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Distinct and Overlapping Cortical Areas for Bilingual Naming and Reading using Cortical Stimulation– Case Report

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Abstract

A bilingual pediatric patient treated for tumor resection was mapped extraoperatively with cortical stimulation to preserve English and Hebrew languages. The authors mapped both languages by using four tasks: 1) English visual naming, 2) Hebrew visual naming, 3) read English/respond Hebrew, 4) Hebrew reading. Essential sites for primary (L1) and secondary (L2) languages were compared, photographically recorded, and plotted onto a schematic brain of the patient. Three types of sites were found in this patient: 1) Multi-use sites (both languages, multiple tasks) in frontal, temporal, and parietal areas, 2) Single-task sites (one task, both languages) in post-central and parietal areas, and 3) Single-use sites (one task, one language) in frontal, temporal, and parietal areas. These results lend support to the concept that bilinguals can have distinct cortical representation both of different languages and of different language tasks in addition to overlapping or shared sites that support both languages and multiple tasks.

Keywords

bilingualism; cortical stimulation; language; naming; reading

Introduction

A driving question behind bilingualism has been whether each language is represented by overlapping or distinct cortical language areas. Research from a variety of neuroimaging techniques, cortical stimulation studies, and clinical findings have brought out several factors that are thought to influence the answer to this question, including: 1) the age of acquisition, 2) degree of fluency or proficiency, 3) type of script, and 4) tasks used to evaluate the languages in question. To date, studies have been consistent with one of two views. The first view is that multiple languages are represented by common, overlapping language areas^{5,6,11,15,16,20,23,24,25}, with initial studies advocating that an early age of acquisition and a high degree of fluency in each language would more likely show overlapping cortical areas²². The second view is that multiple languages are represented by distinct cortical areas, usually in addition to overlapping areas^{8,22,26,33,37,38,39,40,42,45,46,47}. Studies advocating this overlapping-plus-distinct view include some imaging studies but more often cortical stimulation studies,

which consistently show distinct cortical areas in addition to overlapping areas, even in early and proficient bilinguals.

Here we report the case of a pediatric bilingual (English-Hebrew) patient who underwent neurosurgical resection of a left temporal anaplastic astrocytoma. Based on past cortical stimulation studies^{26,42,45,46}, we made two hypotheses: 1) overlapping as well as distinct cortical areas representing this patient's two languages would be found, and 2) distinct areas would be found for the specific tasks administered, namely that visual naming areas would be distinct from reading areas due to the different cognitive strategies involved with each task.

Cognitive theories of object identification propose that several stages of processing need to occur from the time the object is viewed until its verbal label is produced. These stages include: 1) early or low-level visual sensory processing⁴¹ and 2) matching this encoded perceptual information to a multi-level memory system, accessing: i) the stored structural description of the object, ii) semantic descriptions (such as functional and associative properties) of the object, and iii) phonological descriptions. Some models argue that a direct route exists from the structural code to the phonological code²⁷, but a more common view is that an abstract stage involving semantic access intervenes⁵³, and that retrieval of the phonological representation takes place subsequent to semantic access^{17,18}. These strategies consistently activate the ventral stream of visual processing, including the inferior and middle temporal and frontal gyri. Previous cortical stimulation studies using visual object naming have shown that sites are consistently found in frontal, temporal, and parietal areas³⁴, and we expected to find a similar pattern here.

In contrast to visual object naming, a cognitive strategy for reading involves orthographic-to-phonological transformations. Evidence for the localization of these transformations in the supramarginal gyrus comes from both imaging^{3,6,11,29,52} and cortical stimulation^{42,46} studies. As such, we expect this general area to be identified during both English and Hebrew reading.

The Read English/Respond Hebrew task is a word-finding task using both languages, where the patient reads a sentence stem in English and fills in the blank with the appropriate Hebrew word. Generating the appropriate Hebrew word is dependent upon comprehension of the semantic material within the English sentence stem, similar to monolingual semantic priming tasks. Evidence suggests that semantic processing is affected by frontal lesions, especially in semantic priming tasks^{30,50}, however because the Read/Respond task involves semantic priming with a strong reading component, we expected that errors would be induced by stimulation in both frontal as well as supramarginal areas.

