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# Real-time functional mapping: potential tool for improving language outcome in pediatric epilepsy surgery

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## Abstract

Accurate language localization expands surgical treatment options for epilepsy patients and reduces the risk of postsurgery language deficits. Electrical cortical stimulation mapping (ESM) is considered to be the clinical gold standard for language localization. While ESM affords clinically valuable results, it can be poorly tolerated by children, requires active participation and compliance, carries a risk of inducing seizures, is highly time consuming, and is labor intensive. Given these limitations, alternative and/or complementary functional localization methods such as analysis of electrocorticographic (ECoG) activity in high gamma frequency band in real time are needed to precisely identify eloquent cortex in children.

In this case report, the authors examined 1) the use of real-time functional mapping (RTFM) for language localization in a high gamma frequency band derived from ECoG to guide surgery in an epileptic pediatric patient and 2) the relationship of RTFM mapping results to postsurgical language outcomes. The authors found that RTFM demonstrated relatively high sensitivity (75%)

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and high specificity (90%) when compared with ESM in a "next-neighbor" analysis. While overlapping with ESM in the superior temporal region, RTFM showed a few other areas of activation related to expressive language function, areas that were eventually resected during the surgery. The authors speculate that this resection may be associated with observed postsurgical expressive language deficits. With additional validation in more subjects, this finding would suggest that surgical planning and associated assessment of the risk/benefit ratio would benefit from information provided by RTFM mapping.

## Keywords

epilepsy; brain-computer interface; SIGFRIED; cortical stimulation mapping; electrocorticography; real-time functional mapping

In the US, epilepsy affects nearly 326,000 children younger than 16 years; 10%–30% of these cases are resistant to antiepileptic medications.[3] Epilepsy surgery is a potentially curative option for these patients. However, it is often not given full consideration due to concern about the impact of surgery on language and cognitive function. Deficits may result when there is an overlap between seizure focus and language-specific regions, similar to risks in adults. However, in children there is added concern about the risk of interrupting developing networks that are connected to, but do not necessarily directly overlap, seizure onset zones. Accurate language localization in children may provide much needed surgical guidance and expand surgical epilepsy treatment options, thereby reducing the risk of postsurgical language deficit and benefiting children's quality of life, educational capacity, and long-term employment potential.

Electrical cortical stimulation mapping (ESM) is considered to be the clinical gold standard for language localization.[18] Although many studies have shown the value of ESM mapping, it can be poorly tolerated by children, requires active participation and compliance, carries a risk of inducing seizures, and is highly time and effort consuming. Electrical cortical stimulation mapping utilizes a "reversible lesion" approach by inhibiting cortical function through electrical stimulation of subdural electrode pairs. This necessarily involves stimulating one pair of electrodes at a time, adding to the challenges noted above. Also, ESM has some restrictions related to the timing of stimulation and subjectivity of interpretation when there is language interruption, especially when there is subtle language interruption (for example, hesitation vs speech arrest). Hence, an activation (rather than suppression) task that would allow for instant visualization of activated networks during language tasks would offer considerable advantages. Functional imaging techniques such as functional MRI share some of the limitations of ESM, with the added concern about specificity and spatial resolution of areas that are engaged during activation tasks.

Many studies over the past 15 years have shown that electrical signals recorded directly from the surface of the brain (electrocorticography [ECoG]) in patients with subdural grids implanted for clinical purposes readily detect and localize signal changes due to different auditory, motor, or language tasks.[10,24] Also, many studies have suggested that ECoG amplitudes in the high gamma band (> 70 Hz) may be most valuable for assessing the task-related activity of cortical neurons directly underneath the electrodes.[1,8,9,19,27] Therefore, task-related test batteries based on the analysis of ECoG high gamma activity can be successfully applied for localization of eloquent cortex. In this way, ECoG-based localization utilizing offline processing approaches has been successfully demonstrated for sensory-motor,[1,9,19,27] auditory,[7] and language function.[12,28,29]

Schalk et al.[20,21] went beyond the offline processing of task-related ECoG changes. They implemented a real-time ECoG signal analysis approach (real-time functional mapping [RTFM]). This created the potential for instant visualization of task-related changes in ECoG signals, which may be used in clinical settings, either directly at the patient's bedside or intraoperatively.

In our previous study[14] we demonstrated the feasibility and usefulness of a new RTFM stimulation paradigm implementation during presurgical evaluation. We showed that block design paradigms used in functional MRI, such as story processing or verb generation task, may be optimal for this purpose. However, it is unclear how RTFM activation is related to postsurgical language outcomes.

