

# A Systematic Review of Native Languages Mapped With Direct Electrical Stimulation During Awake Craniotomy

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## Abstract

Human language exhibits both universal characteristics and remarkable diversity. While neuroimaging has identified a shared fronto-temporo-parietal network across languages, causal inferences require techniques such as direct electrical stimulation (DES), which is performed during awake craniotomy. However, it is unclear which native languages have been mapped using DES. We conducted an analysis of which native languages were mapped in monolingual patients undergoing DES during awake craniotomy. Data was extracted from an open-access systematic review dataset of language errors from patients during awake craniotomy. An additional literature review and author communication were performed to identify the language type. Descriptive statistics and chi-squared analysis were used. The analysis identified 893 stimulation sites across 73 studies, involving nine languages: French, English, Chinese, Japanese, Italian, Dutch, Spanish, German, and Persian. These languages represent 27.2% of native languages spoken globally. The predominant mapped language family was Indo-European (670 stimulation sites; 75%), followed by Sino-Tibetan (186 stimulation sites; 20.8%) and Japonic (37 stimulation sites; 4.1%). There was a significant difference between the frequencies of the total number of global native speakers and stimulation sites ( $\chi^2 = 2071.33$ ,  $df = 28$ ,  $p < 0.00001$ ). We calculated a 'stimulation site per million native speakers' metric and identified that the top mapped languages per population size were French (4.62), Dutch (0.99), and English (0.65). This study underscores a significant bias in DES-based language mapping literature, with under-representation of languages spoken by most of the global population. Standardized, multi-language testing paradigms are crucial for addressing these disparities and advancing inclusive cognitive neuroscience.

**Categories:** Neurosurgery

**Keywords:** awake craniotomy, direct electrical stimulation, functional mapping, glioma, language research

## Introduction And Background

Human language is a complex system of communication that lies at the heart of building relationships, personal growth, and cultural dissemination. Globally, there is a huge diversity of human language with approximately 7000 spoken languages from over 100 language families [1]. Human languages are characterised by a set of universal characteristics that set them apart from other forms of animal communication. Charles Hockett defined 13 universal features of human language, including displacement (the capability of language to communicate about things that are not immediately present), cultural transmission (language is passed through socio-cultural interaction rather than genetics), and duality (use of a small number of meaningless sounds to produce a large number of meaningful words) [2]. Despite these universal features, human languages do differ in their phonology (tonal versus non-tonal languages), syntax, and writing systems. This raises the question of whether the neurobiology of language is based on a universal neural architecture or whether differing brain regions are involved with different languages.

Large-scale functional MRI (fMRI) studies have shown a common fronto-temporo-parietal network across 45 languages from 12 language families [3]. However, fMRI is an associative imaging modality and does not allow for the causal inference of function to brain anatomy. Several key criteria for defining causality in human brain mapping involve stimulation [4]. Neurosurgeons are in a unique position to study brain function during awake craniotomy with language mapping using direct electrical stimulation (DES). During awake craniotomy, neurosurgeons use DES to identify language errors by applying a brief electrical current to discrete cortical and subcortical regions while the patient performs naming or counting tasks, thereby identifying language-essential sites that must be preserved during tumour resection. The collection of this data has permitted the building of functional language maps using DES [5,6]. These maps have played a major role in shaping theoretical frameworks on the perception and production of language [7].

However, comparison of different languages mapped using DES revealed differences in the neuroanatomy of certain language errors [8]. This raises the question of which languages mapped with DES have been

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described in the literature. In particular, whether there is evidence of bias towards a small number of languages. To address this question, we conducted a secondary analysis of an open systematic review dataset to understand which native languages have been mapped using DES in awake craniotomy and how this relates to global native-speaker populations.

## Review

### Methods

In this analysis, we asked the question: which native languages have been mapped in monolingual patients using DES during awake craniotomy? To answer this, an open-access dataset was leveraged from a previously published systematic review [9]. This review was performed according to the PRISMA statement guidelines and was registered on PROSPERO (CRD42020196727) [10]. The authors of the systematic review conducted a search using Embase, Medline Ovid, Web of Science, Cochrane, and Google Scholar for all articles published until 6th July 2020. The inclusion criteria for the studies were: all articles that reported on adult monolingual patients with gliomas (WHO grade II-IV) who underwent awake craniotomies with DES and had documented intraoperative language errors. Monolingual patients were selected to isolate native language effects on brain mapping without confounding multilingual influences. The systematic review included 102 studies with a total of 930 errors. First, we conducted a comprehensive assessment of the dataset to check its integrity, in particular examining for duplications (using author and year as a comparator). This was followed by a review of the references and our knowledge of the literature to determine if any additional studies could be included.

We attempted to contact the corresponding author of the systematic review if we identified any discrepancies in the dataset or identified non-included research articles that we thought met the inclusion criteria. Subsequently, we aimed to identify which language (ie, English, French, Chinese, etc) was mapped in the identified studies. To do this, we took a sequential approach, first examining the abstract and then the full research article. A language was included when explicitly stated in the article or abstract. This process was performed by two authors (SA, AJ), and any disagreements were discussed and resolved with the support of a third reviewer (HH). If the language was not found in either of these sources, we contacted the corresponding author. For a study to be in the final dataset, there needed to be confirmation of the type of language that was mapped from either the article or the corresponding author. Studies were excluded if the mapped language could not be identified from these sources or if the study included a mixed language population. The risk of bias was assessed using the Joanna Briggs Institute (JBI) Critical Appraisal Checklist for Cases Series [11].

### Statistical analysis

For each language, *Ethnologue: Languages of the World, 16th Edition* was used to define which family the language belonged to and how many native speakers there were globally [1]. The data were published on the Center for Open Science (OSF) registries as an open-access dataset [12]. Descriptive analysis was used to define the frequency of the languages, language families, and intraoperative paraphasias. A chi-square goodness-of-fit test was used to compare the observed distribution of DES stimulation sites across the 30 most widely spoken languages globally (by native speaker count, sourced from *Ethnologue*) against the distribution expected if stimulation sites were proportional to native speaker populations. Expected frequencies were calculated by multiplying the total number of stimulation sites by each language's proportion of the combined native speaker population across all 30 languages. Our null hypothesis was that there was no difference between the native speaking population and DE stimulation sites in that language. Statistical significance was set at  $p < 0.05$ . A global heatmap of study numbers per country was generated using DataWrapper. Data visualisations were generated using R (R Foundation for Statistical Computing, Vienna, Austria) through the BioRender interface (BioRender, Toronto, Canada).

