Available online at www.sciencedirect.com
ScienceDirect
Neuroscience Research 61 (2008) 309–318
Neuroscience Research
www.elsevier.com/locate/neures

Functional segregation of the inferior frontal gyrus for syntactic processes: A functional magnetic-resonance imaging study

Yuji Uchiyama [a,b,c], Hiroshi Toyoda [c], Manabu Honda [d], Haruyo Yoshida [e], Takanori Kochiyama [f], Kazutoshi Ebe [a], Norihiro Sadato [b,c,g,h,*]

[a] *Toyota Central R&D Labs., Inc., Nagakute, Aichi 480-1192, Japan*
[b] *Department of Physiological Sciences, The Graduate University for Advanced Studies (Sokendai), Kanagawa 240-0193, Japan*
[c] *National Institute for Physiological Sciences, Okazaki, Aichi 444-8585, Japan*
[d] *National Center of Neurology and Psychiatry, Kodaira, Tokyo 187-8502, Japan*
[e] *Osaka Kyoiku University, Kashiwara, Osaka 582-8582, Japan*
[f] *Brain Activity Imaging Center, ATR, Kyoto 619-0288, Japan*
[g] *Japan Science and Technology Corporation (JST)/Research Institute of Science and Technology for Society (RISTEX), Kawaguchi 332-0012, Japan*
[h] *Biomedical imaging Research Center, University of Fukui, Fukui 910-1193, Japan*

Received 13 December 2007; accepted 31 March 2008
Available online 18 April 2008

Abstract

We used functional magnetic resonance imaging in 18 normal volunteers to determine whether there is separate representation of syntactic, semantic, and verbal working memory processing in the left inferior frontal gyrus (GFi). We compared a sentence comprehension task with a short-term memory maintenance task to identify syntactic and semantic processing regions. To investigate the effects of syntactic and verbal working memory load while minimizing the differences in semantic processes, we used comprehension tasks with garden-path (GP) sentences, which require re-parsing, and non-garden-path (NGP) sentences. Compared with the short-term memory task, sentence comprehension activated the left GFi, including Brodmann areas (BAs) 44, 45, and 47, and the left superior temporal gyrus. In GP versus NGP sentences, there was greater activity in the left BAs 44, 45, and 46 extending to the left anterior insula, the pre-supplementary motor area, and the right cerebellum. In the left GFi, verbal working memory activity was located more dorsally (BA 44/45), semantic processing was located more ventrally (BA 47), and syntactic processing was located in between (BA 45). These findings indicate a close relationship between semantic and syntactic processes, and suggest that BA 45 might link verbal working memory and semantic processing via syntactic unification processes.

Keywords: fMRI; Garden-path effect; Language; Memory; Semantics; Syntax

---

1. Introduction

Sentence comprehension requires individuals to combine information from a sequence of words and phrases in order to compute their syntactic and thematic relationships (that is, ‘‘who did what to whom’’), and then to use world knowledge to construct the meaning of the sentence (Just et al., 1996). Syntactic processing refers to the mental processes that are involved in applying grammatical rules to analyze the meaning of a sentence (Hashimoto and Sakai, 2002). Several previous imaging studies have identified cortical regions that are selectively involved in syntactic processing in the left inferior frontal gyrus (GFi; Dapretto and Bookheimer, 1999; Embick et al., 2000), the left dorsal prefrontal cortex (DPFC), and the left dorsolateral prefrontal cortex (DLPFC; Kang et al., 1999; Indefrey et al., 2001; Newman et al., 2001).

Syntactic processing might be carried out by part of the verbal working memory system (Just and Carpenter, 1992; Dick et al., 2001). This brain system provides the temporal storage and the active manipulation of verbal information that are necessary for language comprehension and other cognitive tasks (Baddeley, 1992). The Baddeley model of verbal working

---

* Corresponding author at: Section of Cerebral Integration, Department of Cerebral Research, National Institute for Physiological Sciences, Myodaiji, Okazaki, Aichi 444-8585, Japan. Tel.: +81 564 55 7841; fax: +81 564 55 7786.
E-mail address: sadato@nips.ac.jp (N. Sadato).

0168-0102/$ – see front matter © 2008 Elsevier Ireland Ltd and the Japan Neuroscience Society. All rights reserved.
doi:10.1016/j.neures.2008.03.013

memory assumes the existence of a phonological store, in which verbal information is registered and maintained by the subvocal rehearsal system. Typical examples of the types of verbal information maintained are word/letter identity (that is, ‘‘what’’) and word/letter order (that is, ‘‘when’’). Considering the ‘‘what’’ aspect, several imaging studies have reported activation of the bilateral DLPFC (Brodmann areas (BAs) 46 and 9), DPFC (BAs 6, 8, and 9), GFi (BAs 44, 45, and 47), superior parietal lobule (LPs), inferior parietal lobule (LPi), and cerebellum (Paulesu et al., 1993; Fiez et al., 1996; Clark et al., 2000). With regard to the ‘‘when’’ aspect, short-term memory for the temporal order of words requires the involvement of the left DLPFC (Smith et al., 1998).

So far, the debate has focused on the nature of the verbal working memory system that is involved in syntactic processing (for a review, see Caplan and Waters, 1999). Caplan et al. (2000) compared the cerebral blood-flow changes when subjects made a sentence plausibility judgment about written sentences with different syntactic complexities. During this task, subjects were required to utter the word ‘‘double’’ aloud repeatedly, in order to prevent them from rehearsing the sentences. Caplan et al. (2000) found that BA 45 was specifically activated by the degree of syntactic complexity; they concluded that the activation in BA 45 represents the recruitment of working memory resources that are specialized for syntactic processing.

According to recently proposed psycholinguistic models of language processing (for a review, see Hagoort, 2005), syntactic processing includes two functional components: memory and unification. The memory component comprises the specification of the different types of language information that are stored in long-term memory, and their retrieval. The unification component refers to the integration of lexically retrieved information into a representation of multi-word utterances. The basic information components are retrieved from long-term memory (the mental lexicon), whereas additional information is derived from combinatorial operations (unification) that assemble the basic components into larger structures. In syntactic processing, each word that is formed in the mental lexicon (memory) is associated with a structural frame. This specifies the possible structural environment of the particular lexical item. The structural frames associated with the individual word forms thus enter the unification workspace incrementally, in an order that is imposed by the input. In this workspace, constituent structures spanning the whole utterance are formed by an on-line unification operation (Hagoort, 2005); this consists of the linking of lexical frames, and the checking of agreement features (such as number, gender, person, and so on). Thus, the unification process is driven by the time course of the inputs of the mental lexicon that are retrieved from the memory component. This characteristic is unique to unification, as distinct from the simple maintenance of information in verbal memory. Thus, the unification process might involve the working memory resources that are specialized for syntactic processing.

However, the precise relationship between the neural substrates of the maintenance of verbal information and its active manipulation during syntactic processes (or unification) has yet to be explored. To depict the neural substrates specific to syntactic processes that are distinct from verbal working memory or semantic processes, we utilized two pairs of tasks. First, the neural activity during a sentence comprehension task (SEN) was compared with that during a short-term memory maintenance task (MEM), using the method proposed by Hashimoto and Sakai (2002). As suggested by Potter (1993), sentence comprehension immediately and automatically generates a stable representation; hence, this comparison should depict the neural substrates of syntactic and semantic processes, while controlling for general verbal working memory processes (that is, short-term memory maintenance).