## Case Report

The institutional review board of the Florida Hospital for Children, Orlando, Florida, approved the study protocol.

### History and Examination

This 13-year-old girl, diagnosed with Turner syndrome shortly after birth, presented with nearly daily seizures despite being on oxcarbazepine monotherapy. Several other antiseizure drugs were also ineffective at managing the patient's complex focal seizures with occasional generalization that began at the age of 2 years. She had experienced cognitive decline for the past few years. Additional patient characteristics are presented in Table 1. The patient underwent the standard preoperative assessment to determine the epileptogenic area and eloquent cortex.

**Presurgical Noninvasive Evaluation—**The evaluation included a neuropsychological examination, long-term video-electroencephalography (video-EEG) to review seizure onset and clinical semiology, MRI with epilepsy surgery protocol, and FDG-PET. Ictal EEG showed diffuse rhythmic theta activity evolving in the left fronto-temporal region, MRI demonstrated diffuse left temporal lobe atrophy without clear evidence of mesial temporal sclerosis, and FDG-PET revealed extensive hypometabolism involving both mesial and lateral structures in the left temporal lobe.

**Presurgical Neuropsychological Evaluation—**A neuropsychologist (C.M.S.) performed the neuropsychological evaluation, which included the Wechsler Intelligence Scale for Children, Fourth Edition. The relevant index scores are provided in Table 1. Of note are the patient's extremely low verbal reasoning and concept formation skills, as measured by the Verbal Comprehension Index.

Consistent with her left temporal lobe epilepsy, the patient also showed extremely low performance on visual confrontation naming (with latent responses and frequent paraphasic errors), very low phonological fluency, border-line semantic fluency, and low average verbal memory. Her nonverbal reasoning skills, as measured by the Perceptual Reasoning Index was borderline. Her processing speed, as measured by Processing Speed Index, was extremely low, and her working memory, as measured by Working Memory Index, was low average.

**Invasive EEG Monitoring—**After a comprehensive review of preoperative data by the epileptologist and neurosurgeon, subdural grid placement for seizure localization and language mapping were recommended since the ictal semiology, postictal characteristics, and review of neuropsychological testing implicated seizure onset zone close to language cortex. For invasive monitoring, the intracranial electrode placement included a 16-contact grid covering the inferior frontal area and a 32-contact grid covering the temporal lobe. A single 6-contact electrode strip was placed in each of the following regions: temporal pole, anterior basal temporal, and middle basal temporal. An 8-contact electrode strip covered the posterior basal temporal region.

**MRI, CT, and ECoG Coregistration—**Three-dimensional volumetric MRI, performed using a 3-T GE scanner (T1 FSPGR, 512 × 512 matrix, FOV 250, 1 mm slice thickness), and a high-resolution CT scanning (512 × 512 matrix, FOV 250, 1-mm slice thickness) were carried out to precisely visualize the location of the subdural electrodes on the brain surface. The MRI and CT were coregistered and 3D segmentation of the brain surface and grid positions was performed using Analyze 11 (Analyze Direct).

**Functional Mapping—**Two types of functional mapping were used to determine localization of eloquent language cortex: ESM and RTFM.

**ESM:** Electrical cortical stimulation mapping was performed for identification of eloquent language cortex. Stimulations consisted of 5-second trains of 200-msec square-wave pulses of alternating polarity at 50 Hz applied to the adjacent electrode pairs using an Ojemann Cortical Stimulator (Integra LifeSciences Corp.).

Functional mapping was conducted by stimulating adjacent pairs of electrodes on the left temporal grid. Stimulation was initiated at low amperage (4–6 mA) and increased in 2-mA increments until an afterdischarge was elicited, a functional response was produced, or a maximum of 10 mA was attained. Sites where stimulation induced speech arrest or other language disruptions were noted and recorded.

Language mapping was conducted using a variety of tasks. Prior to conducting the mapping, baseline assessment of visual confrontation naming and reading was conducted with the mapping stimuli. It was done to identify stimuli that the patient could readily and consistently respond to with a high degree of accuracy. The patient was able to maintain optimal responding to naming stimuli, and most of the mapping was conducted with repetition of the visual naming items (that is, name pictures of objects presented on a computer screen), or responding to pictures with a brief sentence identifying an object (for example, “This is a bird”). These tasks were alternated with repetition of over-learned sequences (for example, counting and reciting the alphabet), and singing along with videos. Areas in which a change in language was noted during stimulation were restimulated to verify the responses before being recorded. One hundred percent interrater reliability between 2 neuropsychologists was achieved.