### Results

#### *Study and Geographic Characteristics*

Initial review of the open-access dataset identified a duplicate study that described a single stimulation site. This yielded a dataset of 929 stimulation sites from 102 studies (Figure 1). We also identified two studies through citation chasing (a total of 373 stimulation sites) that we deemed to meet the inclusion criteria but were not in the initial systematic review [8,13]. We attempted to contact the corresponding author of the systematic review to ascertain why these studies were not included but got no response. After reviewing the articles and contacting corresponding authors, we excluded a total of 31 studies (there was no neuroanatomical data (n=4), and the author confirmed a mixed language population (n=27)). The final dataset for analysis included 893 stimulation sites from 73 studies [8,13-84] (Table 1).

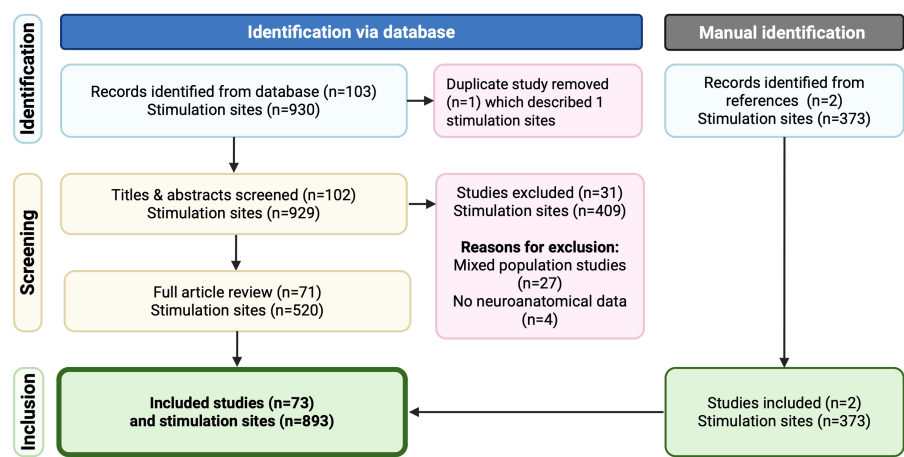


FIGURE 1: PRISMA flowchart

PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses

| Study                     | Year | Language | Number of Stimulation Sites | Risk of Bias |
|---------------------------|------|----------|-----------------------------|--------------|
| Alimohamadi et al. [14]   | 2016 | Persian  | 1                           | Moderate     |
| Altieri et al. [15]       | 2019 | Italian  | 2                           | Moderate     |
| Barone et al. [16]        | 2018 | Italian  | 2                           | Moderate     |
| De Benedictis et al. [17] | 2012 | French   | 10                          | Moderate     |
| De Benedictis et al. [18] | 2010 | French   | 13                          | Moderate     |
| Benzagmout et al. [19]    | 2007 | French   | 9                           | Moderate     |
| Breshears et al. [20]     | 2019 | English  | 2                           | Moderate     |
| Bresson et al. [21]       | 2013 | French   | 6                           | High         |
| Chan-Seng et al. [22]     | 2014 | French   | 39                          | Moderate     |
| Chang et al. [23]         | 2011 | English  | 11                          | Low          |
| Chernoff et al. [24]      | 2019 | English  | 6                           | High         |
| Duffau et al. [25]        | 2001 | French   | 5                           | High         |
| Duffau et al. [27]        | 2009 | French   | 12                          | Low          |
| Duffau et al. [26]        | 2008 | French   | 34                          | Moderate     |
| Duffau et al. [28]        | 2009 | French   | 7                           | Low          |
| Fernández et al. [29]     | 2020 | Spanish  | 14                          | Moderate     |
| Fujii et al. [30]         | 2015 | Japanese | 7                           | Moderate     |
| Gayoso et al. [31]        | 2019 | Spanish  | 1                           | Moderate     |
| Geemen et al. [32]        | 2014 | French   | 21                          | Moderate     |
| Gharabaghi et al. [33]    | 2006 | German   | 1                           | High         |
| Gil-Robles et al. [34]    | 2013 | French   | 5                           | Moderate     |
| Herbet et al. [35]        | 2017 | French   | 4                           | Moderate     |
| Hirono et al. [36]        | 2018 | Japanese | 1                           | High         |
| Hiroshima et al. [37]     | 2014 | Japanese | 6                           | Moderate     |

|                           |      |          |     |          |
|---------------------------|------|----------|-----|----------|
| Iijima et al. [52]        | 2017 | Japanese | 1   | High     |
| Joswig et al. [38]        | 2016 | German   | 4   | Moderate |
| Kamada et al. [39]        | 2007 | Japanese | 6   | Moderate |
| Kemerdere et al. [40]     | 2016 | French   | 12  | Moderate |
| Khan et al. [41]          | 2014 | French   | 5   | Moderate |
| Kurimoto et al. [42]      | 2010 | Japanese | 1   | High     |
| Lang et al. [43]          | 2001 | English  | 2   | Moderate |
| Magrassi et al. [44]      | 2010 | Italian  | 9   | High     |
| Maldonado et al. [45]     | 2011 | French   | 30  | Moderate |
| Martino et al. [46]       | 2012 | Spanish  | 3   | High     |
| Matsuda et al. [47]       | 2014 | French   | 38  | Moderate |
| Moritz-Gasser et al. [48] | 2013 | French   | 10  | High     |
| Morrison et al. [49]      | 2016 | English  | 5   | Moderate |
| Morrison et al. [50]      | 2016 | English  | 1   | Moderate |
| Motomura et al. [51]      | 2014 | Japanese | 4   | High     |
| Motomura et al. [54]      | 2019 | Japanese | 3   | Low      |
| Motomura et al. [53]      | 2019 | Japanese | 3   | Low      |
| Mukae et al. [55]         | 2017 | Japanese | 4   | Moderate |
| Nomura et al. [56]        | 2013 | English  | 3   | High     |
| Oelschlägel et al. [57]   | 2020 | German   | 1   | Moderate |
| Ogawa et al. [58]         | 2014 | Japanese | 1   | Moderate |
| Pallud et al. [59]        | 2019 | French   | 2   | High     |
| Papagno et al. [60]       | 2011 | Italian  | 5   | Low      |
| Parney et al. [61]        | 2010 | English  | 1   | High     |
| Petrovich et al. [62]     | 2014 | English  | 2   | High     |
| Petrovich et al. [63]     | 2005 | English  | 5   | Low      |
| Plaza et al. [64]         | 2009 | French   | 5   | High     |
| Pouratian et al. [65]     | 2004 | English  | 12  | High     |
| Rech et al. [66]          | 2020 | French   | 6   | Moderate |
| Rech et al. [67]          | 2017 | French   | 1   | Moderate |
| Gil Robles et al. [68]    | 2005 | French   | 10  | Moderate |
| Rofes et al. [69]         | 2017 | Italian  | 4   | Moderate |
| Ruge et al. [70]          | 1999 | English  | 5   | Moderate |
| Sanai et al. [13]         | 2008 | English  | 187 | Low      |
| Sarubbo et al. [71]       | 2011 | Italian  | 2   | Moderate |
| Satoer et al. [72]        | 2014 | Dutch    | 1   | High     |
| Sierpowska et al. [73]    | 2015 | Spanish  | 2   | High     |
| Southwell et al. [74]     | 2017 | English  | 1   | Low      |
| Spena et al. [75]         | 2015 | Italian  | 1   | High     |
| Tomasino et al. [76]      | 2015 | Italian  | 5   | High     |