To isolate the syntactic and verbal working memory processes from the semantic processes, for the second paradigm we combined center-embedded and left-branched sentences (Inui et al., 1998). In Japanese, it is possible to create a pair of sentences that are semantically identical and differ only in the syntactic structure of the sentence embedding (Inui et al., 1998). In the present study, we utilized a special type of center-embedded sentence with a garden-path (GP) effect together with left-branched sentences that had the same meaning but no GP effect (Hopf et al., 2003; Appendix A). The human sentence-parsing mechanism or ‘‘parser’’ continuously updates one single preferred analysis without considering any possible alternatives; however, if disambiguation occurs towards a non-preferred syntactic analysis, the parser will ‘‘stumble’’ because no information is available about possible alternatives. This is known as the ‘‘GP effect’’ and has been demonstrated by prolonged reading times, which is key evidence in favor of a serial parsing architecture. After being ‘‘garden-pathed’’, the parser must re-parse at least some parts of the sentence in order to derive an appropriate re-analysis. Hence, GP sentences generate a greater syntactic workload than non-GP (NGP) sentences (Hopf et al., 2003). Additionally, the verbal working memory load is expected to increase during comprehension of GP sentences, because non-integrated material is kept active during the processing of other words, as ‘‘syntactically ambiguous sentences require the maintenance of two alternative syntactic structures up to the point at which a new word disambiguates the sentence to one of the two alternatives’’ (Fiebach et al., 2005). This is the case in Japanese, which is characterized by its head-final left-branching nature (Mazuka and Itoh, 1996). Thus, differences in activity should highlight the critical regions for syntactic processing and verbal working memory, while minimizing the contribution of semantic processing. By comparing the amount of spatial overlap between the regions activated by comparing the syntactic and semantic processes (SEN–MEM), and the syntactic processes with the verbal working memory (GP–NGP) conditions, one should be able to segregate the neural substrates of syntactic processing.

2. Materials and methods

2.1. Participants

Eighteen volunteers (nine male and nine female; mean age ± standard deviation (S.D.) = 32.4 ± 6.0 years) participated in this study. All of the subjects were right-handed according to the Edinburgh handedness inventory

(Oldfield, 1971). The subjects had no history of neurological or psychiatric illness, and no developmental disorders, including reading disabilities. All of the participants gave their written informed consent, and the protocol was approved by the Ethical Committee of the National Institute for Physiological Sciences, Japan.

2.2. Tasks

2.2.1. SEN/MEM run

The event-related design consisted of three types of trial: sentence (SEN), memory (MEM), and control (CTRL; Fig. 1a). Each trial consisted of three phases: a 2-s cue phase, a 4-s presentation phase, and a 4-s response phase. The cue phase began with a beep tone (frequency = 1 kHz; duration = 160 ms). The response phase began with a high or low beep tone (frequency = 2 kHz or 500 Hz, respectively; duration = 160 ms for both).

During SEN trials, the subjects participated in audio versions of subject–predicate agreement tasks (Hashimoto and Sakai, 2002). Initially, an auditory cue indicated that it was a SEN trial. During the following presentation phase, a spoken sentence that included two names, two verbs, and one pronoun was presented. The grammatical collocation was identical to that used in the Hashimoto SEN-1 task (Hashimoto and Sakai, 2002). The sentence set consisted of six types of grammatical collocation, as follows: [N1–*wa* N2–*ga* P-o V1–*to* V2], [N1–*ga* N2–*ni* P–*ga* V1–*to* V2], [N1–*ni* N2–*ga* P-o V1–*to* V2], [N1–*ga* P-o V1–*to* N2–*ni* V2], [N1–*ga* P–*wa* N2–*to* V1–*to* V2], and [N1–*ga* P–*ni* V1–*to* N2–*ni* V2]. Here, N denotes a proper noun, V denotes a verb, P denotes a pronoun, –*ga* denotes a nominative or accusative marker, –*wa* denotes a topic marker, –*ni* denotes a dative marker, -o denotes an accusative marker, N2–*to* denotes a post-position "with N2", and V1–*to* denotes a complementizer "that V1" (Hashimoto and Sakai, 2002). During the response phase, the speech sounds were made up of a noun and a verb that were used in the preceding sentence. The participants judged whether the subject of the verb corresponded to the person mentioned in the paired words.

During MEM trials, the subjects participated in an audio version of the short-term memory for words (STM-W) tasks described by Hashimoto and Sakai (2002). Initially, an auditory cue indicated that it was a MEM trial. During the presentation phase, the speech sounds presented were made up of the three nouns and the two verbs used in the SEN trials. We added either a "–wo:" accusative marker or a "–ni:" dative marker to all three nouns, because these case particles are known to have important roles in thematic assignment (Inui et al., 2007). The order of presentation was randomized, to eliminate any effects of sentence structure. During the response phase, the speech sounds presented were made up of the two nouns used in the preceding sentence. The participants judged whether the order of the nouns presented during the response phase corresponded to the order of those presented during the sentence phase.

For CTRL trials, an auditory cue indicated the trial type. During the presentation and response phases, the sounds presented were reversed versions of those used in each phase of the SEN trials. The participants judged whether the beep tone presented in the response phase was high or low.

We used a rapid event-related design with a trial duration of 10 s. The distribution of the stimulus onset asynchrony (SOA) for each trial was optimized (Sadato et al., 2005; Saito et al., 2005) and fixed across subjects. Each run included 20 10-s trials of each of the three different trial types, with a total run time of 10 min. The sentences for each trial were selected randomly from the sentence set.

2.2.2. GP/NGP run

The design of the GP/NGP run was similar to that of the SEN/MEM run. There were three types of trial: subject–predicate agreement tasks with GP sentences (GP), those with NGP sentences (NGP), and tone discrimination tasks (CTRL; Fig. 1b). The GP and NGP trials were similar to the SEN trials of the SEN/MEM run, with the exception that the speech sounds in the presentation and response phases differed. During the presentation phase, the sentences were composed of six phrases. In the GP trials, the sentences were center-embedded, whereas in the NGP trials they were left-branching (Fig. 1c). An independent experiment showed that syntactic processing difficulties arose when parsing preferences were disconfirmed at the fifth phrase of the GP sentences, and so syntactic re-analysis occurred (Appendix A). During the response phase, the sentence was made up of a noun and a verb connected with a "–ga:" nominative marker. The CTRL trials were similar to those described for the SEN/MEM run, except that the reversed sounds from the GP trials were used.