Materials and Methods

History and Neurological Examination

This 13-year-old right-handed male originally presented in 2001 at an outside medical facility with intractable seizures as a result of a left temporal anaplastic astrocytoma. Extraoperative cortical stimulation had been done at this outside facility to preserve English language areas and a partial left temporal lobectomy was performed to remove the mass. This first resection removed the first four centimeters of the left superior and middle temporal lobe and the patient received focal radiation and chemotherapy following surgery. Following the first resection, no transient language deficit was noted for English, but he had significant deficits in his Hebrew language skills such that his scheduled Bar Mitzvah was cancelled. He underwent intensive Hebrew language skills training over the next six months and recovered most of his Hebrew language, to the point he had a new Bar Mitzvah scheduled for six weeks after his second surgery. It was therefore an important requirement to obtain language maps for both Hebrew

and English with the second resection. Approximately 18 months following the first procedure, and while being treated with the antiepileptic Keppra, he presented to Duke University Medical Center (DUMC) with intractable grand mal seizures. MR imaging studies of his brain showed a post-surgical cavity in the first four centimeters of the left superior and middle temporal gyrus with an adjacent deep lesion, diagnosed as recurrent anaplastic astrocytoma at the posterior superior margin of the resection cavity. The post-surgical cavity and recurrent tumor are outlined in Figure 1A.

Preoperative neurological examinations yielded normal findings with no focal deficits. It was noted that the patient was proficient in both English and Hebrew. According to the patient and his family, English and Hebrew were both spoken in the home since he was an infant and he was also engaged in Hebrew study as part of his Bar Mitzvah preparations at the time of his DUMC admission. English, however, was spoken more frequently on a daily basis with the patient's friends and at school, and Hebrew was recovered following the first resection through training. The patient reported mild difficulty in reading the Hebrew text. For these reasons, English is referred to here as L1 and Hebrew as L2. Extensive preoperative language testing was done in both languages. No impairments were found in reception, reading, or production for either language. A subdural grid was inserted to map the location of each language for naming and reading as well as for word finding between languages using a bilingual read/response task. Postoperative language testing over the next seven days showed hesitations for visual object naming in both English and Hebrew, while reading and read English/respond Hebrew showed mild production errors. These errors resolved within 3 months.

Language history

At the time of the first surgery at the outside center, only visual object naming in English was mapped in the dominant hemisphere. Generalized speech arrest was found in the inferior frontal gyrus while naming errors were found in the posterior portion of the supramarginal gyrus as well as the angular gyrus. These sites, the margins of the first resection, and the recurrent tumor are shown on a schematic diagram in Figure 1B.

Mapping of language function

Parental consent and child assent were obtained in accordance with the Internal Review Board of Duke University Medical Center. Testing was done in two sessions over two days. The area of exposure included frontal, temporal, and parietal areas. Twelve sites were tested on the first day -- the patient experienced focal seizures but maintained intact visual and auditory naming, reading, and sentence completion in both languages. Seizures were resolved overnight and twenty sites were tested on the second day, avoiding the sites that led to seizure activity (see Figure 2).

The patient performed four tasks on the second day of testing: 1) Visual object naming in English, 2) Visual object naming in Hebrew, 3) Reading English sentences and completing with Hebrew responses (Read English/Respond Hebrew) 4) Reading Hebrew sentences (see Appendix for stimuli). Baseline performance was measured by pretesting all tasks several days prior to grid placement. Only items that the patient successfully completed at least twice each at baseline were administered during cortical mapping.

To ensure receptive language was not compromised during testing, stimulation was administered following presentation of the picture (naming) or written text (reading). Before each response, the patient spoke the carrier phrase "This is a ..." (naming) or "This says ..." (reading, read/response) to ensure that stimulation was not causing a general speech arrest. The presentation of the picture or written text is accompanied by an aural cue within the presentation software, alerting the neurosurgeon that the stimulus is on the screen. Stimulation

is initiated immediately following this aural cue with a delay of approximately 1000ms. This short delay allows stimulation to proceed after the stimulus is on the screen but before the patient begins their oral response of the carrier phrase and stimulus item/text.