|                       |      |         |     |          |
|-----------------------|------|---------|-----|----------|
| Vassal et al. [77]    | 2014 | French  | 3   | Moderate |
| Vidorreta et al. [78] | 2011 | French  | 24  | Moderate |
| Wilden et al. [79]    | 2013 | English | 1   | Moderate |
| De Witte et al. [80]  | 2015 | Dutch   | 11  | Moderate |
| De Witte et al. [81]  | 2015 | Dutch   | 13  | Moderate |
| Wu et al. [8]         | 2015 | Chinese | 186 | Low      |
| Yordanova et al. [82] | 2011 | French  | 4   | Moderate |
| Zammar et al. [83]    | 2018 | English | 2   | High     |
| Zemmoura et al. [84]  | 2015 | French  | 27  | Moderate |

TABLE 1: Characteristics of included studies, including risk of bias

The global distribution of the studies revealed significant concentration in Western Europe and North America (Figure 2). Specifically, 58 studies (79%) were conducted in Western Europe and North America, 14 studies (19%) were conducted in Asia, and only one (2%) study was conducted in Africa. The top three countries were France (23 studies), the United States of America (13 studies), and Japan (12 studies). Across the 73 studies, the three commonest language error types were speech arrest (321 stimulation sites; 36.0%), anomia (213 stimulation sites; 23.9%), and dysarthria (86 stimulation sites; 9.6%).

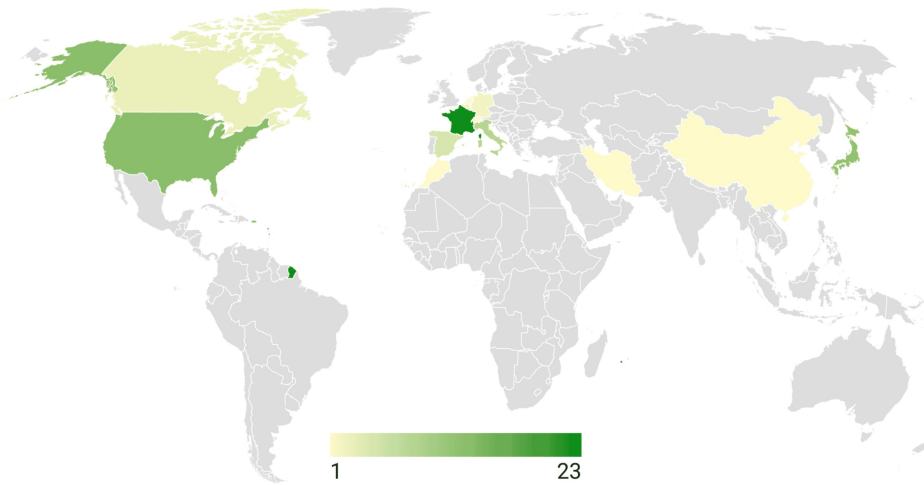


FIGURE 2: Global distribution of corresponding author affiliation by country

Distribution of Cortical Stimulation Sites Across Languages

From the 893 stimulation sites, we identified a total of nine languages: French, English, Chinese, Japanese, Italian, Dutch, Spanish, German, and Persian (Figure 3A). The top three mapped languages were: French (342 stimulation sites; 38.2%), English (246 stimulation sites; 27.5%), and Chinese (186 stimulation sites; 20.8%). These nine languages are spoken by 2.23 billion native speakers, which equates to 27.2% of the global population (8.2 billion humans). These nine languages were then divided into their associated language families, including: Indo-European (French, English, Italian, Dutch, Spanish, German, and Persian), Sino-Tibetan (Chinese), and Japonic (Japanese). The predominant mapped language family was Indo-European (670 stimulation sites; 75%), followed by Sino-Tibetan (186 stimulation sites; 20.8%) and Japonic (37 stimulation sites; 4.1%) (Figure 3B). We then examined the relationship between the total number of global native speakers of the language and stimulation site numbers (Table 2). Chi-squared analysis revealed a significant difference between the frequencies of the total number of global native speakers and stimulation sites ( $\chi^2 = 8166.89$ ,  $df = 29$ ,  $p < 0.00001$ ). We calculated a ‘stimulation site per million native speaker’ metric and identified that the top mapped languages per population size were French (4.62), Dutch (0.99), and English (0.65) (Figure 3C).

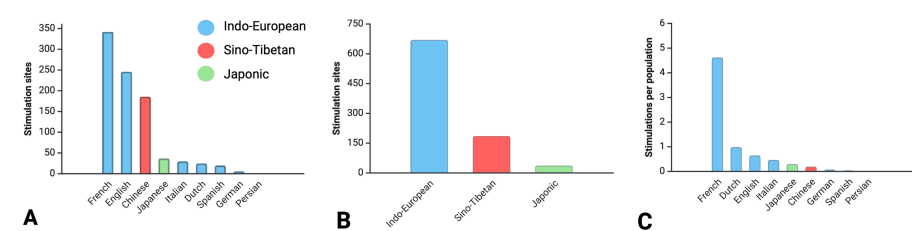


**FIGURE 3: Bar charts of stimulation sites by language (A); stimulation sites by language family (B); and stimulation sites per native speaker population size (C)**