Each participant performed four runs (two SEN/MEM runs and two GP/NGP runs) in one scanning session. The interval between the runs was 3–5 min. The order of the runs was counterbalanced. Two different run orders were used across the participants: SGGS and GSSG (where S = SEN/MEM run and

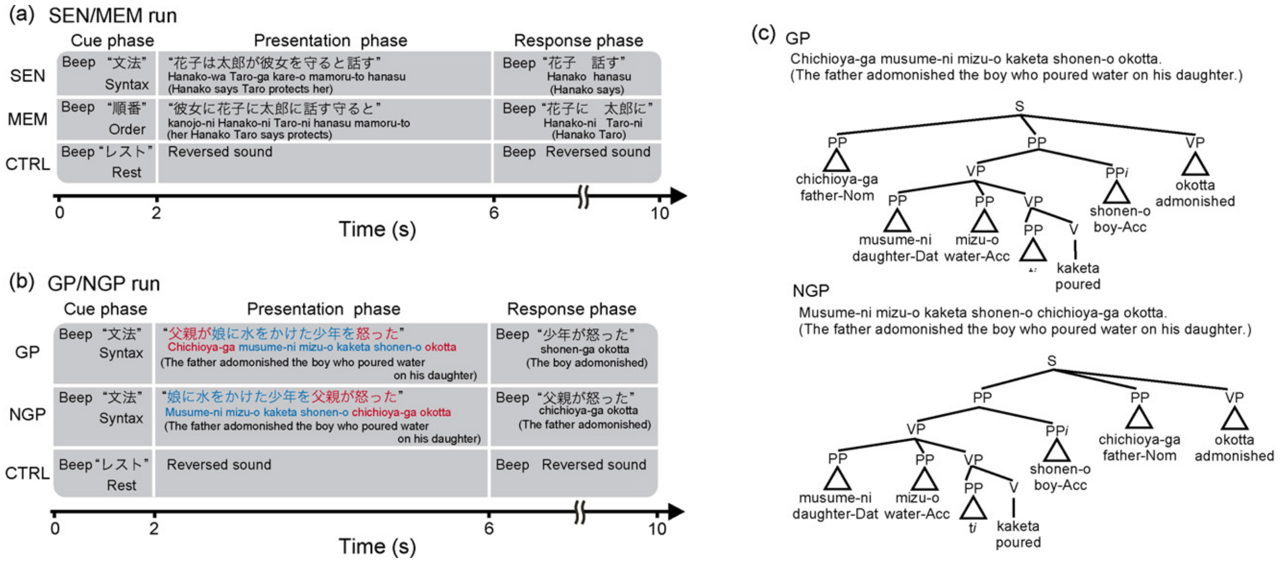

Fig. 1. The four tasks used to identify the neural substrates for syntactic processing. (a) Examples of auditory stimuli used in the SEN/MEM run: a SEN task, a MEM task, and a CTRL condition. The first 2 s was the cue phase, indicating which task was to follow. For the next 4 s, a sentence with five phrases was presented, followed by a beep, and then the paired phrases to be assessed were presented. An example of a Japanese sentence is shown. A white crosshair was always shown at the center of the screen for gaze fixation (not depicted in the figure). All language stimuli were generated by voice-synthesis software. (b) Examples of the auditory stimuli used in the GP/NGP run: a syntactic decision-making task with GP sentences, NGP sentences, and a CTRL condition. The format and timing were identical to those described for the SEN/MEM run. (c) Tree diagram showing the syntactic structures of the GP (top) and NGP (bottom) sentences. The triangle indicates that the corresponding phrase is decomposable. Acc, accusative; Dat, dative; i, co-referential index; Nom, nominative; PP, post-positional phrase; S, sentence; t, trace; V, verb; VP, verb phrase.

G = GP/NGP run). Participants performed two practice runs (one SEN/MEM run and one GP/NGP run) outside the scanner before the experiment commenced.

All language stimuli were presented through headphones (Hitachi Advanced Systems, Yokohama, Japan). The speech sounds were made using a male voice generated by speech-synthesis software (SMARTTALK Ver. 3.0; Oki Electric Industry, Tokyo, Japan). The participants heard the speech sounds and then pushed a response button (HH-1×4D; Current Designs, PA, USA) with their left thumb. While performing the auditory tasks, the participants were instructed to focus on a fixation crosshair. The presentation of the sounds and the fixation crosshair, the response time measurements, and the position of the response button were controlled using Presentation software (Neurobehavioral Systems, CA, USA).

2.3. Magnetic resonance imaging (MRI) data acquisition

During each run, a time-course series of 205 volumes was acquired using T2-weighted gradient-echo echo-planar imaging (EPI) sequences with a 3.0 T MR imager (Allegra; Siemens, Erlangen, Germany). Each volume consisted of 36 transaxial slices, with a slice thickness of 4 mm without a gap, which covered the entire cerebral and cerebellar cortices. The slices were acquired in the interleaved mode. Oblique scanning was used to exclude the eyeballs from the obtained in-plane images. The time interval between two successive acquisitions of the same image (repetition time, TR) was 3000 ms with a flip angle (FA) of 85° and an echo time (TE) of 30 ms. The field of view (FOV) was 192 mm, and the in-plane matrix size was 64 × 64 pixels.

For anatomical reference, T1-weighted fast-spin echo images (TR = 300 ms; TE = 4.6 ms; FA = 90°) collected at the same positions as the echo-planar images, and T1-weighted high-resolution three-dimensional images covering the whole brain (TR = 11.08 ms; TE = 43 ms; FA = 6°; FOV = 210 mm; matrix size = 256 mm × 256 mm), were obtained for each participant.

2.4. Functional MRI (fMRI) data analysis

2.4.1. Preprocessing

The MRI data were analyzed using statistical parametric mapping (SPM2; Wellcome Department of Cognitive Neurology, London, UK) implemented in Matlab (Mathworks, Sherborn, MA, USA; Friston et al., 1995a,b). The first five volumes of each fMRI run were discarded to allow for stabilization of the magnetization, and the remaining 200 volumes/run (totaling 800 volumes/participant) were used for the analysis. The MRI data were realigned to correct for head-motion: the echo-planar images of each run were realigned to the first image of the run, and the four images were then realigned together. The realigned data were spatially normalized into a standard stereotaxic brain space (Evans et al., 1994) using an EPI template. The anatomically normalized fMRI data were resampled to a voxel size of 2 mm × 2 mm × 2 mm, and were spatially smoothed using a Gaussian kernel with a full-width at half maximum of 8 mm in the x, y, and z axes.

Statistical analysis was conducted at two levels. First, the individual task-related activation was evaluated. Second, the summary data for each individual were incorporated into a second-level analysis using a random-effect model (Friston et al., 1999), in order to make inferences at a population level.

2.4.2. Individual analysis

The signal was proportionally scaled by setting the whole-brain mean value to 100 arbitrary units. The signal time course for each participant was modeled with a general linear model. Regressors of interest (trial effects) were generated using a box-car function convolved with a hemodynamic-response function. Regressors of no interest, such as run effect and high-pass filtering with a cut-off period of 256 s, were also included. To test the hypotheses about the regionally specific trial effects, the estimates for each model parameter were compared with the linear contrasts. The resulting set of voxel values for each contrast constituted a statistical parametric map (SPM) of the t statistic (SPM$\{t\}$).

2.4.3. Group analysis with a random-effect model

The weighted sum of the parameter estimates in the individual analysis constituted "contrast" images, which were used for the group analysis (Friston et al., 1999). Contrast images obtained via individual analyses represented the normalized task-related increment of the MR signal of each participant. For each contrast, a one-sample Student's t-test was performed for every voxel within the brain, in order to obtain population inferences. The resulting set of voxel values for each contrast constituted an SPM$\{t\}$. The threshold value for the SPM$\{t\}$ was set at $p < 0.05$ with a correction for multiple comparisons at the cluster level for the entire brain (Friston et al., 1996).

