Two Different Subcortical Networks of Language System: Morphogram and Phonogram, Through the Analysis of Unique Japanese Characters

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Abstract

Language systems worldwide are based on morphograms or phonograms, and Japanese is a unique language that uses a complicated combination of kanji (morphogram) and kana (phonogram) characters. The white matter networks associated with reading have been investigated previously but remain unclear. In this study, we performed intraoperative language mapping under local anesthesia and postoperative language assessments of 65 consecutive patients who underwent surgical resection for cerebral glioma within the dominant temporal or parietal lobe. The cases showing intraoperative dyslexia elicited by direct electrical stimulation (DES) or postoperative kanji and/or kana dyslexia were extracted. Five patients showed transient kanji or kana dyslexia intraoperatively, and 8 patients showed kanji or kana dyslexia postoperatively. During intraoperative mapping, kanji or kana dyslexia were indeed reproduced by DES. We investigated the maximal overlapping lesions of the resection cavity that were associated with kanji or kana dyslexia, and then determined the subcortical elicited points that evoked kanji or kana dyslexia. These areas were localized near three white matter bundles: the arcuate fascicle, posterior superior longitudinal fascicle, and inferior longitudinal fascicle (ILF). The intraoperative DES distributions for kanji dyslexia were especially associated with the anterior-inferior side of the ILF. On the other hand, the DES point associated with kana dyslexia was localized on the posterior-superior side of the complex of these three tracts. These results suggested the presence of specific non-interfering networks that subserved the reading process for morphograms and phonograms.

Introduction

Linguistically, human phonetic language systems worldwide can be categorized based on morphograms and phonograms. Chinese ideographic characters are examples of morphograms, while the alphabets widely used in countries of Europe and America are examples of phonograms (Koyama et al. 1998). Almost all languages contain either morphograms or phonograms; however, the Japanese language consists of both. Specifically, the Japanese language system contains two different types of letters, kanji (morphogram) and kana (phonogram) (Koyama et al. 1998; Sakurai 2011). Kanji are ideographic characters of Chinese origin that represent a lexical morpheme of spoken language and are used for writing most nouns and roots of verbs. In contrast, kana are written characters used to represent Japanese short syllables (Koyama et al. 1998). There are about 2000 kanji and 71 kana characters in daily use for Japanese writing and are also intimately involved in reading.

Some studies have revealed a neural foundation in the human cerebral cortex for the reading process. Previous reports mentioned the importance of the angular gyrus in the reading process (Henderson 1986). Further studies revealed that the dual streams consisting of the ventral semantic and the dorsal phonological streams, which were constructed by white matter neural networks, were important in the neural foundations of language. The inferior longitudinal fascicle (ILF) is a part of the ventral stream connecting the temporal–parietal–occipital systems. In contrast, the arcuate fascicle (AF) and the posterior segment of the superior longitudinal fascicle (SLF) are known to be subcortical structural components of the dorsal stream that connects the inferior parietal and frontal systems (Hickok and

Poeppel 2000). In addition, the visual word form system, which connects the occipital cortex to the posterior occipito-temporal cortices, is consistent with the systems described above (Koyama et al. 1998). Some previous studies have suggested the contribution of the inferior fronto-occipital longitudinal fascicle (IFOF) to semantic processing (Moritz-Gasser S et al. 2013).

Previous reports mentioned that some of neural networks, such as a written and spoken processing, would be universal regardless of morphogram or phonogram languages (Rueckl et al. 2015). On the other hand, other studies suggested that the neural network about reading process would be different between these two language systems (Hu et al. 2010). However, because of some limitations, such as the difference of the facilities and the examination based on their languages (Rueckl et al. 2015; Hu et al. 2010), it is still difficult to compare these two language systems accurately. Other reports have discussed patients with kanji or kana dyslexia caused by cerebral infarction and assessed the neuroanatomical localization of Japanese alexia (Sakurai et al. 2008). The specific lesion of pure kanji dyslexia would be located in the mid-fusiform gyrus, and the lesion of selective kana dyslexia lies in a more posterior area of the fusiform/inferior occipital gyri (Sakurai 2011). As for the subcortical network, some papers hypothesized that the functional regions in reading kana or kanji would be localized respectively in the dorsal side or the ventral side of temporal lobe associated with the ILF (Enatsu et al. 2017; Sakurai et al. 2000; Sakurai et al. 2008). However, the subcortical networks for reading kanji and kana are not completely understood. It is also unknown whether the neural networks for reading morphograms and phonograms are separate.