|    | Language         | Native speakers (in millions) | Stimulation sites | Stimulation Sites per Million Speakers |
|----|------------------|-------------------------------|-------------------|----------------------------------------|
| 1  | Mandarin Chinese | 941                           | 186               | 0.197                                  |
| 2  | Spanish          | 486                           | 20                | 0.041                                  |
| 3  | English          | 380                           | 246               | 0.647                                  |
| 4  | Hindi            | 345                           | 0                 | 0                                      |
| 5  | Bengali          | 237                           | 0                 | 0                                      |
| 6  | Portuguese       | 236                           | 0                 | 0                                      |
| 7  | Russian          | 148                           | 0                 | 0                                      |
| 8  | Japanese         | 123                           | 37                | 0.300                                  |
| 9  | Yue Chinese      | 86                            | 0                 | 0                                      |
| 10 | Vietnamese       | 85                            | 0                 | 0                                      |
| 11 | Turkish          | 84                            | 0                 | 0                                      |
| 12 | Marathi          | 83                            | 0                 | 0                                      |
| 13 | Telugu           | 83                            | 0                 | 0                                      |
| 14 | Wu Chinese       | 83                            | 0                 | 0                                      |
| 15 | Western Punjabi  | 82                            | 0                 | 0                                      |
| 16 | Korean           | 81                            | 0                 | 0                                      |
| 17 | Tamil            | 79                            | 0                 | 0                                      |
| 18 | Egyptian Arabic  | 78                            | 0                 | 0                                      |
| 19 | German           | 76                            | 6                 | 0.078                                  |
| 20 | French           | 74                            | 342               | 4.621                                  |
| 21 | Urdu             | 70                            | 0                 | 0                                      |
| 22 | Javanese         | 68                            | 0                 | 0                                      |
| 23 | Italian          | 64                            | 30                | 0.468                                  |
| 24 | Persian          | 62                            | 1                 | 0.016                                  |
| 25 | Gujarati         | 58                            | 0                 | 0                                      |
| 26 | Hausa            | 54                            | 0                 | 0                                      |
| 27 | Bhojpuri         | 53                            | 0                 | 0                                      |
| 28 | Levantine Arabic | 51                            | 0                 | 0                                      |
| 29 | Southern Min     | 51                            | 0                 | 0                                      |
| 30 | Dutch            | 25.3                          | 25                | 0.988                                  |

**TABLE 2: Popularity of each language, with their native-speaker population and stimulation sites reported in this study**

## Discussion

In this systematic review, we defined which languages have been mapped using DES during awake craniotomy. Of the 7000 languages spoken globally, we found only nine had been mapped using DES and described in the literature. These native languages represent just over a quarter of the global population. There was a predominance of Indo-European languages (French, English, Italian, Spanish, Dutch, German, and Persian). French was the most mapped language with DES by the number of stimulation points, but this

dominance became even more pronounced when looked at as a ratio to the number of global native speakers. The large amount of data on French speakers is due to the major contributions made by Professor Hugues Duffau, a French neurosurgeon based at Montpellier. Collectively, this data highlights a bias in the literature with a predominance of Indo-European languages and a lack of representation of the native languages spoken by three-quarters of the global population. The underlying reason for this dominance of Indo-European languages is likely driven by a number of factors, including the historic concentration of global neurosurgical infrastructure in North America and Europe and a longer-established tradition of research.

Despite sharing universal features, languages exhibit remarkable variation. How this variation relates to the underlying neural architecture remains an open question. Neuroimaging has played an important role in trying to answer this question. A major study in the field examined 45 languages from 12 language families [3]. The study revealed a universal fronto-temporo-parietal language network in the human brain, predominantly left-lateralized, that supported language processing across diverse linguistic systems. Despite structural and lexical differences among the studied languages, this network exhibited consistent activation patterns, highlighting a shared neurocognitive architecture for language comprehension and production. The study had a number of limitations, including the participants being bilingual, small sample size per language ( $n=1-2$ ), and a predominance of Indo-European languages (31 out of 45 languages). Neuroimaging provides important evidence on brain function. However, causal inferences on brain function cannot be made from it.

Siddiqi and colleagues defined criteria for causality in human brain mapping [4]. This included reversibility, dose response, and experimental manipulation. DES meets these criteria and is therefore a stronger experimental paradigm for causal mapping of human language function. Lu and colleagues retrospectively developed a multi-centre functional map of DES-induced speech errors by integrating four datasets comprising English, French, and Mandarin [85]. Their analysis revealed a shared fronto-temporo-parietal language network across the languages, aligning with findings from the large-scale fMRI study [3]. However, they also observed nuanced differences, such as a higher incidence of speech arrest in the posterior middle frontal gyrus in the Chinese cohort compared to the English and French cohorts, consistent with earlier research [8]. This finding highlights the value of DES in studying human language function and the importance of ensuring data from a diverse range of languages is captured from awake craniotomy surgeries.

Currently, there is no standardized language testing paradigm for awake craniotomy. There is diversity in the test batteries used and how clinicians interpret language errors [86,87]. This is an important weakness in the field, and efforts should be made to define a core set of language tests for awake craniotomy. Importantly, these tests should be multilingual to ensure they can be used globally by awake craniotomy teams. Our group is working on developing Map-OR - a digital platform for the delivery of language tests during awake craniotomy and collaborative brain mapping [88]. Map-OR has two objectives: first, to allow the administration of standardized language tests during awake craniotomy, encompassing a variety of languages. Second, to enable the mapping of positive stimulation sites onto a digital brain atlas, with the goal of creating a prospective functional multi-language map of the human brain.

The study has several limitations. Firstly, we opted to utilise a previously published systematic review [9]. This was done as the inclusion criteria were the same as our requirements, and the review was the most comprehensive assessment of the language mapping literature to date. However, it did mean we did not conduct a fresh assessment of the literature with our own quality checks. We attempted to address this by performing a thorough review of the data quality. Additionally, the data from the original review only extended to 2020, meaning we have likely missed more recent studies that could have contributed additional stimulation data. We also found that there were 27 studies with a mixed language population. These studies were predominantly by Hugues Duffau ( $n=22$ ; 81%), meaning we likely under-estimated the number of French stimulation sites. In conjunction, we did not analyse neuro-anatomical differences between the languages. This limits any conclusions about differences in the neural architecture of different languages. We plan future analyses, including novel data collected using map-OR, to answer these questions.

## Conclusions

This analysis highlights a predominance of Indo-European languages in the DES awake craniotomy literature. This work supports the need for developing a global research consortium of awake craniotomy teams to collectively pool stimulation data from a diverse range of languages. To do this, the consortium would agree on a standardized multi-language testing paradigm and then collectively pool the neuro-anatomical location of their positive stimulation sites. We are developing a digital platform (map-OR) with the objective of creating a multi-language functional map of the human brain. This endeavour would not only advance cognitive neuroscience but also enhance neurosurgical planning for a globally diverse patient population.