The activated clusters in the left GFi were further examined by investigating whether activity was predominantly located in BA 44 and/or 45, using the SPM Anatomy Toolbox (Eickhoff et al., 2005; Amunts et al., 1999) implemented in SPM5. Within the clusters activated by GP–NGP alone, GP–NGP and SEN–MEM, and SEN–MEM alone, the activation probabilities of BA 44 ($P_{\mathrm{BA\ 44}}$) and BA 45 ($P_{\mathrm{BA\ 45}}$) were calculated on a voxel-by-voxel basis. The numbers of voxels that were located predominantly in BA 44 ($P_{\mathrm{BA\ 44}} > P_{\mathrm{BA\ 45}}$) and BA 45 ($P_{\mathrm{BA\ 45}} > P_{\mathrm{BA\ 44}}$), and those that were activated with equal probability ($P_{\mathrm{BA\ 44}} = P_{\mathrm{BA\ 45})} > 0$), and were not active in either BA 44 or BA 45 ($P_{\mathrm{BA\ 44}} = P_{\mathrm{BA\ 45})} = 0$), were calculated and presented as a percentage of the total number of each cluster.

3. Results

3.1. Task performance

All of the subjects performed well on the SEN, MEM, GP, and NGP tasks. The response accuracy (all data are presented as the mean ± S.D.) for the SEN task was 74.7 ± 11.6%, which was slightly lower than that for the MEM task; this difference was statistically significant (80.4 ± 13.8%; $p = 0.023$, paired t-test). The response accuracy for the GP sentences was 93.6 ± 6.4%, while that for the NGP sentences was 94.7 ± 5.3%; these values were not significantly different ($p = 0.386$, paired t-test). The response accuracy for the GP and NGP sentences combined was significantly better than that for the SEN task ($t = 7.345$, $p < 0.001$, paired t-test).

The mean reaction time for the SEN task was 2196.2 ± 425.9 ms, while that for the MEM task was 2232.2 ± 315.6 ms; these values were not significantly different ($p = 0.596$, paired t-test). The reaction time for GP sentences was 1756.8 ± 295.9 ms, which was slightly slower than that for the NGP sentences (1673.9 ± 190.4 ms); this difference was not significant, although it was close to the predefined statistical threshold ($n = 18$, $p = 0.052$, paired t-test). The combined reaction time for the GP and NGP sentences was significantly faster than that for the SEN condition ($n = 18$, $t = 6.235$, $p < 0.001$, paired t-test).

The response accuracy for the CTRL condition during the SEN/MEM run was 99.3 ± 1.5%, while that during the GP/NGP run was 98.1 ± 2.9%; these values were not significantly different ($p = 0.070$, paired t-test). The mean reaction time for the CTRL condition during the SEN/MEM run was 949.4 ± 431.1 ms, while that during the GP/NGP run was 878.8 ± 179.8 ms; again, there was no significant difference ($p = 0.824$, paired t-test) between these values.

3.2. Task-related activation

A direct comparison of the SEN–MEM condition masked with the SEN–CTRL condition revealed activation in the left GFi (BA 47), middle temporal gyrus (GTm; BA 21), and right cerebellum (Fig. 2). A direct comparison of the GP–NGP

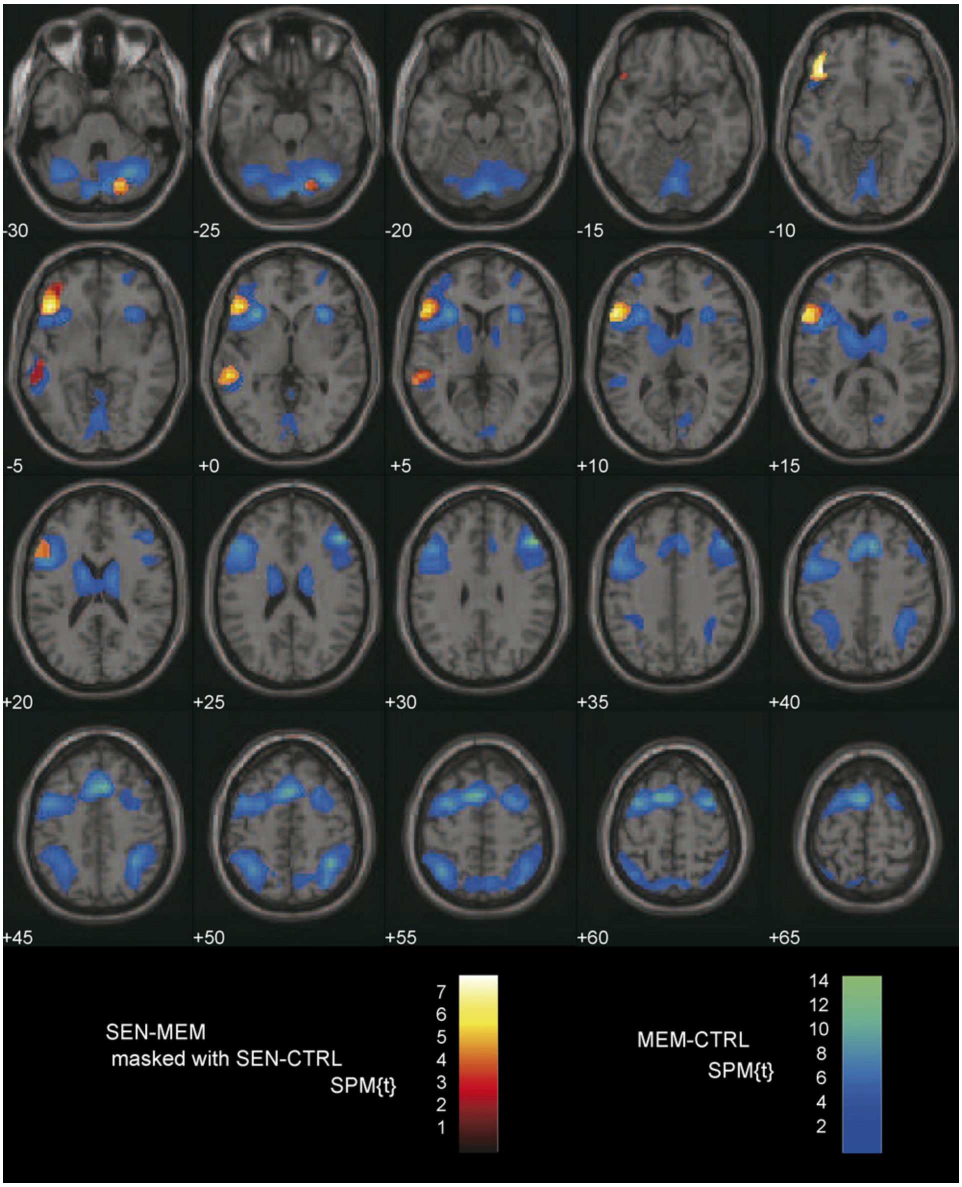

Fig. 2. SPMs of the enhanced neural activity during the MEM task compared with the CTRL condition (blue), and during the SEN task compared with the MEM condition (red). Activated foci are shown as a pseudocolor functional MRI superimposed on a high-resolution anatomical MRI in 20 contiguous transaxial planes with a 5-mm interval, extending from 30 mm below the anterior commissure–posterior commissure (AC–PC) plane (top left) to 65 mm above the AC–PC plane (bottom right). The statistical threshold was $p < 0.05$, corrected for multiple comparisons at the cluster level.

condition masked with the GP–CTRL condition showed significant activation in the left GFi (BA 45), GFm (BA 46), ventral premotor (PMv), dorsal premotor (PMd), pre-supplementary motor area (pre-SMA), and right cerebellum (Fig. 3). The activation of the left GFi extended to the anterior insula.

