in the left F3op/F3t shown by our previous study (Embick *et al.*, 2000). Activation in a grammatical error-detection (GR) task was directly compared with that in a spelling error-detection (SP) task, revealing a single locus in the left F3op/F3t. The threshold was set at $P < 0.05$, corrected for multiple comparisons.

Friederici *et al.*, 2000b; Moro *et al.*, 2001; Indefrey *et al.*, 2001). In these studies, syntactic knowledge of the English, German, or Italian languages was tested in native speakers. Although various aspects of sentence processing for their contrasts, including syntax, semantics and phonology, were substantially different, the consistent activation of the left F3op/F3t in these studies and our study using Japanese, a non-Indo-European language, suggests that syntactic specialization of the left F3op/F3t is universal among natural languages.

We found that *N* and *A* sentences yielded generally similar activation in each task (Fig. 1). This result indicates that common processes were involved both in judging a sentence to be *N* and in judging it to be *A* for each task. Even if normal sentences are physically identical among the contrasting tasks, we demonstrated that *N* sentences elicited differential activation patterns that paralleled the patterns for *A* sentences, depending on the types of explicit linguistic processing. This finding was achieved by differentiating *N* and *A* sentences in each trial event, which was in perfect agreement with the syntax-selective activation of the left F3op/F3t for both sentence types in our event-related OT study (Noguchi *et al.*, 2002), as well as with the syntax-selective priming effect of stimulating the left F3op/F3t for both sentence types in our event-related TMS study (Sakai *et al.*, 2002). A previous fMRI study tested judgments on normal versus anomalous sentences in separate blocks, but failed to reveal activation of the left IFG (Kuperberg *et al.*, 2000). Possible reasons for this negative evidence would be the task with fixed numbers of normal/anomalous sentences, which can be solved by simple counting, as well as the presence of semantic anomalies in sentences with syntactic violation. Some other event-related fMRI studies have identified activation of the left IFG when syntactically anomalous as opposed to normal sentences were presented (Kang *et al.*, 1999; Ni *et al.*, 2000). The present task differed from previous ones in controlling for deployment of attention to the nature of the anomaly, as ensured by the following three procedures. First, we explicitly explained

the nature of the tasks to the participants before the experiments. Secondly, there were distinct task demands for linguistic knowledge: syntactic knowledge about the *vt/vi* distinction in the Syn task; lexico-semantic knowledge about selectional restrictions in the Sem task; and phonological knowledge about accent patterns in the Pho task. Thirdly, the three tasks were conducted in separate runs and before each run we explicitly informed the participants about which task they should perform. Because of these three procedures, the explicit task demands directed attention to a particular processing, even if the sentences used for Syn *N*, Sem *N* and Pho *N* were physically identical. Our results of left F3op/F3t activation are consistent with this differentiation. In contrast to previous studies reporting left IFG activation induced by syntactic anomalies, the present results suggest that the activation is not due to the presence or absence of a syntactic anomaly, but due to syntactic processing *per se* being required in both Syn *N* and Syn *A*. Indeed, syntactic information is utilized not only to check syntactic consistency in sentences, but to enhance comprehension in normal sentence processing. If there are brain regions specialized for syntactic processing, one presumes that they would act to parse sentence structures for this purpose.

Among the common regions activated in the Syn, Sem and Pho tasks, we hypothesize that the region along the left PrCS [its local maximum at (-60, 12, 30)] is involved in implicit syntactic processing, because we found in our previous fMRI study that the left dorsal prefrontal cortex [DPFC, (-39, 6, 36)], which overlaps with the left PrCS in the present study, is selectively activated when syntactic information is processed at the sentence level without explicit instructions (Hashimoto and Sakai, 2002). Although prefrontal activations have been attributed to executive processes for working memory or cognitive demands in general (Smith and Jonides, 1999; Duncan and Owen, 2000), we have clearly established that syntax-selective activation cannot be explained by such general cognitive factors (Hashimoto and Sakai, 2002). As proposed by Fodor, modular processes are by their very nature automatic and implicit (Fodor, 1983). The suggested specialization of the left PrCS for implicit information processing in the syntactic domain indicates that it is a putative syntactic module. In normal language comprehension, one does not process syntactic information explicitly. 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. In the presence of explicit task requirements such as the Syn task, explicit syntactic processing is employed for judgment about 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 previous study demonstrated that both the left DPFC and the left IFG (BA 45) are activated when the explicit use of syntactic rules is required by the syntactic tasks (Hashimoto and Sakai, 2002). In the present study, we observed activations of both the left PrCS and the left F3op/F3t for Syn *N* and Syn *A*. The left F3op/F3t activation in Syn - (Sem + Pho + Voi), as well as that in the study of Embick *et al.* (Fig. 5), can thus be interpreted as reflecting its selective role in explicit syntactic processing. Recent imaging studies using 'Jabberwocky sentences', in which all content words were replaced with pseudowords while inflections and function words were maintained to preserve syntactic structures, have indicated that the left DPFC and the left IFG are involved in syntactic processing (Friederici *et al.*, 2000a; Indefrey *et al.*,

2001; Moro *et al.*, 2001). These results support the involvement of at least two distinct prefrontal regions in syntactic processing.