In addition, in some cases of left temporal glioma, one of the primary brain tumors, kanji or kana dyslexia was observed after resection of the lesion. Awake craniotomy, a neurosurgical technique for brain tumors under local anesthesia, can preserve neurological and neuropsychological functions using intraoperative cortical and subcortical direct electrical stimulation (DES), thereby providing unique opportunities to map brain functions (Duffau et al. 2005). The transient neurological deficits provoked by the subcortical DES also contribute to lesion study which could investigate the function of the fiber bundle (Duffau et al. 2005). Herein, we investigated a series of 65 patients who underwent surgery for left temporal glioma with perioperative language assessments. In our experience, kanji and kana dyslexia can be transiently provoked by subcortical DES during awake craniotomy for left temporal glioma. On the basis of intraoperative functional mapping and postoperative MRI using voxel-based morphometry analysis, it is suggested that there would be two different phonological processing methods in the cortical and subcortical networks for reading morphograms and phonograms in humans.

Patients And Methods

Patients

Between January 2014 and December 2019, a total of 65 consecutive patients who underwent craniotomy for resection of gliomas located in the left temporal or parietal lobe were recruited in our hospital. Among them, 51 patients were followed up after surgery until 6 months postoperatively

(Supplementary Information 1), and 46 patients underwent awake craniotomy (Supplementary Information 2). Written informed consent was obtained from the individual(s) or next of kin for the publication of any potentially identifiable images or data included in this article. This study was performed according to the guidelines of the Internal Review Board of Kanazawa University and approved by the medical ethics committee of Kanazawa University (Approval number: 3293).

Neuropsychological assessment

Before and after surgery, patients underwent language assessment tests, such as the Western Aphasia battery (WAB; Japanese version), conducted by a well-experienced speech specialist and an occupational therapist (OH and RN, respectively). The WAB test consists of eight subcategories (spontaneous speech, auditory comprehension, naming, repetition, reading, writing, praxis, and construction) (Kertesz 1982; Shewan 1986). In particular, reading skill was evaluated for both kanji and kana in the WAB test. On the basis of the scores of these subcategories, the aphasia quotient (AQ), an individual parameter for the severity of aphasia, was calculated. Patients with severe aphasia, including other language disorders, were excluded from our study. Subsequently, all patients were categorized by the speech specialist and occupational therapist (OH and RN) into three groups as follows: no dyslexia, kanji dyslexia, and kana dyslexia.

Magnetic resonance imaging (MRI) and postprocessing

Structural MRI was performed as part of standard perioperative care. Diffusion-weighted MRI (DW-MRI) was performed using a 3.0 Tesla MRI scanner (Signa™ Excite HDx 3.0T, General Electric Healthcare, Little Chalfont, UK) under the same conditions as previously reported (Kinoshita et al. 2016). A series of axial diffusion-weighted images (b-value: 0 to 1,000 s/mm²) with a diffusion-sensitizing gradient along 30 directions were obtained. Other parameters for this study were as follows: repetition time = 1,4000 ms, echo time = 69.6 ms, number of extractions = 2, 60 axial slices with slice thickness = 2.5 mm with no interslice gap, and field of view = 220 × 220 mm with a matrix = 88 × 88, resulting in an effective resolution of 2.5-mm³ isotropic voxels. The DW-MRI data were transferred to a workstation using iPlan Cranial 3.0 software (Brainlab, Feldkirchen, Germany), and white-matter tracts of the AF, posterior SLF, and ILF were selected and visualized. All the fiber tracts were constructed with fiber propagation (fractional anisotropy threshold > 0.18). To reconstruct each fiber tract, regions of interest were determined manually by referring to the diffusion tensor imaging tractography atlas and previous reports (Catani et al. 2002; Kinoshita et al. 2016; Makris et al. 2005). Each MRI was converted to the Montreal Neurological Institute (MNI) template using SPM12 (<http://www.fil.ion.ucl.ac.uk/spm/software/spm12/>), which was implemented in the MATLAB environment (<http://www.mathworks.com/products/matlab/>). The resection cavities were reconstructed manually using MRICron software (<http://www.mccauslandcenter.sc.edu/mricro/mricron/>). We investigated the regions showing maximum overlap in kanji or kana dyslexia and identified the regions that overlapped in all cases of postoperative kanji or kana dyslexia on the three-dimensional (3D) MNI template.