3.3. Functional subdivisions in the left GFi

Within the left GFi, the ventral portion was activated predominantly by the SEN–MEM condition (Fig. 4, red), whereas the dorsal portion was mainly activated by the GP–NGP condition (Fig. 4a, blue). A region that was commonly activated by both comparisons was found in between these two areas (Fig. 4a, green). The commonly activated areas were located predominantly in BA 45 (Fig. 4b, Table 1). By contrast, the areas activated exclusively by GP–NGP included BAs 44 and 45 (Fig. 4b, Table 1).

4. Discussion

4.1. Task contrasts

4.1.1. SEN–MEM

Syntactic and semantic processes were assessed by means of the SEN–MEM contrast, which explicitly controlled the verbal working memory component. The activation of the left GFi, including BAs 44, 45 (Amunts et al., 1999), and 47, and the left GTs/GTm (BA 22/21), confirmed the results of a previous study by Hashimoto and Sakai (2002), which involved reading sentences. These findings were also consistent with recent

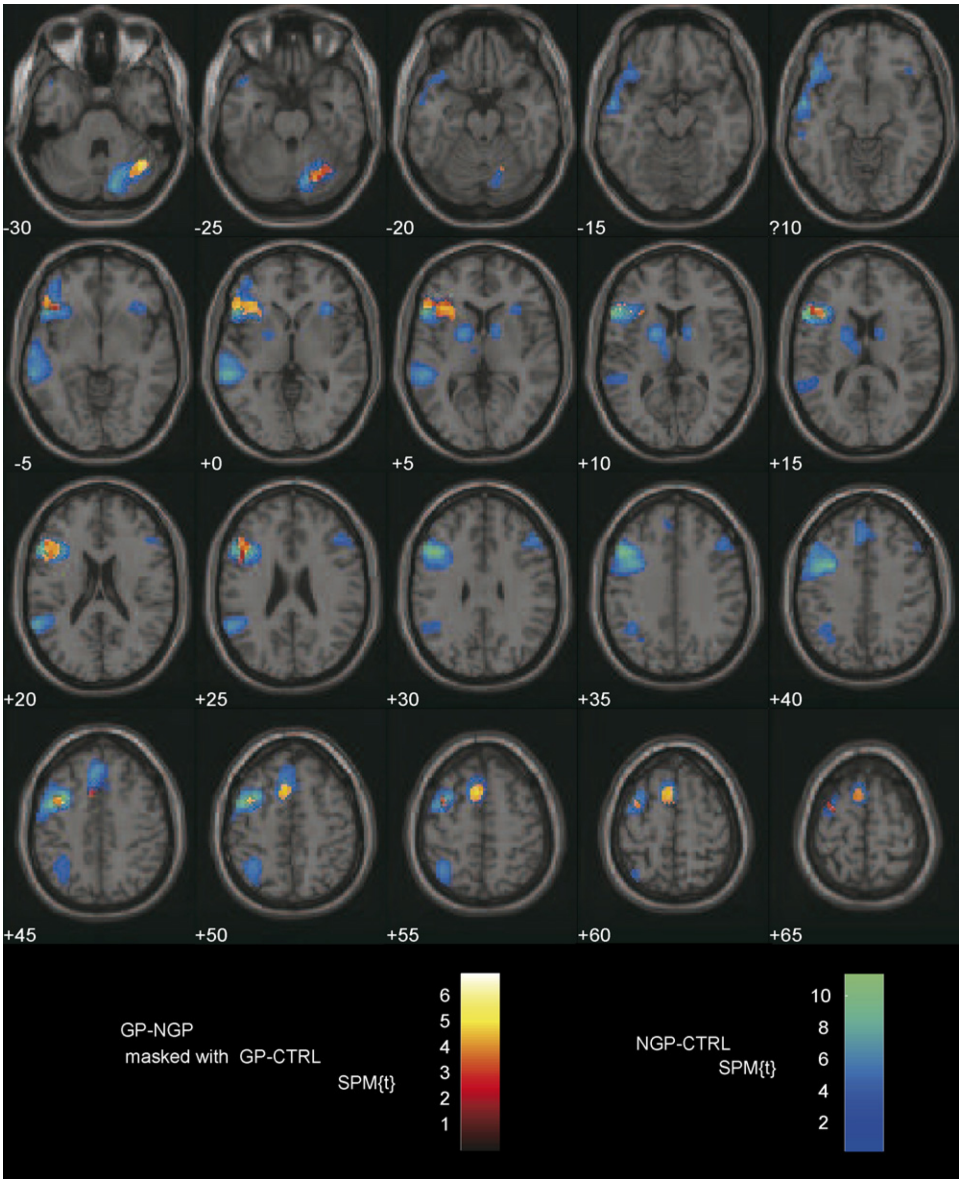

Fig. 3. SPMs of the enhanced neural activity during syntactic decision-making for an NGP sentence compared with the CTRL condition (blue), and during syntactic decision-making for a GP sentence compared with an NGP sentence (red), masked with the GP–CTRL condition. The same format and statistical thresholds were used as described for Fig. 2.

neuroimaging studies of speech comprehension, which suggested that the left GTm and BA 45/47 were relevant areas in the semantic domain (see Friederici, 2002, for a review). The left temporal cortex plays a crucial role in the storage and retrieval of linguistic information that is encoded in the mental lexicon, whereas BA 45/47 is recruited for semantic processing when strategic decisions and/or memory come into play (see Friederici, 2002, for a review).

4.1.2. GP–NGP

The comparison of syntactically complex (GP) and simple (NGP) sentences (Stromswold et al., 1996; Inui et al., 1998) revealed activation in BA 45 extending to BA 44, partly confirming the findings of previous studies (Inui et al., 1998; Stowe et al., 2004). BA 45 is related to syntactic processes (Dapretto and Bookheimer, 1999; Caplan et al., 2000). Additionally, the left GFm (BA 46), PMv, PMd, pre-SMA, left anterior insula, and right cerebellum were activated.