The distinction between explicit and implicit syntactic processing raises a further question as to whether the left F3op/F3t is always dormant in implicit syntactic processing. We observed no significant activation of this region in the Sem and Pho tasks, in spite of the fact that they involved implicit processing of syntactically normal sentences (Fig. 1). Activation of the left F3op has been reported for implicit syntactic processing (simple reading) of syntactically anomalous phrases (Kang *et al.*, 1999). In another study (Dapretto and Bookheimer, 1999), which required listening to a pair of sentences to decide whether they had the same literal meaning, the left F3op/F3t was activated for implicit syntactic processing of syntactically normal sentences. The activation of the left F3op/F3t for syntactic processing may stem from the fact that subjects explicitly paid attention to syntactic processing in spite of the absence of task requirements. The present study indicates that explicit tasks are more effective for clarifying the neural mechanism involved in syntactic processing than implicit tasks. Here, we assume that the activation observed in the contrast Syn - (Sem + Pho + Voi) reflects the difference between explicit and implicit syntactic processing (Table 2). It might be possible that the activation is related to the difference between implicit and explicit processing of semantic or phonological information. However, this possibility can be excluded, because the contrast Pho - Sem for the difference between implicit and explicit semantic processing, as well as other comparisons, did not induce activation of the left F3op/F3t.

Generally speaking, syntactic analyses are typically performed in the service of semantics and the meaning of a sentence is derived from syntactic analyses of the sentence structure. Because the sentences in Syn *A* had intransitive verbs that were accompanied by nouns case-marked for object, the sentences in Syn *A* become semantically impossible. This type of semantic anomaly stems from syntactic violations imposed in the Syn task and thus it is an indirect or secondary anomaly, which should be conceptually distinguished from the primary anomaly in the Syn task. Although we cannot entirely rule out the possibility that F3op/F3t activation reflected the secondary anomaly in the Syn task, it is qualitatively different from the semantic anomalies created by selectional restriction violations in the Sem task. Moreover, the anomalies in the Syn task are all-or-none type, because syntactic violations can be present or not in sentences. In contrast, the range of anomalies in the Sem task is continuous, as it corresponds to the acceptability of word-to-word associations. Therefore, semantic anomalies in the two tasks are quantitatively different as well. We should bear this possibility in mind when comparing any syntactic and semantic tasks during sentence comprehension.

In contrast to the Syn task, no region was selectively activated in the Sem task. In the present paradigm, the baseline Con task with pseudowords required not only accent-pattern matching but also lexical decision, because the participants had to switch from the Con task to the other task when real words appeared (see Materials and Methods). Therefore, any regions related to pseudoword processing as well as semantic processing at the lexical level may have been eliminated in Figure 1. Moreover, when we directly compare explicit with implicit processing for each linguistic process, we may not observe any activation for semantic processing by contrasting Sem with other tasks if there is little difference in neural activity between explicit and implicit semantic processing. Another possibility is that many cortical regions are involved in various aspects of semantic

processing. Previous imaging studies have provided conflicting results, such that the cortical regions implicated in processing semantic information, as opposed to syntactic information, include the right BA 45, 10, 46 (Kang *et al.*, 1999), the left BA 21/37 (Friederici *et al.*, 2000b) and the right BA 22/21 (Kuperberg *et al.*, 2000). Some studies of explicit semantic processing have consistently indicated the involvement of the left F3t/F3O, although its exact role remains to be elucidated (Petersen *et al.*, 1988; Wagner *et al.*, 1997; Dapretto and Bookheimer, 1999; Roskies *et al.*, 2001). We have recently proposed that activation of the left F3t/F3O is related to the selection and integration of semantic information during sentence comprehension (Homae *et al.*, 2002). Future study using a strict task design and control for lexical subprocesses should clarify the localization of explicit/implicit semantic processing.

We found a region in the left MTG in which *A* sentences elicited stronger activation than *N* sentences in the Syn and Sem tasks. This activation of the left MTG may reflect the general load of sentence comprehension, which would be enhanced by the presence of semantic anomalies. Some previous imaging studies have shown that the left MTG is involved in sentence processing (Mazoyer *et al.*, 1993; Sato *et al.*, 1999). Moreover, event-related brain potential (ERP) studies have identified components which correlated with participants' recognition of anomaly: P600 for syntactic anomaly and N400 for semantic anomaly (Kutas and Hillyard, 1980; Osterhout and Holcomb, 1992). While some generators of N400 were identified in the anterior fusiform gyrus by intracortical recording (Nobre *et al.*, 1994), a recent magnetoencephalography (MEG) study has identified the possible generators of N400 mostly in the left STG and MTG (Helenius *et al.*, 1998). Our results of left MTG activation are consistent with this MEG study, in that this region may be one of the generators of N400 and P600 components.

We also found stronger activation of the left STG than of the right STG during explicit processing of pitch discrimination. Previous imaging studies involving phonological tasks have reported such activation of the left STG [(-56, -12, 4) (Démonet *et al.*, 1992) and (-46, -32, 16) (Paulesu *et al.*, 1993)], which are close to our regions [(-66, -24, 12) and (-57, -18, 0)]. Moreover, the right STG has been also implicated in pitch perception [(62, -25, 3) (Zatorre *et al.*, 1994) and (43, -28, 5) (Klein *et al.*, 2001)], which may be counterparts of our regions [(60, -15, 0), (51, -21, 3) and (57, -36, 6)]. In addition, both Syn and Sem tasks showed weaker, but significant activation of the bilateral STG (Fig. 1), suggesting that these regions are either recruited in implicit phonological processing, or in processing of common components in Syn, Sem, Pho and Voi, such as successful lexical access.

In conclusion, the present study involving the minimal-pair paradigm and event-related fMRI unequivocally established that the left F3op/F3t is primarily involved in explicit syntactic processing, suggesting the existence of a universal syntactic domain among natural languages. The importance of explicit error-detection tasks with strict linguistic controls should be noted for elucidating the particular aspects of linguistic processing. In the present study, we established the minimal-pair paradigm, which can be used as a powerful tool for further dissociating linguistic subsystems. Future work will allow us to address questions regarding domain-specific brain areas and how they actually perform linguistic computations.

Notes

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