The following error types⁷ were noted: 1) semantic paraphasias (e.g. substituting a semantically related item such as “cow” for “horse”), 2) phonological paraphasias (e.g. clear substitution of one phoneme for another/f/for/v/or/tr/for/dr/, etc.), 3) semantic/phonological blends (e.g. “train” for “plane”), 4) off target responses, i.e. not semantically or phonologically related to the correct response (e.g. “tree” for “fork”), 5) no target responses, i.e. the patient correctly says the carrier phrase but is unable to give a response to the stimulus, 6) perseverations, where the patient responds to a previous stimulus, 7) incorrect language, where the patient names the object or responds in the wrong language, 8) apraxic errors such as a slur or stutter, and 9) phonological reduction, where a syllable is dropped from a word (e.g. responding “can” for “candle”). In the Read English/Respond Hebrew task the English reading portion of the trial was analyzed separately from the Hebrew word-finding portion. Errors are classified in this task as either English only, Hebrew only, or mixed. The reliability of errors for each site in each task was calculated relative to the unstimulated baseline error rate by Fisher’s Exact Tests. Although *p*-values less than 0.05 are considered significant here, values less than 0.3 are included for purposes of a complete description. Values between 0.05 and 0.3 are considered weakly significant sites and are color-coded lighter than more robustly significant sites ($p < 0.05$) in corresponding figures.

Grid mapping

Extraoperative mapping was done using a 6×8 cm (i.e., 48 contact) grid array, with 5-mm-diameter electrodes embedded in Silastic with center-to-center interelectrode distances of 1 cm. The grid was positioned over the frontal parietal temporal region. The exposed cortical surface and grid position were documented by digital photography and schematic diagrams. The amplitude of the current was progressively increased by 1 mA, beginning at 4 mA. We used a standard procedure of stimulation¹⁰ with biphasic square wave pulses of 1 msec at 60 Hz, with a maximum train duration of 4 seconds until afterdischarge activity was evoked or maximum stimulation current reached 14 mA. Functional sites were marked with a sterile 5 mm² tag (see Figure 3A).

Results

Using extraoperative cortical stimulation mapping, we observed that rather than showing strictly overlapping areas for the two languages in this early and proficient bilingual, the two languages are represented as a combination of overlapping and distinct sites in frontal, temporal, and parietal gyri. More specifically, we show two types of overlapping sites: 1) multi-use sites (several tasks, both languages), and 2) single-task sites (one task, both languages) for naming as well as reading. Distinct single-use sites (one task, one language) were found for visual naming and reading in Hebrew and for English reading. No distinct site was found for visual naming in English.

A photograph of tagged sites and a schematic map of all tasks with significant error rates are included below in Figures 3A and 3B and described in Table 1. Reading is analyzed separately from responding for the Read English/Respond Hebrew task. Unless otherwise noted, errors were found both in English reading and in Hebrew responses within the same site; sites where errors were confined only to English reading are denoted by E in Figure 3B and E(R) in Table 1. See figure caption for non-language numerical tag descriptions.

As seen in Table 1, three types of sites are found. The first two types are overlapping, and the third type is distinct. Overlapping, multi-use sites were significant for multiple tasks in both

languages and were found in the middle frontal gyrus, superior temporal gyrus, supramarginal gyrus, and post-central gyrus. Overlapping, single-task sites were significant for a single task in both languages and were found in the middle frontal gyrus and post-central gyrus. Distinct, single-use sites were found for Hebrew visual naming in middle and inferior frontal gyri and angular gyrus, for Hebrew reading in the posterior supramarginal gyrus, and for English reading in the middle temporal gyrus.