Baseline assessment prior to ESM also included testing for receptive language. However, baseline testing indicated that the patient was not able to consistently respond in a reliable manner adequate for identifying receptive language due to the complexity of the task and the relatively brief stimulation train (5 seconds).

**RTFM:** Electrocorticography signals from subdural electrodes implanted for presurgical evaluation were separated into a clinical and a research signal path through a splitter box. This ensured that the ECoG recording for seizures remained uninterrupted during the procedure. The clinical signal path went to the Nihon Kohden EEG 1200 system for clinical diagnosis, while the research signal path went to an array of g.USBamp amplification/ digitization devices (g.tec). The g.USBamp system was controlled by a dedicated research personal computer that records ECoG signals and delivers auditory and visual stimuli through speakers and a monitor.

BCI2000 software[22] acquired signals from the g.USBamps, provided visual/auditory stimulation, and performed real-time analyses using the SIGnal modeling For Real-time Identification and Event Detection (SIGFRIED) module (Schalk et al.[21] and Brunner et al.[5]). Subdural electrodes away from the seizure zone and eloquent areas served as the ground and reference electrodes. The patient sat upright in a raised bed in front of a computer screen and was instructed to relax and remain as still as possible.

Baseline cortical activity was first recorded for about 6 minutes followed by administration of several different paradigms, including those that assess receptive and expressive language function. More detailed paradigm descriptions can be found in Korostenskaja et al.[14] For determining the areas associated with speech comprehension (Wernicke’s areas), stories were presented to the subject through the speakers.[25] In contrast to ESM testing in which the patient was unable to respond in a reliable manner adequate for identifying receptive language, we were able to successfully conduct RTFM testing for receptive function localization. For determining expressive language function, we used a picture-naming paradigm, where the subject was asked to name pictures of different objects presented on the computer screen.[15]

The results from the real-time signal analyses (described in detail by Schalk et al.[21] and Brunner et al.[5]) were visualized at the bedside using a topographic interface. For each task (for example, story processing) the interface included a display that contained 1 circle at each electrode’s location. For each circle, the size of the circle and its tint were proportional to the coefficient of determination ($r^2$), calculated between brain signals at rest and brain signals during the particular task. Thus, a large red circle represented a large statistical difference between the corresponding task and rest, whereas a small black dot indicated a small statistical difference (Fig. 1).

**Establishing Concordance Between Functional Mapping Modalities—**We referred to electrode sites at which we observed RTFM activation (red circle on RTFM map) as RTFM positive, and those at which we did not as RTFM negative. We also referred to electrode sites at which ESM affected task performance as ESM positive and those at which they did not as ESM negative, (for the list of main findings, see Table 3). The sensitivity and specificity of RTFM were calculated only for sites where both RTFM and ESM were tested (see Tables 4 and 5). The RTFM sensitivity was calculated as the percentage of sites that were both RTFM positive and ESM positive among all ESM positive sites, and RTFM specificity was calculated as the percentage of sites that were both RTFM negative and ESM negative among all ESM negative sites.

## Operation

After the presurgical evaluation, the patient underwent a tailored temporal lobectomy according to the intracranial ictal EEG onset and the ESM language map. Based on the surgical report and postsurgical MRI results (Fig. 2), the resection included removal of the left middle, inferior, and anterior part of the superior temporal gyrus. The neurosurgeon worked posteriorly up until approximately 1.5 cm anterior to the area identified as the “language cortex” by ESM in the superior temporal gyrus. Therefore, there was partial sparing of the posterior and superior temporal lobes to avoid possible postsurgical expressive language deficits predicted by ESM mapping. The resection also included medial temporal lobe structures together with the hippocampus and amygdala. Importantly, the anterior temporal pole was removed, which was associated with expressive language function demonstrated by RTFM (Fig. 3).

## Postoperative Course

**Seizure Outcome—**The patient had no seizures after surgery. Antiseizure medication (oxcarbazepine) was discontinued at the 12-month postoperative follow-up, and the patient remained seizure free (at the 18-months postoperative follow-up). The pathology specimen revealed mesial temporal sclerosis without evidence of focal cortical dysplasia.

**Postsurgical Neuropsychological Evaluation—**A 2-month acute postsurgical neuropsychological testing follow-up showed expressive language decline (Table 2). The patient demonstrated very low performance in visual confrontation naming compared with same-aged peers. The patient exhibited a mild decline in phonemic fluency and a noticeable decline in semantic fluency. Furthermore, the patient’s mother’s report during clinical interviews suggested a decline in language functioning within the patient’s everyday environment.