## Additional Information

### Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

**Concept and design:** Aimun A. Jamjoom, Salih Al-Ani, Hana Hallak

**Acquisition, analysis, or interpretation of data:** Aimun A. Jamjoom, Salih Al-Ani, Hana Hallak

**Drafting of the manuscript:** Aimun A. Jamjoom, Salih Al-Ani, Hana Hallak

**Critical review of the manuscript for important intellectual content:** Aimun A. Jamjoom, Salih Al-Ani, Hana Hallak

**Supervision:** Aimun A. Jamjoom

## Disclosures

**Conflicts of interest:** In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

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## References

1. Lewis MP: Ethnologue: Languages of the World . SIL International, Dallas; 2009.
2. Hockett CF: Animal "languages" and human language. *Hum Biol.* 1959, 31:32-39.
3. Malik-Moraleda S, Ayyash D, Gallée J, et al.: An investigation across 45 languages and 12 language families reveals a universal language network. *Nat Neurosci.* 2022, 25:1014-9. [10.1038/s41593-022-01114-5](https://doi.org/10.1038/s41593-022-01114-5)
4. Siddiqi SH, Kording KP, Parvizi J, Fox MD: Causal mapping of human brain function . *Nat Rev Neurosci.* 2022, 23:361-75. [10.1038/s41583-022-00583-8](https://doi.org/10.1038/s41583-022-00583-8)
5. Tate MC, Herbet G, Moritz-Gasser S, Tate JE, Duffau H: Probabilistic map of critical functional regions of the human cerebral cortex: Broca's area revisited. *Brain.* 2014, 137:2773-82. [10.1093/brain/awu168](https://doi.org/10.1093/brain/awu168)
6. Chang EF, Breshears JD, Raygor KP, Lau D, Molinaro AM, Berger MS: Stereotactic probability and variability of speech arrest and anomia sites during stimulation mapping of the language dominant hemisphere. *J Neurosurg.* 2017, 126:114-21. [10.3171/2015.10.JNS151087](https://doi.org/10.3171/2015.10.JNS151087)
7. Hickok G, Venezia J, Teghipco A: Beyond Broca: neural architecture and evolution of a dual motor speech coordination system. *Brain.* 2023, 146:1775-90. [10.1093/brain/awac454](https://doi.org/10.1093/brain/awac454)
8. Wu J, Lu J, Zhang H, et al.: Direct evidence from intraoperative electrocortical stimulation indicates shared and distinct speech production center between Chinese and English languages. *Hum Brain Mapp.* 2015, 36:4972-85. [10.1002/hbm.22991](https://doi.org/10.1002/hbm.22991)
9. Collée E, Vincent A, Visch-Brink E, De Witte E, Dirven C, Satoer D: Localization patterns of speech and language errors during awake brain surgery: a systematic review. *Neurosurg Rev.* 2023, 46:38. [10.1007/s10143-022-01943-9](https://doi.org/10.1007/s10143-022-01943-9)
10. Liberati A, Altman DG, Tetzlaff J, et al.: The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate healthcare interventions: explanation and elaboration. *BMJ.* 2009, 339:b2700. [10.1136/bmj.b2700](https://doi.org/10.1136/bmj.b2700)
11. Munn Z, Barker TH, Moola S, et al.: Methodological quality of case series studies: an introduction to the JBI critical appraisal tool. *JBIEvid Synth.* 2020, 18:2127-33. [10.11124/JBISIR-D-19-00099](https://doi.org/10.11124/JBISIR-D-19-00099)
12. OSF | Which native languages have been mapped using direct electrical stimulation during awake craniotomy? A systematic review. (2025). Accessed: March 18, 2026: <https://doi.org/10.17605/OSF.IO/AWHCN>.
13. Sanai N, Mirzadeh Z, Berger MS: Functional outcome after language mapping for glioma resection . *N Engl J Med.* 2008, 358:18-27. [10.1056/NEJMoa067819](https://doi.org/10.1056/NEJMoa067819)
14. Alimohamadi M, Shirani M, Shariat Moharari R, et al.: Application of awake craniotomy and intraoperative brain mapping for surgical resection of insular gliomas of the dominant hemisphere. *World Neurosurg.* 2016, 92:151-8. [10.1016/j.wneu.2016.04.079](https://doi.org/10.1016/j.wneu.2016.04.079)
15. Altieri R, Melcarne A, Junemann C, et al.: Inferior Fronto-Occipital fascicle anatomy in brain tumor surgeries: from anatomy lab to surgical theater. *J Clin Neurosci.* 2019, 68:290-4. [10.1016/j.jocn.2019.07.039](https://doi.org/10.1016/j.jocn.2019.07.039)
16. Barone F, Alberio N, Iacopino DG, et al.: Brain mapping as helpful tool in brain glioma surgical treatment-toward the "perfect surgery"? *Brain Sci.* 2018, 8:10.3390/brainsci8110192
17. De Benedictis A, Sarubbo S, Duffau H: Subcortical surgical anatomy of the lateral frontal region: human white matter dissection and correlations with functional insights provided by intraoperative direct brain stimulation: laboratory investigation. *J Neurosurg.* 2012, 117:1053-69. [10.3171/2012.7.JNS12628](https://doi.org/10.3171/2012.7.JNS12628)
18. De Benedictis A, Moritz-Gasser S, Duffau H: Awake mapping optimizes the extent of resection for low-grade gliomas in eloquent areas. *Neurosurgery.* 2010, 66:1074-84; discussion 1084. [10.1227/01.NEU.0000369514.74284.78](https://doi.org/10.1227/01.NEU.0000369514.74284.78)