The accuracy scores for the GP and NGP sentences were equivalent, whereas the reaction times were slightly longer for the former. This was consistent with the theoretical expectations, and also with the results of an independent experiment that showed an elongation of the reading time during the fifth phrase of the GP sentences (Appendix A). The differences between the GP and NGP sentences were minimized. In this study, the stimuli were produced by a speech-synthesis program, which provided identical prosodic phrasing for both GP and NGP sentences. The GP and NGP sentences differed in the order of the phrases, which forced syntactic re-analysis (re-parsing). Additionally, the complex conditions might have differed from the simple conditions in terms of memory load (that is, keeping non-integrated material active while proces-

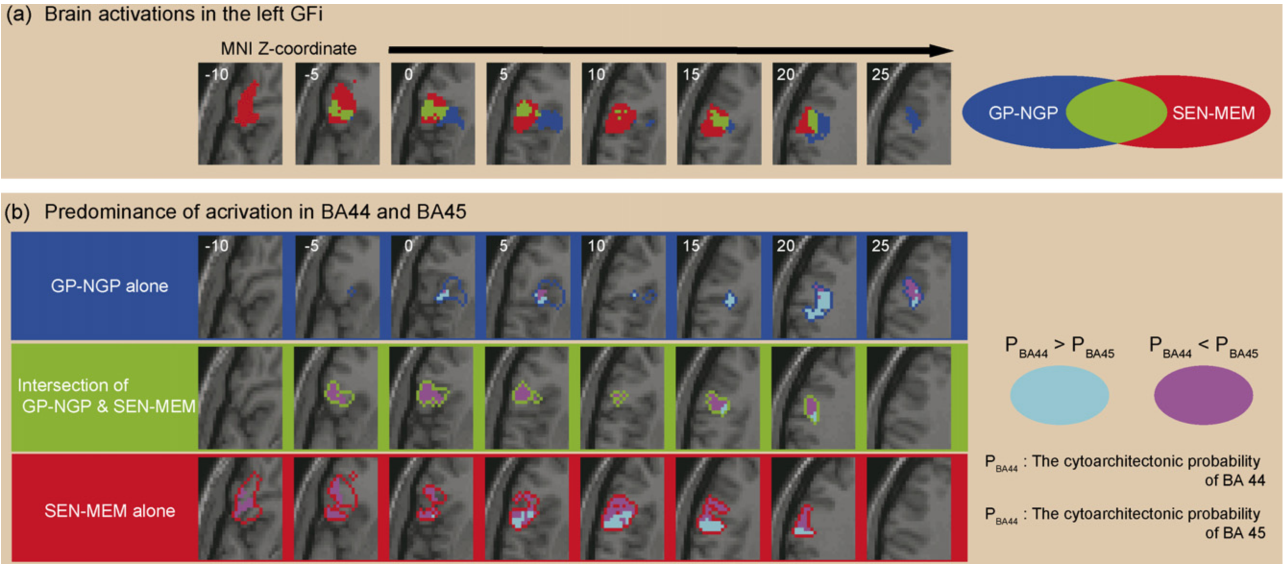

Fig. 4. Functional segregation in the left GFi. (a) Combined SPMs of the SEN–MEM condition, the GP–NGP condition, and their intersection in the left GFi. Red indicates the areas activated by SEN–MEM alone, blue indicates the areas activated by GP–NGP alone, and green indicates the areas commonly activated by both SEN–MEM and GP–NGP. (b) The top row shows the predominance of activation in BA 44 (light blue) within the clusters activated by GP–NGP alone (blue outline). The middle row shows the predominance of activation in BA 45 (purple) within the clusters activated by both GP–NGP and SEN–MEM (green outline). The bottom row shows that, within the cluster activated by SEN–MEM (red outline), the ventral portion is located in neither BA 44 nor BA 45. The dorsal portion is predominantly BA 44, and BA 45 activation is prevalent in between.

Table 1
Predominant activity in BA 44/45

Conditions	$P_{\text{BA 44}} > P_{\text{BA 45}}$	$P_{\text{BA 45}} > P_{\text{BA 44}}$	$P_{\text{BA 44}} = P_{\text{BA 45}} > 0$	$P_{\text{BA 44}} = P_{\text{BA 45}} = 0$
GP–NGP alone	36.9	20.4	0.0	42.7
GP–NGP and SEN–MEM	10.1	79.4	0.0	10.5
SEN–MEM alone	20.0	48.3	0.6	31.1

In the activated regions in the left GFi highlighted by GP–NGP alone, GP–NGP and SEN–MEM, and SEN–MEM alone, the percentages of the voxels with the larger probability of activation in BA 44 or BA 45 as compared to the total number of activated voxels are shown. $P_{\text{BA 44}}$, the cytoarchitectonic probability for BA 44; $P_{\text{BA 45}}$, the cytoarchitectonic probability for BA 45 (Amunts et al., 1999).

sing other words; Kaan and Swaab, 2002). Hence, the activation produced by the GP sentences compared with the NGP sentences represented an increased load on verbal working memory as well as syntactic re-analysis.

4.1.3. Differences between SEN–MEM and GP–NGP

During the SEN trials, sentence comprehension immediately and automatically generated a stable representation. Such processing did not occur during the MEM trials, in which word lists without any sentence structure were presented and memorized. Hence, the SEN–MEM comparison depicted the neural substrates of syntactic and semantic processes by controlling for general verbal working memory processes. The semantic processing included in the SEN–MEM comparison included grasping the meaning of the whole sentence, because no sentence structure was provided during the MEM trials, but the individual words were identical. Furthermore, the presence of case particles, which are known to activate BA 47 (Inui et al., 2007), was also controlled.

By contrast, the GP and the corresponding NGP sentences had identical meanings but differed in their syntactic structures. After being ‘‘garden-pathed’’ in GP sentences, the parser must re-parse at least some parts of the sentence in order to derive an appropriate re-analysis to finally reach the same meaning as in the NGP sentences. For example, ‘‘The father poured water on his daughter’’ (Fig. 1c) is a transient constituent that is syntactically ambiguous.

Chichioya-ga musume-ni mizu-o kaketa

father daughter water poured

(The father poured water on his daughter)

This constituent is abolished and re-parsed when ‘‘*shonen-o*’’ is encountered.

Chichioya-ga [musume-ni mizu-o kaketa shonen-o]

father [daughter water poured boy]

(Father [the boy who poured water on his daughter])

Thus, differences in activity should highlight the regions that are critical for the syntactic processing required to re-parse the sentence and the verbal working memory required for the maintenance of the transient constituent.

4.2. Functional segregation in the left GFi

4.2.1. BA 47

The left BA 47 has been shown to reflect semantic rather than syntactic processing (Kapur et al., 1994; Gabrieli et al., 1996; Wagner et al., 1997; Dapretto and Bookheimer, 1999). The present study showed that the ventral portion of BA 47 was activated only by the SEN–MEM condition. As we compared sentences with a list of words that did not have syntactic structure, the SEN–MEM comparison inevitably included semantic processes that were automatically triggered during sentence comprehension. Within the GFi, the task-related activation highlighted by SEN–MEM was largest in BA 47 (which was not significantly activated by GP–NGP), whereas the GP–NGP component increased gradually in the dorsal portion of the GFi. The lack of activation in BA 47 in the GP–NGP contrast suggests that the degree of ‘‘semantic’’ re-analysis in GP sentences is negligible, if it takes place at all.

4.2.2. BA 44 and other areas

In the present study, the dorsal portion of BA 44 (the pars opercularis; Amunts et al., 1999) and BA 45 was activated by the GP–NGP contrast, suggesting a role in verbal working memory. This is consistent with previous studies. To discriminate syntactic integration from syntactic working memory, Fiebach et al. (2005) used fMRI and independently varied the working memory load and syntactic complexity. They found that the left BA 44 was activated by an increased working memory load, whereas there was no change with increased syntactic complexity (Fiebach et al., 2005). They concluded that the left BA 44 plays a critical role in syntactic working memory during on-line sentence comprehension (but, see also Bornkessel et al., 2005). Bahlmann et al. (2007) also showed that German sentences with non-canonical word order, which demand greater working memory than those with canonical word order, activated BA 44. However, BA 44 was not related to syntactic re-analysis (Bahlmann et al., 2007). Together with these previous findings, our results suggest that the dorsal portion of BA 44/45 might be more closely related to verbal working memory than to syntactic unification.