Correspondence between first and second mapping for English naming

Correspondence between the first and second English mapping sessions is moderate and shown in Figure 4. The first mapping shows a speech arrest site in the inferior frontal gyrus that corresponds to speech arrest in the second mapping (tag 10 in Figure 3B). Two sites in the inferior portion of the posterior supramarginal gyrus and angular gyrus from the first mapping are proximal to where we found errors for English visual naming (pink donut in PSMG in Figure 3B). Two sites in a more superior portion of the posterior supramarginal gyrus and angular gyrus from the first mapping were proximal to a multi-use site for Hebrew naming, Read English/Respond Hebrew, and Hebrew reading in the posterior supramarginal gyrus. This multi-use site also showed 5/16 errors for English naming in the second mapping, but this error rate did not reach a significant statistical level ($p = 0.38$). One site in the superior temporal gyrus from the first mapping was near a site for Hebrew naming and Read English/Respond Hebrew, while one site in the superior part of the supramarginal gyrus from the first mapping appears more superior than the top edge of our grid placement.

Discussion

Bilingual language organization continues to be a source of debate. Several factors theoretically influence whether two languages are located in overlapping cortical areas or in distinct areas, including age of acquisition, proficiency in the second language, orthographic/script differences, and the tasks used to evaluate cortical representation of each language. Although a case study does not allow conclusions to be drawn about general factors that influence the distribution of one or more languages, these results are able to add evidence to existing views.

Overlapping areas of activation for bilinguals are found under a wide range of circumstances. While some imaging studies advocate overlapping cortical areas in early and proficient bilinguals^{6,15,16,22,23,24,31,39,57} other studies have thrown this view into question by showing overlapping areas in late bilinguals, over a variety of second-language acquisition ages, and despite less fluency and different orthographic scripts in the secondary language^{5,6,11,20,25,31,56}. Based on these studies, it seems generally established that one or more languages can share a cortical area under a variety of subject, task, and stimulus conditions, particularly in classic language areas.

More debatable is the issue of distinct cortical areas and which linguistic factors influence their detection^{8,22,38,39,57}. Before adding this case study to the cortical stimulation evidence consistent with an “overlapping plus distinct sites” bilingual map, the neurological history of this patient must be examined to question whether the finding of distinct cortical areas could be due to language reorganization following the first resection. The structures involved in the first resection include the anterior portion of the left superior and middle temporal gyri. No transient language deficit was noted for English, but the patient had significant deficits in his Hebrew language. He underwent intensive retraining over a six month period and had recovered most of his Hebrew language skills when he underwent his second surgery. Most sites essential for naming and reading in both languages were located in the superior and anterior areas of the brain, away from the recurrent tumor and the resection cavity. The results of the first English mapping show good consistency with our English mapping results. Taken together with the facts that the patient had no transient deficits and no need for speech rehabilitation in English,

we suggest that the functional remapping of his English language was unlikely or minimal and that the distinct site for English reading was not due to reorganization.

In contrast, it is likely that his Hebrew language did undergo functional remapping. Over the course of six months, the patient recovered from significant deficits to a level of proficiency that allowed him to perform at his Bar Mitzvah approximately six weeks following his second surgery. It is unknown whether Hebrew was ever represented bilaterally — with the present left-lateralization indicating a shift to the left hemisphere during recovery — or whether Hebrew had previously been lateralized in the left hemisphere and was reorganized within the same hemisphere. Studies of children with extensive left hemisphere damage from perinatal strokes or other brain insults show they are able to develop competent language skills in the healthy right hemisphere^{1,14,48}, though the reorganization into the right hemisphere seems most common and language competence more likely if the injury is sustained before the age of 5 years^{12,28,43}. In older children, insult to the dominant hemisphere in the form of refractory partial seizures is associated with a redistribution of language function within that hemisphere³⁴. The recovery of perilesional tissue to support impaired language functions is also seen in adult aphasic stroke patients⁵⁵, and several studies indicate that the recovery of perilesional tissue is associated with better verbal recovery and performance than increases in the right-sided homologue of language areas^{2,4,13,19,44,51,55}. Language reorganization into areas adjacent to the first resection may account for the independent Hebrew naming site that was found in the inferior frontal gyrus, and possibly for joining a Hebrew naming site to what was already a multi-use site for Read English/Respond Hebrew in the middle portion of the superior temporal gyrus. Both of these sites were found near the edges of the resected portions of the superior temporal gyrus. While the original extent of Hebrew lateralization is unknown, it seems likely that his Hebrew language underwent some functional reorganization within the left hemisphere concurrent with language recovery.