Twelve-month postsurgical neuropsychological testing follow-up revealed a moderate (or 24 standard score point) decline in receptive language skills compared with postacute assessment. The patient demonstrated more prominent difficulty with sentence repetition and comprehension of contextually based information. She also showed a severe (or 45 standard score point) decline in her ability to make semantic associations. Notably, she showed a mild to moderate decline in complex attention or working memory (21 standard point reduction), which may have been a contributing factor to her reduced performance on complex verbal comprehension tasks. Consistent with her longstanding history of epilepsy, the patient exhibited ongoing confrontation naming as well as phonological fluency deficits that have remained stable despite surgical intervention (that is, no significant improvement over longer follow-up duration). In summary, although the patient exhibited low baseline performance, she exhibited further deterioration in category fluency skills, which are typically mediated by the temporal lobe. At the 1-year follow-up the patient also showed a more dramatic decline in receptive language as well as complex attention. These findings reflect a true decline due to surgery as well as a developmental lag compared with her same-aged peers.

## Discussion

This study for the first time demonstrates the relationship between RTFM and postoperative language outcome as measured by detailed neuropsychological testing. It also provides important details on how RTFM can contribute to presurgical functional language mapping. Understandably, postsurgical deficits cannot always be predicted with ESM.[11,13] This may make RTFM a valuable technique with the potential to reduce postsurgical language morbidity. We took advantage of the detailed ESM mapping conducted in our facilities and demonstrated that when the “next-neighbor” approach is used, RTFM shows high sensitivity and specificity during mapping of expressive language function when compared with ESM.

### ESM Versus RTFM

Findings from published studies that attempt to delineate the relationship between ECoG-related changes and ESM mapping are inconsistent. For example, Brunner et al.[5] showed highly congruent results between these 2 mapping approaches with a motor task—a “next-neighbor” evaluation showed no false negatives, and only 0.46% and 1.10% false positives for hand and tongue maps, respectively. These authors speculated about possible higher sensitivity and lower specificity of the RTFM procedure when compared with ESM. In their real-time language mapping study, Miller et al.[17] argued that RTFM might have lower sensitivity and higher specificity to detect language-specific regions, which is the opposite from what was observed in the motor modality by Brunner et al.[5]

However, offline analysis of the ECoG signal in the frequency domain “electrocorticographic frequency alteration mapping” (see the study by Leuthardt et al.[16]) did not match ESM results accurately on a language task with an 83.9% sensitivity and a 40.4% specificity found in a study with 7 patients.[29] In addition, Brown et al.[4] evaluated the concordance between ECoG and ESM findings in 4 children. They reported larger activation in ECoG data when compared with ESM at similar electrode sites, but they did not evaluate sensitivity and specificity of ECoG-based activation relative to ESM. Their offline-derived study results are in line with our observed real-time language activation pattern (based on SIGFRIED methodology), which is more broadly represented in RTFM than in ESM.

Several more studies have been published that demonstrated discrepancies between ECoG mapping and ESM findings. Sinai et al.[23] showed 38% sensitivity and 78% specificity for a picture-naming task for ECoG-based mapping against ESM. Similar results with low sensitivity and high specificity of ECoG-based mapping when compared with ESM mapping were demonstrated in a study by Bauer et al.[2] in a picture-naming task. These authors suggested that the different nature of ESM and ECoG-based mapping ("all-or-none" ESM principle vs variable and changing in time ECoG activation) may be responsible for the discrepancies. Moreover, different from ECoG-based mapping, ESM does not allow testing language function on the electrode sites, associated with mouth-related motor function. This, in turn, could have affected the comparison of ECoG-based mapping and ESM results. A study by Cervenka et al.,[6] who used both visual object naming and auditory descriptive naming tasks, revealed discrepancies between sensitivity and specificity of ECoG-based mapping to predict postsurgical language deficits. The authors suggested that taking into account the results from both mapping approaches would lead to improved postsurgical language outcomes.