19. Benzagmout M, Gatignol P, Duffau H: Resection of World Health Organization Grade II gliomas involving Broca's area: methodological and functional considerations. *Neurosurgery*. 2007, 61:741-52; discussion 752-3. [10.1227/01.NEU.0000298902.69473.77](https://doi.org/10.1227/01.NEU.0000298902.69473.77)
20. Breshears JD, Southwell DG, Chang EF: Inhibition of manual movements at speech arrest sites in the posterior inferior frontal lobe. *Neurosurgery*. 2019, 85:E496-501. [10.1093/neuros/nyy592](https://doi.org/10.1093/neuros/nyy592)
21. Bresson D, Madadaki C, Poisson I, Habas C, Mandonnet E: Functionally tailored transcortical approach of deep-seated lesions: an alternative to the transulcal approach? a technical case report. *Neurochirurgie*. 2013, 59:159-62; discussion 163. [10.1016/j.neuchi.2013.08.002](https://doi.org/10.1016/j.neuchi.2013.08.002)
22. Chan-Seng E, Moritz-Gasser S, Duffau H: Awake mapping for low-grade gliomas involving the left sagittal stratum: anatomofunctional and surgical considerations. *J Neurosurg*. 2014, 120:1069-77. [10.3171/2014.1.JNS132015](https://doi.org/10.3171/2014.1.JNS132015)
23. Chang EF, Clark A, Smith JS, et al.: Functional mapping-guided resection of low-grade gliomas in eloquent areas of the brain: improvement of long-term survival. Clinical article. *J Neurosurg*. 2011, 114:566-73. [10.3171/2010.6.JNS091246](https://doi.org/10.3171/2010.6.JNS091246)
24. Chernoff BL, Sims MH, Smith SO, Pilcher WH, Mahon BZ: Direct electrical stimulation of the left frontal aslant tract disrupts sentence planning without affecting articulation. *Cogn Neuropsychol*. 2019, 36:178-92. [10.1080/02643294.2019.1619544](https://doi.org/10.1080/02643294.2019.1619544)
25. Duffau H, Bauchet L, Lehericy S, Capelle L: Functional compensation of the left dominant insula for language. *Neuroreport*. 2001, 12:2159-63. [10.1097/00001756-200107200-00023](https://doi.org/10.1097/00001756-200107200-00023)
26. Duffau H, Leroy M, Gatignol P: Cortico-subcortical organization of language networks in the right hemisphere: an electrostimulation study in left-handers. *Neuropsychologia*. 2008, 46:3197-209. [10.1016/j.neuropsychologia.2008.07.017](https://doi.org/10.1016/j.neuropsychologia.2008.07.017)
27. Duffau H, Gatignol P, Moritz-Gasser S, Mandonnet E: Is the left uncinate fasciculus essential for language? A cerebral stimulation study. *J Neurol*. 2009, 256:382-9. [10.1007/s00415-009-0053-9](https://doi.org/10.1007/s00415-009-0053-9)
28. Duffau H, Moritz-Gasser S, Gatignol P: Functional outcome after language mapping for insular World Health Organization Grade II gliomas in the dominant hemisphere: experience with 24 patients. *Neurosurg Focus*. 2009, 27:E7. [10.3171/2009.5.FOCUS0938](https://doi.org/10.3171/2009.5.FOCUS0938)
29. Fernández L, Santos C, Gómez E, Velásquez C, Martino J: Eliciting smiles and laughter during intraoperative electric stimulation of the cingulum: surgical scenario. *World Neurosurg*. 2020, 133:55. [10.1016/j.wneu.2019.09.101](https://doi.org/10.1016/j.wneu.2019.09.101)
30. Fujii M, Maesawa S, Motomura K, Futamura M, Hayashi Y, Koba I, Wakabayashi T: Intraoperative subcortical mapping of a language-associated deep frontal tract connecting the superior frontal gyrus to Broca's area in the dominant hemisphere of patients with glioma. *J Neurosurg*. 2015, 122:1390-6. [10.3171/2014.10.JNS14945](https://doi.org/10.3171/2014.10.JNS14945)
31. Gayoso S, Perez-Borrada P, Gutierrez A, García-Porrero JA, Marco de Lucas E, Martino J: Ventral precentral fiber intersection area: a central hub in the connectivity of perisylvian associative tracts. *Oper Neurosurg*. 2019, 17:182-92. [10.1093/ons/opy331](https://doi.org/10.1093/ons/opy331)
32. van Geemen K, Herbet G, Moritz-Gasser S, Duffau H: Limited plastic potential of the left ventral premotor cortex in speech articulation: evidence from intraoperative awake mapping in glioma patients. *Hum Brain Mapp*. 2014, 35:1587-96. [10.1002/hbm.22275](https://doi.org/10.1002/hbm.22275)
33. Gharabaghi A, Fruhmann Berger M, Tatagiba M, Karnath HO: The role of the right superior temporal gyrus in visual search-insights from intraoperative electrical stimulation. *Neuropsychologia*. 2006, 44:2578-81. [10.1016/j.neuropsychologia.2006.04.006](https://doi.org/10.1016/j.neuropsychologia.2006.04.006)
34. Gil-Robles S, Carvallo A, Jimenez Mdel M, Gomez Caicoya A, Martinez R, Ruiz-Ocaña C, Duffau H: Double dissociation between visual recognition and picture naming: a study of the visual language connectivity using tractography and brain stimulation. *Neurosurgery*. 2013, 72:678-86. [10.1227/NEU.0b013e318282a361](https://doi.org/10.1227/NEU.0b013e318282a361)
35. Herbet G, Moritz-Gasser S, Duffau H: Direct evidence for the contributive role of the right inferior fronto-occipital fasciculus in non-verbal semantic cognition. *Brain Struct Funct*. 2017, 222:1597-610. [10.1007/s00429-016-1294-x](https://doi.org/10.1007/s00429-016-1294-x)
36. Hirono S, Ozaki K, Ito D, Matsutani T, Iwadate Y: Hammock middle cerebral artery and delayed infarction in lenticulostriate artery after staged resection of giant insular glioma. *World Neurosurg*. 2018, 117:80-3. [10.1016/j.wneu.2018.05.226](https://doi.org/10.1016/j.wneu.2018.05.226)
37. Hiroshima S, Anei R, Murakami N, Kamada K: Functional localization of the supplementary motor area. *Neurol Med Chir (Tokyo)*. 2014, 54:511-20. [10.2176/nmc.0a2012-0321](https://doi.org/10.2176/nmc.0a2012-0321)
38. Joswig H, Bratelj D, Brunner T, Jacomet A, Hildebrandt G, Surbeck W: Awake craniotomy: first-year experiences and patient perception. *World Neurosurg*. 2016, 90:588-596.e2. [10.1016/j.wneu.2016.02.051](https://doi.org/10.1016/j.wneu.2016.02.051)
39. Kamada K, Ogawa H, Kapeller C, Prueckl R, Guger C: Rapid and low-invasive functional brain mapping by realtime visualization of high gamma activity for awake craniotomy. *Annu Int Conf IEEE Eng Med Biol Soc*. 2014, 2014:6802-5. [10.1109/EMBC.2014.6945190](https://doi.org/10.1109/EMBC.2014.6945190)
40. Kemerdere R, de Champfleure NM, Deverdun J, Cochereau J, Moritz-Gasser S, Herbet G, Duffau H: Role of the left frontal aslant tract in stuttering: a brain stimulation and tractographic study. *J Neurol*. 2016, 263:157-67. [10.1007/s00415-015-7949-3](https://doi.org/10.1007/s00415-015-7949-3)
41. Khan OH, Herbet G, Moritz-Gasser S, Duffau H: The role of left inferior fronto-occipital fascicle in verbal perseveration: a brain electrostimulation mapping study. *Brain Topogr*. 2014, 27:403-11. [10.1007/s10548-013-0343-5](https://doi.org/10.1007/s10548-013-0343-5)
42. Kurimoto M, Takaiwa A, Nagai S, Hayashi N, Endo S: Anomia for people's names after left anterior temporal lobe resection--case report. *Neurol Med Chir (Tokyo)*. 2010, 50:36-40. [10.2176/nmc.50.36](https://doi.org/10.2176/nmc.50.36)
43. Lang FF, Olansen NE, DeMonte F, Gokaslan ZL, Holland EC, Kalhorn C, Sawaya R: Surgical resection of intrinsic insular tumors: complication avoidance. *J Neurosurg*. 2001, 95:638-50. [10.3171/jns.2001.95.4.0638](https://doi.org/10.3171/jns.2001.95.4.0638)
44. Magrassi L, Bongetta D, Bianchini S, Berardesca M, Arianta C: Central and peripheral components of writing critically depend on a defined area of the dominant superior parietal gyrus. *Brain Res*. 2010, 1346:145-54. [10.1016/j.brainres.2010.05.046](https://doi.org/10.1016/j.brainres.2010.05.046)
45. Maldonado IL, Moritz-Gasser S, Duffau H: Does the left superior longitudinal fascicle subserve language semantics? A brain electrostimulation study. *Brain Struct Funct*. 2011, 216:263-74. [10.1007/s00429-011-](https://doi.org/10.1007/s00429-011-)