This functional reorganization of L2, however, still does not seem to account for all distinct Hebrew sites. It is important to note that distinct Hebrew naming and reading sites were also found in areas distant from his first resection -- such as in the middle frontal and angular gyri for naming and the supramarginal gyrus for reading. These results suggest that the distinct sites found for L2 are not solely due to the functional reorganization of the secondary language but represent the detection of genuine distinct sites that is consistent with other cortical stimulation studies of bilinguals^{26,33,42,45,46,54}.

Multi-use, single-task, and single-use sites in the present study

The multi-use sites for naming, reading, and read-respond tasks are comparable to previous cortical stimulation studies that show different tasks can share a site. Verb generation and naming tasks, for example, were shown to share sites in frontal areas by Ojemann et al.³⁵, as were naming and reading tasks in frontal and supramarginal areas in studies by Ojemann³² and across languages in a study by Roux et al.⁴⁶. It is unclear whether a site is able to sustain multiple tasks across languages because the site is able to sustain multiple cognitive strategies or because the tasks share common cognitive strategies that are performed by one site, such as phonological production for naming and reading⁴⁶. In the case study described here, multiuse sites showed a variety of errors across tasks, including speech arrest, semantic paraphasias, phonological paraphasias, apraxic errors, and general anomia. From these data, the possibility is raised that a multiuse site is capable of sustaining a variety of language tasks even if those tasks employ different cognitive strategies, though this question needs to be examined on a much bigger scale than a single case study.

Single-task sites are defined as those sites where one task is disrupted across both languages. These sites were found for both visual naming and for reading, suggesting a common cognitive strategy across languages was being disrupted for each task. The area of the single-task site

found for reading in the middle frontal gyrus, for example, is often found as part of a network involved in semantic analyses of sentences^{21,49} as well as during verbal working memory⁹, which could disrupt contextual cues needed to successfully read a given sentence in either language. Similarly, reading errors in the post-central gyrus were always associated with apraxic or articulatory errors and were adjacent to an area identified as mouth motor and tongue movement (tag 1 in Figure 3A and 3B), suggesting this area has more to do with articulatory processes during reading, leading to disruptions across languages with stimulation.

Single-use sites, where only one task in one language is disrupted, were found for reading in L1 (English) in middle temporal gyrus and for visual naming and reading in L2 (Hebrew) in both anterior and posterior regions. The distribution of L2 in anterior regions is inconsistent with the findings of Lucas et al.²⁶ who show that distinct sites for L2 were located exclusively in posterior temporal and parietal regions, while L1 and overlapping sites were found throughout the mapped area of cortex. In contrast, we found L2 naming sites both in the middle frontal gyrus and the anterior temporal gyrus, and an L2 reading site in the middle temporal gyrus despite a similar region of exposed cortex. Since pediatric patients are thought to have fewer language sites than adults and tend to gain sites with maturation³⁶, the young age of this patient can likely be ruled out as a reason for the discrepancy. Distinct sites for L2 in the frontal lobe have also been reported in the cortical stimulation literature for both naming and counting^{45,46}, making it unclear why such a discrepancy exists other than due to normal variability.

Conclusions

Cortical stimulation data from this pediatric bilingual show distinct as well as overlapping sites for English and Hebrew, consistent with studies showing functional separation of languages. These data also show distinct as well as overlapping cortical sites across and within different tasks, specifically visual naming, reading, and a bilingual read/response task. Multi-use sites for different languages and tasks are found in frontal, temporal, and parietal areas. Single-task (one task, both languages) sites are found in frontal, temporal, post-central, and parietal areas, while distinct, single-use (one task, one language) sites are found in frontal, temporal, and parietal areas. Inconsistent with Lucas et al.²⁶, single-use sites in the secondary language were not limited to posterior temporal or parietal areas. Further research is needed to determine if mapping and preserving essential areas for reading as well as naming in each language will improve the postoperative quality of life for the patient.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.