### Possibility to Test Receptive Language and Additional Electrode Sites

The language network distribution was more broadly represented with RTFM than with ESM. The eloquent language cortex determined by RTFM was located more anterior and closer to the resection margin than the language cortex determined by ESM, although similar tasks were implemented (for example, picture naming). This may reflect essential differences between RTFM and ESM approaches ("activation" vs "inhibition"). The wider distribution of RTFM activation is in line with the ability of RTFM to visualize activation of a language network related to a particular task. Additional advantages of RTFM include the ability to more extensively test language function. This is clinically relevant since children may have variable abilities to cooperate and respond to language tasks during mapping, and the parameters of ESM are limiting. In addition, medications administered to reduce seizures during stimulation produce fatigue. Stimulation duration is limited due to increased risk of afterdischarges with increasing length of stimulation, and children with processing-speed deficits (as was the case for our patient) may not be able to respond with adequate reliability or accuracy within the limited time frame. In this patient, we were unable to perform receptive language mapping with ESM, but RTFM identified areas of activation related to language processing. In addition, the length of time needed for sustained cooperation may present a challenge for many children, resulting in the need to select regions of interest rather than mapping the entire electrode array. In contrast, all implanted electrodes can be monitored simultaneously with RTFM. Moreover, there is no need to limit or artificially constrain the response parameters (for example, requiring responses within a particular time frame). The advantages of flexible brain mapping approaches that are free of time constraints were demonstrated by Vansteensel et al.[26] These authors were able to analyze ECoG activity in frequency domains by choosing periods of ECoG data related to different movements performed by patients during real-time events, such as grabbing eating utensils and other goal-directed movements. Finally, RTFM may improve prediction of postsurgical outcomes because more ecologically oriented language responses can be recorded and mapped. While ESM relies mainly on eliciting specific language responses to regulated presentations of stimuli within a limited time frame, RTFM is capable of recording activity during conversations and other more natural acts.

### Relation to Postsurgical Language Outcome

The main purpose of presurgical mapping is the reduction of functional morbidity postsurgery. The RTFM approach is still in its early development stages, and studies determining its usefulness for localization of eloquent cortex have yet to be performed. Taking advantage of the comprehensive approach used by our neuropsychologists for assessing language function pre- and postsurgery, we have made it our priority to evaluate the impact of RTFM on postsurgical language outcomes. We examined the relationship between RTFM and ESM findings in conjunction with cortical resection data and comprehensive postsurgical neuropsychological testing. Real-time functional mapping demonstrated relatively high sensitivity and high specificity when compared with ESM by using a “next-neighbors” approach. Moreover, it provided valuable results not available from ESM mapping. For example, in addition to areas stimulated with ESM showing language in the posterior temporal lobe, RTFM showed several other areas of activation related to expressive language function, which were eventually resected during the surgery. This resection may have been associated with observed postsurgical expressive language deficits. It is well known that patients who undergo dominant anterior temporal lobectomy, including medial temporal lobe structures, may exhibit language and verbal memory deficits after surgery. In our patient, immediate postoperative changes in language were found in areas related to function that was activated during RTFM. Real-time functional mapping was also able to test language comprehension with narrative information. This language skill had a significant decline at 1-year follow-up. Detection of this area with RTFM could have had direct implications on this patient’s outcome. The mapping results allow us to speculate that surgical planning and assessment of the risk/benefit ratio may benefit from RTFM information provided in conjunction with ESM results.

Although RTFM identified areas relevant to predicting outcome, not all of the postoperative changes could be predicted from the ESM and RTFM alone. This patient showed a significant decline in working memory, which would also affect performance on many language tasks that have a working memory load (for example, recalling sentences, concepts, and following directions). Additionally, several language tasks that have a verbal memory load also showed decline, a cognitive ability that frequently shows decline following dominant temporal lobectomy. While this report focuses on predicting language outcomes, RTFM procedures have the potential for developing mapping for other cognitive functions that cannot be mapped with ESM.

## Conclusions

Our case study illustrated that RTFM may be a valuable tool for guiding and assisting ESM or other functional mapping methodologies, thus decreasing duration and improving the accuracy of eloquent cortex localization, resulting in reduction of postsurgical language morbidity. Whether RTFM truly provides more accurate language mapping results than ESM, and thus better neuropsychological outcomes, needs to be validated through a large-scale prospective study.

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## Abbreviations used in this paper

| | |
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| **ECoG** | electrocorticography |
| **EEG** | electroencephalography |
| **ESM** | electrical cortical stimulation mapping |
| **RTFM** | real-time functional mapping |
| **SIGFRIED** | SIGnal modeling For Real-time Identification and Event Detection |