Procedure for identification of overlapping positive mapping points

The procedure for identification of overlapping positive mapping points was the same as that described in previous reports (Nakajima et al. 2020a). First, subcortical positive mapping points were plotted on postoperative 3D T1 MR images while referring to the operative findings and intraoperative records with iPlan Cranial 3.0 software (BrainLab). The locations of these mapping points were confirmed by determining their spatial relationships to anatomical landmarks: gyri, sulci, artery, and lateral ventricles. We also checked the mapping points on 2D axial, sagittal, and coronal MRI images. These procedures were first performed by ST and inspected systematically by RN and MK.

Procedure for awake craniotomy

Using the same procedure as that described in previous reports, all 46 patients underwent awake craniotomy using the “Asleep-Awake-Asleep” technique, with cortical and subcortical brain mapping achieved by DES using a bipolar electrode with 5-mm spaced tips (Duffau et al. 2002). A biphasic current was used with a pulse frequency of 60 Hz and amplitude depending on cortical mapping stimulation (3–6 mA). Surgical resection was stopped when DES revealed specific neurological findings and disorders during task execution, including picture-naming tasks and alternate reading tasks for kana or kanji (Supplementary Information 3 and 4, Video). All positive mapping sites were labeled by number tags, and intraoperative photographs were obtained. We investigated the relationship between the subcortical DES mapping points and the intraoperative kanji or kana dyslexia.

The operative view and intraoperative neuropsychological assessments were recorded using a video camera. Intraoperative tasks for glioma patients were selected depending on their social background, motivation, and tumor location. To address the oncological priorities in these patients, we performed surgical resection as follows: first, we resected the enhanced lesion of the tumor, which was followed by extended resection with the appropriate intraoperative assessments (Esquenazi et al. 2017). In particular, the typical measurement for aphasia in Japanese was based on naming tasks. Intraoperatively, we showed slides that alternately indicated kana and kanji words every 4 seconds and evaluated whether the patients could read these words correctly. We identified the following situations as incorrect reading: no response, sequential reading, and phonetic error.

Results

Behavioral data

Of the 65 consecutive patients, 8 patients had postoperative dyslexia (kanji: 5 cases; kana: 3 cases) (Supplementary Information 5). Five patients showed kanji or kana dyslexia in DES mapping during awake surgery (Table 1).

Lesions related to postoperative kanji or kana dyslexia

We assessed the overlapping area of each resection cavity in these cases. The lesion showing the maximum overlapping lesion in kanji dyslexia was localized at the middle part of the inferior temporal cortex and the deep part of the cortex (Fig. 1Aa). The subcortical area was located on the course of the ILF (Fig. 1Ab). On the other hand, the overlapping lesion in kana dyslexia was localized at the dorsoposterior sides of the region for kanji dyslexia (Fig. 1Ba), and the subcortical area was overlaid with the ILF which nearby the AF and posterior SLF (Fig. 1Bb).

Intraoperative findings during awake surgery

Five patients showed kanji dyslexia (cases 1, 2, 3, and 4) or kana dyslexia (case 5) during awake surgery, and 4 positive points (cases 1, 2, 3, and 5) were identified in the subcortical regions. Two positive points (cases 3, and 4) which showed kanji dyslexia were identified in the cortical region. In this section, we present illustrative cases of kanji dyslexia (case 1) and kana dyslexia (case 5) during subcortical DES mapping (Supplementary Information 3 and 4).

Analysis of positive mapping points

We analyzed the subcortical mapping points in these four cases (cases 1, 2, 3, and 5) (Fig. 2). As for case 4, the positive mapping point was only located at the cortical region. The results revealed that the subcortical positive mapping points of kanji and kana dyslexia were located at independent lesions. On the basis of the operative view and postoperative images, we analyzed the relationship between the positive mapping points of dyslexia and white matter tracts. The results suggested that the positive mapping points for kanji and kana dyslexia were localized near the AF, posterior SLF, and ILF in all four cases (Fig. 2).