0309-x

46. Martino J, de Lucas EM, Ibáñez-Plágaro FJ, Valle-Folgueral JM, Vázquez-Barquero A: Foix-Chavany-Marie syndrome caused by a disconnection between the right pars opercularis of the inferior frontal gyrus and the supplementary motor area. *J Neurosurg.* 2012, 117:844-50. [10.3171/2012.7.JNS12404](#)
47. Matsuda R, Moritz-Gasser S, Duvaux S, Fernández Coello A, Martinoni M, Duffau H: The persistent crucial role of the left hemisphere for language in left-handers with a left low grade glioma: a stimulation mapping study. *Acta Neurochir (Wien).* 2014, 156:661-70; discussion 670. [10.1007/s00701-014-2003-2](#)
48. Moritz-Gasser S, Duffau H: The anatomo-functional connectivity of word repetition: insights provided by awake brain tumor surgery. *Front Hum Neurosci.* 2013, 7:405. [10.3389/fnhum.2013.00405](#)
49. Morrison MA, Tam F, Garavaglia MM, et al.: Sources of variation influencing concordance between functional mri and direct cortical stimulation in brain tumor surgery. *Front Neurosci.* 2016, 10:461. [10.3389/fnins.2016.00461](#)
50. Morrison MA, Tam F, Garavaglia MM, et al.: A novel tablet computer platform for advanced language mapping during awake craniotomy procedures. *J Neurosurg.* 2016, 124:938-44. [10.3171/2015.4.JNS15312](#)
51. Motomura K, Fujii M, Maesawa S, Kuramitsu S, Natsume A, Wakabayashi T: Association of dorsal inferior frontooccipital fasciculus fibers in the deep parietal lobe with both reading and writing processes: a brain mapping study. *J Neurosurg.* 2014, 121:142-8. [10.3171/2014.2.JNS131234](#)
52. Iijima K, Motomura K, Chalise L, Hirano M, Natsume A, Wakabayashi T: Efficacy of the transtemporal approach with awake brain mapping to reach the dominant posteromedial temporal lesions. *Acta Neurochir (Wien).* 2017, 159:177-84. [10.1007/s00701-016-3035-6](#)
53. Motomura K, Chalise L, Ohka F, et al.: Neurocognitive and functional outcomes in patients with diffuse frontal lower-grade gliomas undergoing intraoperative awake brain mapping. *J Neurosurg.* 2020, 132:1683-91. [10.3171/2019.3.JNS19211](#)
54. Motomura K, Chalise L, Ohka F, et al.: Supratotal resection of diffuse frontal lower grade gliomas with awake brain mapping, preserving motor, language, and neurocognitive functions. *World Neurosurg.* 2018, 119:30-9. [10.1016/j.wneu.2018.07.193](#)
55. Mukae N, Mizoguchi M, Mori M, et al.: The usefulness of arcuate fasciculus tractography integrated navigation for glioma surgery near the language area; clinical investigation. *Interdiscip Neurosurg.* 2017, 7:22-8. [10.1016/j.inat.2016.11.003](#)
56. Nomura K, Kazui H, Tokunaga H, et al.: Possible roles of the dominant uncinate fasciculus in naming objects: a case report of intraoperative electrical stimulation on a patient with a brain tumour. *Behav Neurol.* 2013, 27:229-34. [10.3233/BEN-110249](#)
57. Oelschlägel M, Meyer T, Morgenstern U, et al.: Mapping of language and motor function during awake neurosurgery with intraoperative optical imaging. *Neurosurg Focus.* 2020, 48:E3. [10.3171/2019.11.FOCUS19759](#)
58. Ogawa H, Kamada K, Kapeller C, Hiroshima S, Prueckl R, Guger C: Rapid and minimum invasive functional brain mapping by real-time visualization of high gamma activity during awake craniotomy. *World Neurosurg.* 2014, 82:912.e1-10. [10.1016/j.wneu.2014.08.009](#)
59. Pallud J, Roux A, Mellerio C: Glioma resection unmasks eloquent brain areas. *World Neurosurg.* 2019, 132:251-2. [10.1016/j.wneu.2019.09.012](#)
60. Papagno C, Miracapillo C, Casarotti A, et al.: What is the role of the uncinate fasciculus? Surgical removal and proper name retrieval. *Brain.* 2011, 134:405-14. [10.1093/brain/awq283](#)
61. Parney IF, Goerss SJ, McGee K, Huston J 3rd, Perkins WJ, Meyer FB: Awake craniotomy, electrophysiologic mapping, and tumor resection with high-field intraoperative MRI. *World Neurosurg.* 2010, 73:547-51. [10.1016/j.wneu.2010.02.003](#)
62. Petrovich NM, Holodny AI, Brennan CW, Gutin PH: Isolated translocation of Wernicke's area to the right hemisphere in a 62-year-man with a temporo-parietal glioma. *AJNR Am J Neuroradiol.* 2004, 25:130-3.
63. Petrovich N, Holodny AI, Tabar V, Correa DD, Hirsch J, Gutin PH, Brennan CW: Discordance between functional magnetic resonance imaging during silent speech tasks and intraoperative speech arrest. *J Neurosurg.* 2005, 103:267-74. [10.3171/jns.2005.103.2.0267](#)
64. Plaza M, Gatignol P, Leroy M, Duffau H: Speaking without Broca's area after tumor resection. *Neurocase.* 2009, 15:294-310. [10.1080/13554790902729473](#)
65. Pouratian N, Cannestra AF, Bookheimer SY, Martin NA, Toga AW: Variability of intraoperative electrocortical stimulation mapping parameters across and within individuals. *J Neurosurg.* 2004, 101:458-66. [10.3171/jns.2004.101.3.0458](#)
66. Rech F, Wassermann D, Duffau H: New insights into the neural foundations mediating movement/language interactions gained from intrasurgical direct electrostimulations. *Brain Cogn.* 2020, 142:105583. [10.1016/j.bandc.2020.105583](#)
67. Rech F, Duffau H, Pinelli C, et al.: Intraoperative identification of the negative motor network during awake surgery to prevent deficit following brain resection in premotor regions. *Neurochirurgie.* 2017, 63:235-42. [10.1016/j.neuchi.2016.08.006](#)
68. Gil Robles S, Gatignol P, Capelle L, Mitchell MC, Duffau H: The role of dominant striatum in language: a study using intraoperative electrical stimulations. *J Neurol Neurosurg Psychiatry.* 2005, 76:940-6. [10.1136/jnnp.2004.045948](#)
69. Rofes A, Spena G, Talacchi A, Santini B, Miozzo A, Miceli G: Mapping nouns and finite verbs in left hemisphere tumors: a direct electrical stimulation study. *Neurocase.* 2017, 23:105-13. [10.1080/13554794.2017.1307418](#)
70. Ruge MI, Victor J, Hosain S, et al.: Concordance between functional magnetic resonance imaging and intraoperative language mapping. *Stereotact Funct Neurosurg.* 1999, 72:95-102. [10.1159/000029706](#)
71. Sarubbo S, Latini F, Panajia A, et al.: Awake surgery in low-grade gliomas harboring eloquent areas: 3-year mean follow-up. *Neurol Sci.* 2011, 32:801-10. [10.1007/s10072-011-0587-3](#)
72. Satoer D, Kloet A, Vincent A, Dirven C, Visch-Brink E: Dynamic aphasia following low-grade glioma surgery near the supplementary motor area: a selective spontaneous speech deficit. *Neurocase.* 2014, 20:704-16. [10.1080/13554794.2013.841954](#)