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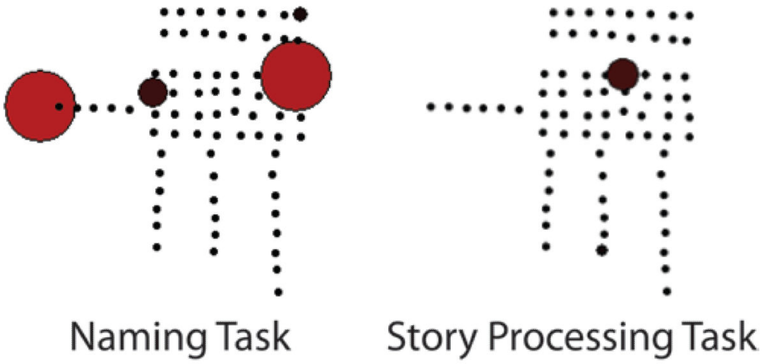

**Fig. 1**

. Cortical RTFM activation map indicating language activation elicited during picture naming **(left)** and the story processing task **(right)**. Locations with significant levels of activation are presented as large *red circles*; grid placement locations are indicated as *black dots*.

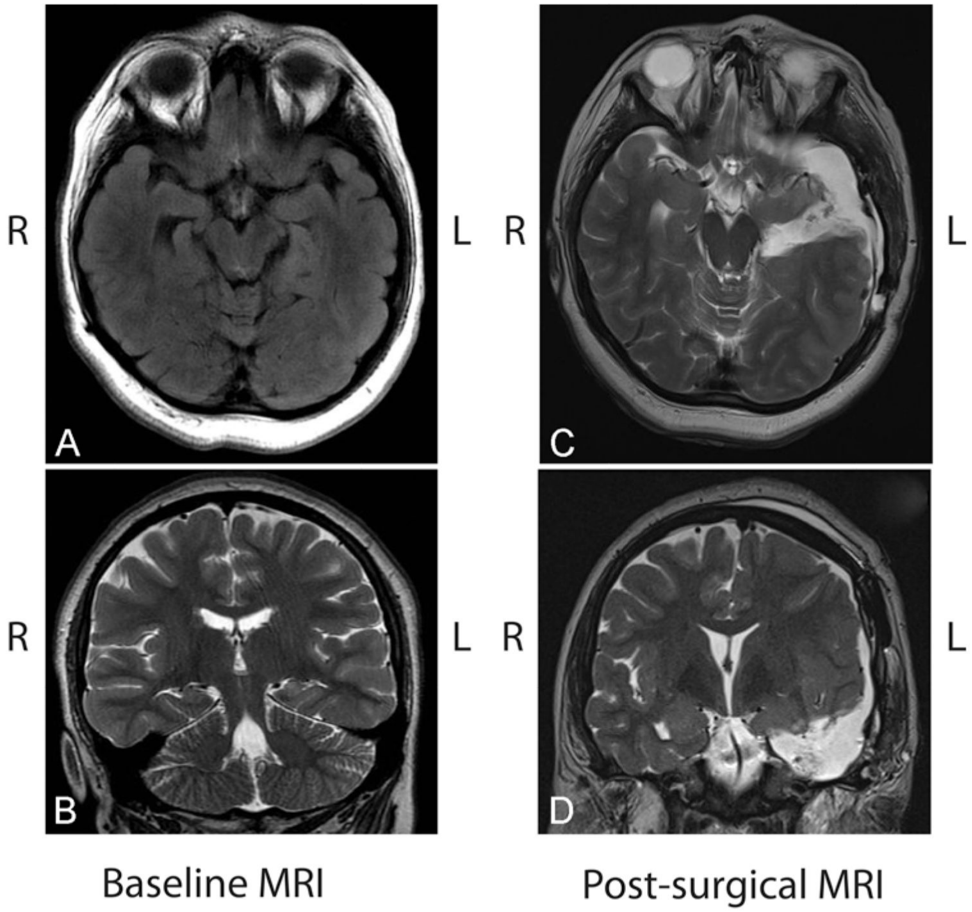

**Fig. 2.**

Magnetic resonance images obtained before **(A and B)** and after **(C and D)** resection of epileptic foci. The imaging results are presented in axial (A and C) and coronal (B and D) planes. Radiological side labeling is used. The presurgical images show that there is abnormal T2 and FLAIR T2 signal involving the entire left mesial temporal lobe, including the amygdala, hippocampus, and parahippocampal gyrus. There is mild thinning throughout, most notable at the amygdala. Findings suggest mesial temporal lobe sclerosis. Focal cortical dysplasia could also be considered. The postsurgical images show that there has been interval resection of the left mesial temporal lobe and anterior temporal pole as well as the lateral portion of the inferior, middle, and partial superior temporal lobe. There is partial sparing of the posterior and superior temporal lobe.