Overlap analysis

All positive mapping points were plotted on the standard brain. The positive points for kanji dyslexia are shown as blue points, and the positive point for Kana dyslexia is shown as a red point (Fig. 3A). Subcortical positive mapping points were located near the region overlapping three white matter tracts: AF, posterior SLF, and ILF (Fig. 3B). The subcortical positive mapping point for kanji dyslexia was along with the course of the ILF. On the other hand, the subcortical points for kana dyslexia were located on the superior and dorsal sides of this region, i.e., the posterior-superior side of the ILF which nearby the AF and posterior SLF (Fig. 3C). Notably, no patient presented kanji or kana dyslexia postoperatively.

Illustrative cases

Case 1, a 44-year-old right-handed man, presented to our hospital complaining of headache. Fluid-attenuated inversion recovery (FLAIR) imaging on MRI showed a high-intensity lesion in the left temporal. During resection of subcortical lesions in the awake condition, DES reproduced kanji dyslexia (see Video in Supplementary Information 3). We preserved the region and then completed the operation. The phonological paraphasia appeared transiently, and the patient showed improvement to the preoperative level after rehabilitation.

Case 5, a 67-year-old right-handed man, presented to our hospital with a left temporal tumor detected by a brain dock. FLAIR imaging on MRI showed a high-intensity lesion in the left middle temporal gyrus. Due to tumor progression during follow-up, awake craniotomy was planned for resection of the left posterior temporal lobe tumor. During subcortical tumor resection, the patient presented kana dyslexia evoked by DES in the subcortical area, while he did not show any disturbances for reading kanji (see Video in Supplementary Information 4).

We analyzed the relationship between intraoperative stimulation points and positive mapping points. The results showed that each positive mapping point was localized at a different lesion and evoked only kanji or kana dyslexia, which did not interfere with the other (Fig. 4).

Discussion

Kanji (morphograms)-Kana (phonograms) dissociation in reading/comprehension has been the central topic in Japanese aphasiology (Sakurai 2019). In this study, we identified the language networks corresponding to the phonological processes for reading morphograms and phonograms through an analysis of patients showing dyslexia in Japanese kanji and kana. The present results denoted that each subcortical network for reading kanji and kana was independent in the anatomo-functional assessment using awake functional subcortical mapping and tractographic imaging.

The cortical region subserving morphograms and phonograms

The overlap map of resected cavities and the anatomical distribution of intraoperative positive mapping points suggested the cortical region about reading would be different in each Japanese phonetic language system. The anatomical distribution of intraoperative cortical positive mapping indicated similar result that the network of kanji-reading would be located at the inferior side of the temporal lobe. In accordance with our results, the neural pathway about reading/comprehension of morphograms and phonograms have been studied and some reports mentioned that the cortical location about each language system would be different (Hu et al. 2010). Previous papers indicated the cortical region about the reading alphabet was associated with left temporoparietal brain (Meyler et al. 2007), and the cortical region about reading Chinese was associated with left occipito-temporal and inferior frontal brain (Liu et al. 2012). Similar analyses were performed in Japanese, and previous papers suggested the cortical regions of kanji and kana reading would be different (Sakurai et al. 2008, Sakurai 2011). The pure alexia of kanji spreads to the inferior side of the temporal lobe originating from the mid-fusiform gyrus (Sakurai 2011). In contrast, the pure alexia of kana would be localized on the superior side of the temporal lobe originating from the fusiform/inferior occipital gyri (Sakurai et al. 2008; Sakurai 2011).

The subcortical region subserving reading process

The analysis about high-probabilistic lesion associated with postoperative dyslexia and the anatomical distribution of intraoperative subcortical mapping points indicated similar results. Our analysis about subcortical region of Japanese dyslexia newly identified the presence of two distinct, non-interfering

reading networks subserving kanji and kana reading. Some papers have mentioned the functions of these individual white matter pathways, and these papers were mainly published from countries where the phonogram language system was popularly used. Anatomically, the AF has multiple cortical terminations for the temporo-parietal regions, including the middle temporal gyrus, superior temporal gyrus, and supramarginal gyrus (Catani et al. 2005). Especially, the left side of AF has been mentioned as the one of the brain language pathways (Catani et al. 2007), and shown to subserve the dorsal phonological stream elucidated by subcortical DESs and the evoked symptoms (Duffau 2008).