Similar to the dorsal portion of BA 44/45, the pre-SMA, left PMv, PMd, anterior insula, left BA 46, and right cerebellum (shown in red in Fig. 3) were activated by the GP–NGP contrast but not by the SEN–MEM contrast. These regions might represent part of the neural substrates of general verbal working memory, recruited by the increased memory load during the GP condition. Verbal materials are maintained using an articulatory rehearsal system (Colle and Welsh, 1976; Baddeley, 1992). The regions within the cerebellum, SMA, and premotor cortices are likely to be part of such a system (Paulesu et al., 1993). The activation of the pre-SMA, premotor cortices, and cerebellum might be affected by the memory load, the amount of covert articulation imposed by a task, or both (Fiez et al., 1996). A human lesion study of patients with and without speech apraxia showed that the left precentral gyrus of the insula is related to articulatory planning (Dronkers, 1996). The DLPFC (BAs 46 and 9) is the central executive of the working memory system, controlling attention and information flow to and from the verbal and spatial short-term memory buffers (D’Esposito et al., 1995). Hence, the left BA 46 activation might be related to the re-distribution of attentional resources due to task difficulty. These findings suggest that BA 44 might be regarded as the part of the verbal working memory network involved in articulatory rehearsal.

4.2.3. BA 45

The left BA 45 was activated by both SEN–MEM and GP–NGP. This cognitive subtraction and conjunction suggests that the area is related to the syntactic unification processes, consistent with the findings of a previous study (Caplan et al., 2000). The present work extends these results by showing that BAs 45 and 44 are functionally different: the latter represents verbal working memory and the former represents syntactic unification, which is a specialized aspect of the working memory system.

Considering the activation patterns in BAs 47, 45, and 44 shown in the present study, there appears to be an apparent dorsal–ventral gradient in the left GFi: working memory processes are localized more dorsally, semantic processing is localized more ventrally, and syntactic processing is localized between the two regions. The findings of a previous fMRI study suggest that semantic processing at the sentence level is related to BA 45/47 activity (Dapretto and Bookheimer, 1999), and that an increase in syntactic complexity and/or related verbal working memory components activate BA 44/45 (Just et al., 1996; Stromswold et al., 1996; Inui et al., 1998; Caplan et al., 2000). BA 45 could therefore be regarded as a node linking the verbal working memory system to the semantic processes embedded in BA 47 through syntactic unification.

In conclusion, our results indicate that within the left GFi, the language-relevant part of the frontal cortex (Bookheimer, 2002), syntactic unification processing is mediated mainly in BA 45, verbal working memory mainly in BA 44, and semantic processing mainly in BA 47. Thus, BA 45 might have a role in linking verbal working memory maintenance and semantic processing via syntactic unification processes.

Acknowledgements

The authors appreciate the contribution of Dr. Hirokazu Yokokawa (Kobe University), who prepared the tree diagrams for the GP and NGP sentences. This study was supported, in part, by Grant-in Aid for Scientific Research S#17100003 (N.S.) from the Japan Society for the Promotion of Science.

Appendix A. Psychophysical testing of GP sentences

A.1. Subjects and methods

In total, 130 native Japanese speakers participated in this study. The subjects were recruited from among the college students majoring in liberal arts and social sciences at Setsunan University (Osaka, Japan). All participants had normal or corrected-to-normal vision, and were naive to the purpose of the experiment.

In total, eight GP and eight NGP sentences were used for the task. The GP sentences contained six phrases (A–F) and were center-embedded; it was expected that the GP effect would occur at the fifth phrase. The corresponding NGP sentences consisted of the same phrases, but were left-branching. The tasks were administered, and the reading time and comprehension accuracy data were collected, using SuperLab Pro (Cedrus Corporation, San Pedro, CA). The stimulus sentences were presented phrase-by-phrase in white text on a black background at the center of a 17-in. monitor. Participants were instructed to read each phrase as quickly as possible, and to press a pacing button as soon as they were ready to move on to the next phrase. After completing the six phrases, a comprehension question appeared on the screen along with the two answer options, which were presented side by side. The participants were instructed to press either the ‘‘f’’ key or the ‘‘j’’ key, depending on which of the answers they thought was correct. At the end of each trial, a message appeared on the screen instructing the participants to press a dedicated key to trigger the start of the next trial. The order of presentation of the 16 sentences was randomized across the participants. All participants completed the task in around 5 min.

The performance scores for reading the sentences were calculated by dividing the number of correct answers by the number of presented sentences (eight GP and eight NGP sentences in total). The differences between the reading times for each phrase for the GP sentences and the times for the corresponding NGP sentences were calculated for each participant. For example, if a center-embedded GP sentence was expressed as Agp–(Bgp–Cgp–Dgp–Egp)–Fgp, the corresponding left-branched NGP sentence was expressed as (Bngp–Cngp–Dngp–Engp)–Angp–Fngp. The delay was calculated as Agp–Angp, Bgp–Bngp, and so on, for every sentence and for each subject. Due to the GP structure, we predicted that the delay for phrase E would be longer than those for the other phrases. A two-way repeated measures analysis of variance (ANOVA) was conducted, including both phrase and sentence effects.

A.2. Results

The mean (±S.D.) percentage of correct answers for the GP sentences was 85.1 ± 21.7%, which was slightly but statistically significantly lowers than that for the NGP sentences (88.9 ± 18.7%, $p = 0.008$, paired *t*-test). A repeated measures two-way ANOVA on the reading performance data for the GP and NGP sentences showed a significant phrase effect ($F(5, 645) = 15.05$, $p < 0.001$, with a Greenhouse–Geisser correction), although there was neither a significant sentence effect ($F(7, 903) = 0.29$, $p = 0.94$, corrected) nor a significant interaction effect between the two ($F(35, 4515) = 1.14$, $p = 0.32$, corrected). The predefined contrasts revealed a significantly longer reading time for the fifth phrase than for all of the other phrases ($F(8, 129) = 26.75$, $p < 0.001$). The table below summarizes the mean delay and S.D. of the delay (ms) times for the six phases across the 130 subjects and for the eight pairs of sentences.

Phrase	Mean delay (ms)	S.D. of delay (ms)
A	−7.5	359.00
B	−10.9	351.70
C	13.20	308.70
D	27.30	324.80
E	147.10	728.90
F	8.70	382.50

References

Amunts, K., Schleicher, A., Burgel, U., Mohlberg, H., Uylings, H.B.M., Zilles, K., 1999. Broca's region revisited: cytoarchitecture and intersubject variability. J. Comp. Neurol. 412, 319–341.

Baddeley, A., 1992. Working memory. Science 255, 556–559.

Bahlmann, J., Rodriguez-Fornells, A., Rotte, M., Munte, T.F., 2007. An fMRI study of canonical and noncanonical word order in German. Hum. Brain Mapp. 28, 940–949.

Bookheimer, S., 2002. Functional MRI of language: new approaches to understanding the cortical organization of semantic processing. Annu. Rev. Neurosci. 25, 151–188.