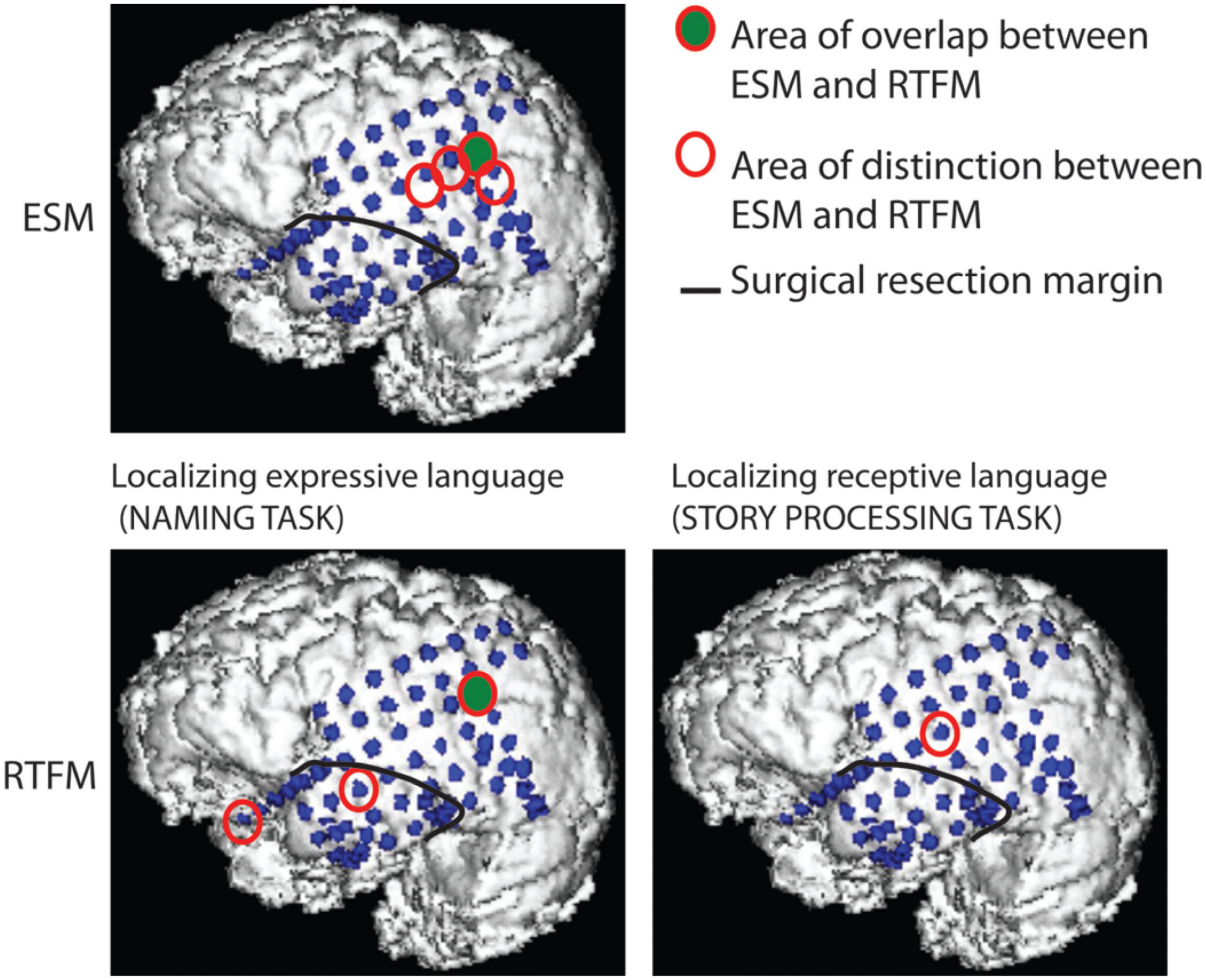

**Fig. 3.**

Results of the left temporal lobe’s eloquent language cortex mapping with ESM and RTFM. Both ESM and RTFM results are overlaid offline on the 3D-rendered cortical surface of the patient’s brain. Electrode locations are presented as *blue dots.*

## TABLE 1

### Characteristics of the patient, a 13-year-old right-handed girl[*]

| Parameter | Time of Testing | | |
|---|---|---|---|
| | | Postop | |
| | Preop | 2 Mos | 1 Yr |
| diagnosis | | | |
| epilepsy focus | temporal | NA | NA |
| side | left | NA | NA |
| epilepsy onset (yrs) | 2 | NA | NA |
| epilepsy duration (yrs) | 11 | NA | NA |
| WISC-IV & IQ scores | | | |
| VCI | 67 | NA | 63 |
| PRI | 73 | NA | 67 |
| WMI | 80 | NA | 59[†] |
| PSI | 59 | NA | 53 |
| FSIQ | 62 | NA | 63 |
| Likert scale[‡] | | | |
| overall severity | | | 0 |
| overall bothersome | | | 0 |
| treatment change | | | +7 |

[*] FSIQ = Full Scale IQ; NA = not applicable; PRI = Perceptual Reasoning Index, PSI = Processing Speed Index, VCI = Verbal Comprehension Index, WISC-IV = Wechsler Intelligence Scale for Children, Fourth Edition; WMI = Working Memory Index.