A. T-2 weighted spin-echo axial anatomical image of resection cavity and recurrent tumor (GE Signa LX 1.5T, AC-PC slice orientation, TR/TE/Flip angle = 3000ms/84ms/90°, matrix = 256 × 256, FOV = 24cm, voxels = 0.92 × 0.92 × 5.0mm). The image shows the resection of portions of left superior and middle temporal gyrus (yellow outline) and recurrent tumor posterior to the cavity (red outline). B. Schematic showing approximate area of the resection area (yellow), recurrent tumor (red), and English visual naming sites (black).

Figure 2. Schematic of grid placement. First resection area shown in yellow, recurrent tumor in red with visible lesion in purple. Boxed electrodes, rows 1–3 show where a focal seizure was induced with 6mA stimulation; naming and reading in both languages remained intact. (contacts 1–4, 9–12, 17–20).

Figure 3.

A) Tagged sites for visual naming, reading, and read/respond in English and Hebrew. Letters A-F show stimulation-induced seizure activity. 1=Tongue (sensory), 2=Mouth (motor), 3=Hand (sensory), 4=Thumb (motor), 5=Jaw movement, 10=Speech arrest (counting). One-centimeter measurement tag reference. B) Schematic map of English Naming (*pink donut*), Hebrew Naming (*yellow squares*), Read English/Respond Hebrew (*green triangles*; E = English reading error only), and Reading Hebrew (*blue diamonds*). Striped symbols represent *p*-values between 0.05 and 0.2. MFG = Middle Frontal Gyrus, PoG = Post Central Gyrus, SMG = Supramarginal Gyrus, AnG = Angular Gyrus, STG = Superior Temporal Gyrus, MTG = Middle Temporal Gyrus. Letters preceding these abbreviations refer to Posterior (P), Middle (M), Ventral (V).

Figure 4.

Map 1: English visual naming sites (black dots) from the first resection. Map 2: Proximate sites from all tasks in second resection. 10=Speech arrest (counting), SMG = Supramarginal Gyrus, AnG = Angular Gyrus, STG = Superior Temporal Gyrus. Letters preceding these abbreviations refer to Posterior (P), Middle (M), Anterior (A).

Table 1

Overlapping vs. distinct language and task sites.

Location	Site (Tag)	Overlapping		Distinct	
		Language	Task	Language	Task
Med MFG	39–40 (24)	E (R), H	3 ^{**} ,4 [†]		
Post MFG	46–47 (25)	E, H	3 [*] ,4 [†]		
Post MFG	31–32 (20)	E, H	1 ^{**} ,4 [*]		
Ven PoCG	29–30 (31)	E (R), H	3 [*] ,4 [*]		
Med PoCG	36–37 (23/37)	E, H	3 ^{**} ,4 [*]		
Post SMG	34 (26/21)	E, H	2 [*] ,3 [†] ,4 ^{**}		
Ant SMG	35–36 (22/36)	E, H	3 [†] ,4 [†]		
Med STG	13–14	E, H	2 ^{**} ,3 [*]		
Post SMG	26–27	E, H	1 [†] ,2 [*]		N
Med MTG	5–6		3 ^{**}	E	R
Med MFG	47–48 (27)		2 [*]	H	N
Post SMG	27–28		4 [*]	H	R
Ang Gyr	25–26		2 [*]	H	N
Ant STG	15–16		2 [*]	H	N

Task 1=Naming English, Task 2=Naming Hebrew, Task 3=Read English/Response Hebrew, Task 4=Reading Hebrew. E=English, H=Hebrew, N=Naming, R=Reading, E (R) = English Reading error only.

*
 $p < 0.3$
**
 $p < 0.05$
[†]
 $p < 0.01$