The SLF connects the frontal and parietal lobes, and it also provides partial interconnection between the parietal and posterior temporal lobes. Neuroimaging and functional analyses have provided some classifications of SLF, and the posterior SLF is a SLF subcomponent determined by anatomo-functional considerations (Nakajima et al. 2020b). In patients with left temporal glioma, surgical resection of inferior termination of the posterior SLF caused postoperative reading impairment, and the posterior SLF has been suggested to be associated with language-related networks, especially in the reading process (Zemmoura et al. 2015).

The ILF connects the occipital and posterior occipito-temporal lobes with the temporal lobe, and it contributes to visual recognition and reading, while subserving the ventral semantic stream connecting the IFOF and SLF (Herbet et al. 2018, Herbet et al. 2019). Previous reports also mentioned the ILF associate with language networks, and the disruption of the ILF induced dyslexia (Herbert et al. 2018, Del Tufo et al. 2019). The electric cortical stimulation of the basal temporal language area induced kanji dyslexia, and the specific area connects with a ventral stream via the ILF, which would contribute to the subcortical network of the kanji-reading process (Enatsu et al. 2017). Recent detailed fiber dissection and tractography studies revealed that the ILF was a multilayered, bidirectional fiber tract (Latini et al. 2017, Pancsar et al. 2018). According to previous papers, the ILF could be divided into several components of bundle, including the dorso-lateral occipital segment running from the dorsolateral occipital cortex to the infero-lateral temporal lobe and the fusiform segment originating from the posterior-basal occipital region to lateral-basal temporal region (Latini et al. 2017). Thus, including the results of cortical and subcortical analysis, the dorso-lateral occipital segment of the ILF which connected occipito-temporal brain would be associated with kana phonogram, and the fusiform segment of the ILF which connected with visual cortical area (Brodmann area 18/19) would be associated with kanji morphogram (Meyler et al. 2007; Liu et al. 2012; Sakurai et al. 2008; Sakurai 2011; Latini et al. 2017).

Limitations

The current study has some limitations. First, only a small number of cases were enrolled. A large number of cases are needed to validate the findings of our study. Second, we focused on three white matter fascicles including AF, ILF, and posterior SLF, not on IFOF, which was considered as a direct pathway of the ventral semantic stream. However, a previous anatomo-functional study using the same methodological approach suggested that IFOF would not be crucial for reading (Zemmoura et al. 2015). The contribution of IFOF to the reading system is controversial and further studies on this topic are

expected. Third, these are some problems about the mechanism of DES. The DES would not stimulate the fiber bundles themselves, but just transiently disconnect between two areas of brain (Yordanova et al. 2017). This fact suggests that there are some potential dissociations in this maneuver outcome. Finally, white matter bundles may change and shift with the invasion of glioma cells. However, some previous papers mentioned that these bundles would not change radically in cases with low-grade glioma, and that the original neural network was preserved well (Mandonnet et al. 2007) although it is debatable in patients with high-grade glioma (Duffau 2014; Roux et al. 2003).

Conclusions

Our report suggests that not only the cortical but also the subcortical networks for the reading process of kanji (morphograms) and kana (phonograms) are independent. The subcortical neural network for reading morphograms ran in the middle to inferior temporal region and was mainly associated with the ILF, while that for reading phonograms was in the cortical posterior temporal region and subcortical posterior ILF region which was mainly associated with the AF and posterior SLF. This result of specific reading networks would be meaningful not only in the field of neurosurgical planning for cerebral glioma within the dominant temporal lobe but also in a developed neuroscience research focusing on the mechanism of dyslexia.

Abbreviations

3D three-dimensional

AF arcuate fasciculus

AQ aphasia quotient

DES direct electrical stimulation

DTI diffusion tensor imaging

DW-MRI diffusion weighted-magnetic resonance imaging

FLAIR fluid-attenuated inversion recovery

IFOF inferior fronto-occipital longitudinal fascicle

ILF inferior longitudinal fascicle

MNI Montreal Neurological Institute

MRI magnetic resonance imaging

SLF superior longitudinal fascicle

Declarations

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Conflicts of interest

The authors declare no conflicts of interest associated with this manuscript.