[†] General test interpretation = 1 standard deviation or 15 standard score reduction.

[‡] The Likert scale ranges from 0 to 7 for overall severity and overall bothersome and −7 to +7 for treatment change.

## TABLE 2

### Summary of neuropsychological examination results for patient’s language functioning[*]

|  |  | DKEFS Verbal Fluency |  |  |  | CELF-IV |  |  |  |
|---|---|---|---|---|---|---|---|---|---|
| **Time of Testing** | **BNT/SS** | **Letter Fluency Total Correct Raw Score/SS** | **Category Fluency Total Correct Raw Score/SS** | **Category Switching Total Correct Raw Score/SS** | **Category Switching Total Switching Accuracy Raw Score/SS** | **Expressive Language Composite/SS** | **Receptive Language Content Composite/SS** | **Language Content** | **Language Memory** |
| preop | 38/63 | 10/65 | 21/75 | 9/85 | 8/90 | — | — | — | — |
| postop |  |  |  |  |  |  |  |  |  |
| 2 mos | 39/66 | 6/55 | 9/55[†] | 7/70[†] | 6/80 | 9/57 | 23/86 | 22/84 | 15/69 |
| 1 yr | 44/74 | 3/55 | 8/55[†] | 7/70[†] | 6/85 | 3/45 | 11/62[†] | 12/64[†] | 3/45[†] |

[*] BNT = Boston Naming Test; CELF-IV = Clinical Evaluation of Language Fundamentals, 4th Edition; DKEFS = Delis Kaplan Executive Function System; SS = standard score; — = not administered at this phase.

[†] General test interpretation = 1 standard deviation or 15 standard score reduction.

## TABLE 3

## Calculation of sensitivity and specificity of language mapping with RTFM and ESM[*]

| Parameter | Formula | Actual Data |
|---|---|---|
| sensitivity | (ESM pos + RTFM pos)/all ESM po × 100% | 1/4 × 100% = 25% |
| specificity | (ESM neg + RTFM neg)/all ESM neg × 100% | 10/11 × 100% = 90.0% |

[*] neg = negative; pos = positive.

## TABLE 4

## Calculation of sensitivity and specificity of language mapping with RTFM and ESM by using "next-neighbors" comparison method

| Parameter | Formula | Actual Data |
|---|---|---|
| sensitivity | (ESM pos + RTFM pos)/all ESM po × 100% | 3/4 × 100% = 75% |
| specificity | (ESM neg + RTFM neg)/all ESM neg × 100% | 10/11 × 100% = 90.0% |

## TABLE 5

### Results of ESM and RTFM mapping*

| Electrode | ESM Results | RTFM Result |
|---|---|---|
| LT1 | not tested | − |
| LT2 | not tested | − |
| LT3 | not tested | − |
| LT4 | not tested | − |
| LT5 | not tested | − |
| LT6 | not tested | − |
| LT7 | not tested | − |
| LT8 | not tested | − |
| LT9 | not tested | − |
| LT10 | not tested | − |
| LT11 | not tested | − |
| LT12 | not tested | − |
| LT13 | not tested | − |
| LT14 | − | − |
| LT15 | − | − |
| LT16 | − | − |
| LT17 | not tested | + |
| LT18 | not tested | − |
| LT19 | − | − |
| LT20 | − | − |
| LT21 | − | − |
| LT22 | − | − |
| LT23 | − | − |
| LT24 | + | − |
| LT25 | not tested | − |
| LT26 | not tested | − |
| LT27 | − | − |
| LT28 | − | − |
| LT29 | − | + |
| LT30 | + | − |
| LT31 | + | − |
| LT32 | + | + |
| LTP1 | not tested | + |
| LTP2 | not tested | − |
| LTP3 | not tested | − |
| LTP4 | not tested | − |
| LTP5 | not tested | − |
| LTP6 | not tested | − |

[*] + = positive response; − = negative response.