73. Sierpowska J, Gabarrós A, Fernandez-Coello A, et al.: Morphological derivation overflow as a result of disruption of the left frontal aslant white matter tract. *Brain Lang.* 2015, 142:54-64. [10.1016/j.bandl.2015.01.005](https://doi.org/10.1016/j.bandl.2015.01.005)
74. Southwell DG, Riva M, Jordan K, et al.: Language outcomes after resection of dominant inferior parietal lobule gliomas. *J Neurosurg.* 2017, 127:781-9. [10.3171/2016.8.JNS16443](https://doi.org/10.3171/2016.8.JNS16443)
75. Spena G, Costi E, Panciani PP, Roca E, Migliorati K, Fontanella MM: Acute functional reactivation of the language network during awake intraoperative brain mapping. *Neurocase.* 2015, 21:403-7. [10.1080/13554794.2014.910306](https://doi.org/10.1080/13554794.2014.910306)
76. Tomasino B, Marin D, Maieron M, et al.: A multimodal mapping study of conduction aphasia with impaired repetition and spared reading aloud. *Neuropsychologia.* 2015, 70:214-26. [10.1016/j.neuropsychologia.2015.02.023](https://doi.org/10.1016/j.neuropsychologia.2015.02.023)
77. Vassal F, Boutet C, Lemaire JJ, Nuti C: New insights into the functional significance of the frontal aslant tract: an anatomo-functional study using intraoperative electrical stimulations combined with diffusion tensor imaging-based fiber tracking. *Br J Neurosurg.* 2014, 28:685-7. [10.3109/02688697.2014.889810](https://doi.org/10.3109/02688697.2014.889810)
78. Vidorreta JG, Garcia R, Moritz-Gasser S, Duffau H: Double dissociation between syntactic gender and picture naming processing: a brain stimulation mapping study. *Hum Brain Mapp.* 2011, 32:331-40. [10.1002/hbm.21026](https://doi.org/10.1002/hbm.21026)
79. Wilden JA, Voorhies J, Mosier KM, O'Neill DP, Cohen-Gadol AA: Strategies to maximize resection of complex, or high surgical risk, low-grade gliomas. *Neurosurg Focus.* 2013, 34:E5. [10.3171/2012.12.FOCUS12338](https://doi.org/10.3171/2012.12.FOCUS12338)
80. De Witte E, Satoer D, Colle H, Robert E, Visch-Brink E, Mariën P: Subcortical language and non-language mapping in awake brain surgery: the use of multimodal tests. *Acta Neurochir (Wien).* 2015, 157:577-88. [10.1007/s00701-014-2317-0](https://doi.org/10.1007/s00701-014-2317-0)
81. De Witte E, Satoer D, Robert E, Colle H, Verheyen S, Visch-Brink E, Mariën P: The Dutch Linguistic Intraoperative Protocol: a valid linguistic approach to awake brain surgery. *Brain Lang.* 2015, 140:35-48. [10.1016/j.bandl.2014.10.011](https://doi.org/10.1016/j.bandl.2014.10.011)
82. Yordanova YN, Moritz-Gasser S, Duffau H: Awake surgery for WHO Grade II gliomas within "noneloquent" areas in the left dominant hemisphere: toward a "supratotal" resection. *Clinical article. J Neurosurg.* 2011, 115:232-9. [10.3171/2011.3.JNS101333](https://doi.org/10.3171/2011.3.JNS101333)
83. Zammar SG, Specht CS, Zacharia BE: Crossed aphasia as a manifestation of glioblastoma . *Cureus.* 2018, 10:e2239. [10.7759/cureus.2239](https://doi.org/10.7759/cureus.2239)
84. Zemmoura I, Herbet G, Moritz-Gasser S, Duffau H: New insights into the neural network mediating reading processes provided by cortico-subcortical electrical mapping. *Hum Brain Mapp.* 2015, 36:2215-30. [10.1002/hbm.22766](https://doi.org/10.1002/hbm.22766)
85. Lu J, Zhao Z, Zhang J, et al.: Functional maps of direct electrical stimulation-induced speech arrest and anomia: a multicentre retrospective study. *Brain.* 2021, 144:2541-53. [10.1093/brain/awab125](https://doi.org/10.1093/brain/awab125)
86. Sefcikova V, Sporrer JK, Ekert JO, Kirkman MA, Samandouras G: High interrater variability in intraoperative language testing and interpretation in awake brain mapping among neurosurgeons or neuropsychologists: an emerging need for standardization. *World Neurosurg.* 2020, 141:e651-60. [10.1016/j.wneu.2020.05.250](https://doi.org/10.1016/j.wneu.2020.05.250)
87. Papatzalas C, Fountas K, Kapsalaki E, Papathanasiou I: The use of standardized intraoperative language tests in awake craniotomies: a scoping review. *Neuropsychol Rev.* 2022, 32:20-50. [10.1007/s11065-021-09492-6](https://doi.org/10.1007/s11065-021-09492-6)
88. Veljanoski D, Ng XY, Hill CS, Jamjoom AA: Theory and evidence-base for a digital platform for the delivery of language tests during awake craniotomy and collaborative brain mapping. *BMJ Surg Interv Health Technol.* 2024, 6:e000234. [10.1136/bmjsit-2023-000234](https://doi.org/10.1136/bmjsit-2023-000234)