Authors' contributions

Conception and design: MK and ST. Acquisition of data: ST, RN, and HO. Analysis and interpretation of data: ST and RN. Drafting the article: ST. Critically revising the article: ST, MK, and MN. Reviewed submitted version of the manuscript: All authors. Approved the final version of the manuscript on behalf of all authors: MK. Study supervision: MN.

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The authors declare no conflicts of interest associated with this manuscript.

Ethics approval

This study was performed according to the guidelines of the Internal Review Board of Kanazawa University and approved by the medical ethics committee of Kanazawa University (Approval number: 3293).

Consent to participate and for publication

Written informed consent was obtained from the individual or next of kin for the publication of any potentially identifiable images or data included in this article.

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Tables

Table 1
Cases with intraoperative dyslexia evoked during awake surgery

Case	Age	Sex	Localization	Diagnosis	Type of dyslexia	Region	Postoperative dyslexia
1	44	M	Temporal	Diffuse astrocytoma	Kanji	Subcortical	None
2	18	M	Temporal	Diffuse astrocytoma	Kanji	Subcortical	None
3	45	F	Temporal	Glioblastoma	Kanji	Subcortical and cortical	None
4	48	M	Temporal	Glioblastoma	Kanji	Cortical	None
5	67	M	Temporal	Diffuse astrocytoma	Kana	Subcortical	None

Figures

A. Kanji

B. Kana

Figure 1

Overlap maps and relationships between resection cavities and white matter tracts Result of overlap maps for the resection cavities in the cases showing left kanji or kana postoperative dyslexia on a normal brain template. The standardized regions of interest of the three white matter tracts are overlaid. AF, arcuate fascicle; ILF, inferior longitudinal fascicle; posterior SLF, posterior superior longitudinal fascicle. A. Lesion overlap in all cases with postoperative kanji dyslexia (red, high-probabilistic value > 80%). The regions showing the maximum overlap in kanji dyslexia were located at the posterior part of the inferior temporal cortex and its subcortical area (a). The lesion overlapping with the ILF (cyan) in all cases showing postoperative kanji dyslexia (b). B. Lesion overlap in all cases with postoperative kana dyslexia (red, high-probabilistic value > 80%). The region showing maximum overlap in kana dyslexia was localized at the superior and dorsal sides of the left temporal lobe (a). The lesion overlapped with the region near the AF (green) and posterior SLF (yellow) in all cases with postoperative kana dyslexia (b).

Figure 2

Case presentation with dyslexia elicited by intraoperative electrical mapping The relationships between postoperative images (right column), intraoperative photos after resection (center column), and diffusion tensor tractography (DTI) images of three white matter tracts with positive mapping sites (left column). Intraoperative transient kanji and kana dyslexia was observed in cases 1-3 and 5, respectively. Yellow

dotted circles indicate positive points in each dyslexia evoked by electrical subcortical stimulation. White dotted line in case 3 indicate Sylvian fissure. The white square is the enlarged view. AF, arcuate fascicle (green); ILF, inferior longitudinal fascicle (cyan); posterior SLF, posterior superior longitudinal fascicle (yellow); intraoperative subcortical positive mapping point (red ball).

A. All positive mapping site

B. Subcortical points

C. Spatial relationship between positive mapping sites and white matter

a. Kanji

MNI coordinates

-48

-50

-30

-16

6

-12

-24

b. Kana

-37

-54

6

Figure 3

Overlap maps and relationships between elicited points for dyslexia and white matter tracts The relationship between positive mapping points for intraoperative dyslexia and three white matter tracts on a normal brain template. AF, arcuate fascicle (green); ILF, inferior longitudinal fascicle (cyan); posterior

superior longitudinal fascicle, posterior SLF (yellow); intraoperative subcortical positive mapping point (red ball). A. All positive mapping points for dyslexia localized in the left temporal lobe. B. Subcortical positive mapping points localized near three fiber bundles. C. Spatial relationships between positive mapping points and three white matter tracts. The positive mapping points that evoked intraoperative kanji dyslexia were localized on the ILF (a). On the other hand, the positive mapping point that evoked intraoperative kana dyslexia was localized in the joint of the complex of three fiber bundles (b).

Figure 4

The intraoperative stimulus points in illustrative cases The intraoperative positive points were elucidated by electrical stimulation in illustrative cases (cases 1 and 5). Each positive mapping point was localized at different regions, and dyslexia of either kanji or kana was noted, although they never interfered with the other.

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