Bornkessel, I., Zysset, S., Friederici, A.D., Von Cramon, D.Y., Schlesewsky, M., 2005. Who did what to whom? The neural basis of argument hierarchies during language comprehension. Neuroimage 26, 221–233.

Caplan, D., Waters, G.S., 1999. Verbal working memory and sentence comprehension. Behav. Brain Res. 22, 77–94.

Caplan, D., Alpert, N., Waters, G., Olivieri, A., 2000. Activation of Broca's area by syntactic processing under conditions of concurrent articulation. Hum. Brain Mapp. 9, 65–71.

Clark, C.R., Egan, G.F., McFarlane, A.C., Morris, P., Weber, D., Sonkkilla, C., Marcina, J., Tochon-Danguy, H.J., 2000. Updating working memory for words: a PET activation study. Hum. Brain Mapp. 9, 42–54.

Colle, H.A., Welsh, A., 1976. Acoustic masking in primary memory. J. Verb. Learn. Learn. Verb. Behav. 15, 17–31.

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

D'Esposito, M., Detre, J.A., Alsop, D.C., Shin, R.K., Atlas, S., Grossman, M., 1995. The neural basis of the central executive system of working memory. Nature 378, 279–281.

Dick, F., Bates, E., Wulfeck, B., Utman, J.A., Dronkers, N., Gernsbacher, M.A., 2001. Language deficits, localization, and grammar: evidence for a distributive model of language breakdown in aphasic patients and neurologically intact individuals. Psychol. Rev. 108, 759–788.

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

Eickhoff, S.B., Stephan, K.E., Mohlberg, H., Grefkes, C., Fink, G.R., Amunts, K., Zilles, K., 2005. A new SPM toolbox for combining probabilistic cytoarchitectonic maps and functional imaging data. Neuroimage 25, 1325–1335.

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

Evans, A.C., Kamber, M., Collins, D.L., MacDonald, D., 1994. An MRI-based probalistic atlas of neuroanatomy. In: Shorvon, S.D. (Ed.), Magnetic Resonance Scanning and Epilepsy. Plenum Press, New York, pp. 263–274.

Fiebach, C.J., Schlesewsky, M., Lohmann, G., von Cramon, D.Y., Friederici, A.D., 2005. Revisiting the role of Broca's area in sentence processing: syntactic integration versus syntactic working memory. Hum. Brain Mapp. 24, 79–91.

Fiez, J.A., Raife, E.A., Balota, D.A., Schwarz, J.P., Raichle, M.E., Petersen, S.E., 1996. A positron emission tomography study of the short-term maintenance of verbal information. J. Neurosci. 16, 808–822.

Friederici, A.D., 2002. Towards a neural basis of auditory sentence processing. Trends Cogn. Sci. 6, 78–84.

Friston, K.J., Ashburner, J., Frith, C.D., Heather, J.D., Frackowiak, R.S.J., 1995a. Spatial registration and normalization of images. Hum. Brain Mapp. 2, 165–189.

Friston, K.J., Holmes, A.P., Worsley, K.J., Poline, J.B., Frith, C.D., Frackowiak, R.S.J., 1995b. Statistical parametric maps in functional imaging: a general linear approach. Hum. Brain Mapp. 2, 189–210.

Friston, K.J., Holmes, A., Poline, J.-B., Price, C.J., Frith, C.D., 1996. Detecting activations in PET and fMRI: levels of inference and power. Neuroimage 4, 223–235.

Friston, K.J., Holmes, A.P., Worsley, K.J., 1999. How many subjects constitute a study? Neuroimage 10, 1–5.

Gabrieli, J.D.E., Desmond, J.E., Demb, J.B., Wagner, A.D., 1996. Functional magnetic resonance imaging of semantic memory processes in the frontal lobes. Psychol. Sci. 7, 278–283.

Hagoort, P., 2005. On Broca, brain, and binding: a new framework. Trends Cogn. Sci. 9, 416–423.

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

Hopf, J.M., Bader, M., Meng, M., Bayer, J., 2003. Is human sentence parsing serial or parallel? Evidence from event-related brain potentials. Brain Res. Cogn. Brain Res. 15, 165–177.

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.

Inui, T., Otsu, Y., Tanaka, S., Okada, T., Nishizawa, S., Konishi, J., 1998. A functional MRI analysis of comprehension processes of Japanese sentences. Neuroreport 9, 3325–3328.

Inui, T., Ogawa, K., Ohba, M., 2007. Role of left inferior frontal gyrus in the processing of particles in Japanese. Neuroreport 18, 431–434.

Just, M.A., Carpenter, P.A., 1992. A capacity theory of comprehension: individual differences in working memory. Psychol. Rev. 99, 122–149.

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.

Kaan, E., Swaab, T.Y., 2002. The brain circuitry of syntactic comprehension. Trends Cogn. Sci. 6, 350–356.

Kapur, S., Rose, R., Liddle, P.F., Zipursky, R.B., Brown, G.M., Stuss, D., Houle, S., Tulving, E., 1994. The role of the left prefrontal cortex in verbal processing: semantic processing or willed action. Neuroreport 5, 2193–2196.

Mazuka, R., Itoh, K., 1996. Can Japanese speakers be led down the garden-path? In: Mazuka, R., Nagai, N. (Eds.), Japanese Syntactic Processing. Lawrence Erlbaum Associates, Philadelphia, pp. 295–329.

Newman, A.J., Pancheva, R., Ozawa, K., Neville, H.J., Ullman, M.T., 2001. An event-related fMRI study of syntactic and semantic violations. J. Psycholinguist. Res. 30, 339–364.

Oldfield, R.C., 1971. The assessment and analysis of handedness: the Edinburgh inventory. Neuropsychologia 9, 97–113.

Paulesu, E., Frith, C.D., Frackowiak, R.S., 1993. The neural correlates of the verbal component of working memory. Nature 362, 342–345.

Potter, M.C., 1993. Very short-term conceptual memory. Mem. Cogn. 21, 156–161.

Sadato, N., Okada, T., Honda, M., Matsuki, K., Yoshida, M., Kashikura, K., Takei, W., Sato, T., Kochiyama, T., Yonekura, Y., 2005. Cross-modal integration and plastic changes revealed by lip movement, random-dot motion and sign languages in the hearing and deaf. Cereb. Cortex 15, 1113–1122.

Saito, D.N., Yoshimura, K., Kochiyama, T., Okada, T., Honda, M., Sadato, N., 2005. Cross-modal binding and activated attentional networks during audio-visual speech integration: a functional MRI study. Cereb. Cortex 15, 1750–1760.

Smith, E.E., Jonides, J., Marshuetz, C., Koeppe, R.A., 1998. Components of verbal working memory: evidence from neuroimaging. Proc. Natl. Acad. Sci. U.S.A. 95, 876–882.

Stowe, L.A., Paans, A.M.J., Wijers, A.A., Zwarts, F., 2004. Activations of "motor" and other non-language structures during sentence comprehension. Brain Lang. 89, 290–299.

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

Wagner, A.D., Desmond, J.E., Demb, J.B., Glover, G.H., Gabrieli, J.D.E., 1997. Semantic repetition priming for verbal and pictorial knowledge: a functional MRI study of left inferior prefrontal cortex. J. Cogn. Neurosci. 9, 714–726.