Brain & Language 271 (2025) 105641

Contents lists available at ScienceDirect

Brain and Language

journal homepage: www.elsevier.com/locate/b&l

# Language-specific regions in the supplementary motor area: Evidence from verb generation during electrical stimulation mapping

Mireia Hernández [a,b], Anna Gasa-Roqué [a,b,c,*], Alba Gómez-Andres [b], Ruth Lau [d], Inmaculada Rico [c], Montserrat Juncadella [e], Àngels Camins [f], Antoni Rodríguez-Fornells [a,b,g,h], Andreu Gabarrós [d,i,j]

[a] Department of Cognition, Development, and Psychology of Education, Institute of Neurosciences, Universitat de Barcelona, Barcelona, Spain
[b] Cognition & Brain Plasticity Unit, Bellvitge Biomedical Research Institute (IDIBELL), Spain
[c] Hospital Universitari de Bellvitge (HUB), Neurology Section, Campus Bellvitge, University of Barcelona, L'Hospitalet de Llobregat, Barcelona, Spain
[d] Hospital Universitari de Bellvitge (HUB), Department of Neurosurgery, Barcelona, Spain
[e] ENTIA, Fundació de Neurorehabilitació i Recerca Cognitiva, Barcelona, Spain
[f] Institut de Diagnòstic per la Imatge, Centre Bellvitge, L'Hospitalet de Llobregat, Hospital Universitari de Bellvitge, Barcelona, Spain
[g] Catalan Institution for Research and Advanced Studies (ICREA), Barcelona, Spain
[h] Aix-Marseille Université, Iméra, Marseille F-13000, France
[i] Neuro-Oncology Unit, Bellvitge Biomedical Research Institute (IDIBELL), Barcelona, Spain
[j] Department of Clinical Sciences, Faculty of Medicine and Health Sciences, University of Barcelona, Barcelona, Spain

ARTICLE INFO

*Keywords:*
Electrical stimulation mapping
Language-specific brain sites
Multilingualism
Supplementary motor area
Verb generation

ABSTRACT

Language representation has been attributed to the perisylvian areas of the left hemisphere, with a more widely distributed network in multilingual populations. However, multilingual evidence has long obviated the involvement of regions outside classical perisylvian areas, such as the supplementary motor area (SMA). We aimed to provide novel evidence on the SMA's role in language localization using electrical stimulation mapping (ESM) during awake brain surgery. We conducted a case-series study of 4 bilingual or multilingual patients with an expansive brain lesion near the SMA who underwent an ESM. Our results evidenced that the stimulation of the left-SMA induced language difficulties during a verb generation task, with a higher proportion of language-specific sites in the pre-SMA region. Moreover, we reported specific language sites for multiple acquired languages. Overall, our study highlighted the SMA as a language-eloquent area, likely linked to lexical decisions, while also being sensitive to different—but not necessarily all—languages of a patient.

## 1. Introduction

Several electrical stimulation mapping (ESM) studies on multilingualism have revealed the existence of language-specific sites in brain regions devoted to language representation, that is, within the perisylvian language network (e.g., Bello et al., 2006; Chan et al., 2019; Fernández-Coello et al., 2017; Lubrano et al., 2012) – possibly also within its white matter tracts (e.g., Bello et al., 2006; but see, Lubrano et al., 2012). The debate over whether and to what extent the different languages of a multilingual individual are represented in shared or separate brain regions has persisted for a long time. Traditionally, the most widespread belief was that only dominant languages were represented in the left hemisphere, while non-dominant languages had to rely on the right one (for an overview of this early myth and arguments for its debunking, see Paradis, 1990). Today, thanks to several functional magnetic resonance imaging (fMRI) and ESM studies, it is widely accepted that languages of a multilingual rely on the gross neural network of (primarily) left cortical and subcortical regions (Cargnelutti et al., 2019; Sebastian et al., 2011; for a brief review of early evidence, see Giussani et al., 2007), with some language-specificity among languages acquired (Bello et al., 2006; Chan et al., 2019; Fernández-Coello et al., 2017; Lubrano et al., 2012). These language-specific cortical sites may be only a few millimeters apart from language-common ones, and their location is inconsistent across individuals. Nevertheless, it is widely accepted that language-specific sites within the perisylvian language network reflect that specific aspects of language production and

* Corresponding author at: Carrer de la Feixa Llarga, s/n, 08907 L'Hospitalet de Llobregat, Barcelona, Spain.
*E-mail address:* annagasar@ub.edu (A. Gasa-Roqué).

https://doi.org/10.1016/j.bandl.2025.105641
Received 23 April 2025; Received in revised form 9 September 2025; Accepted 13 September 2025
Available online 24 September 2025

comprehension are represented separately (at least to a certain extent) for each language of a multilingual. Although the supplementary motor area (SMA) lies outside the classical perisylvian language network, it is sometimes included in clinical language mapping due to its role in speech initiation and the risk of postoperative language deficits following resection (e.g., Duffau et al., 2002; Rutten, 2015). However, the specific linguistic functions of SMA language-related sites—and their potential language-specificity in multilinguals—remain largely overlooked in the ESM literature.

The most prominent established role of the SMA is initiating and controlling voluntary body movements (Lau et al., 2004; Picard & Strick, 2001). When it comes to language, the SMA has been classically associated with the volitional drive leading to articulatory motor initiation rather than language representation (understood here as any speech production operation occurring before the motor execution of an articulatory plan). This is because lesions in the SMA (e.g., Bleasel et al., 1996; Krainik et al., 2003; Laplane et al, 1977; Pai, 1999) and its electrical stimulation during ESM (e.g., Chauvel et al., 1996) most typically result in different degrees of speech reduction (e.g., slow speech production, reiterative articulation patterns, and mutism in the most severe cases) rather than in the alteration of linguistic representations per se. In fact, the language disorder typically associated with this region is the so-called transcortical motor aphasia (Freedman et al., 1984), mainly characterized by difficulties initiating spontaneous speech, with a spared comprehension and production.

Importantly, however, evidence from several studies indicates that the SMA is not limited to articulatory functions but also contributes to language representation (Alario et al., 2006; Rozanski et al., 2015; Ziegleret al., 1997). More in detail, results from an fMRI (Alario et al. 2006) experiment evidenced that the entire SMA became recruited during tasks requiring language production, being the rostral portion of the SMA (pre-SMA) associated with lexical selection. In contrast, the most caudal portion (SMA-proper) was related to the following language-processing step, that is linear sequence encoding, which consists of selecting and organizing the linguistic components of the word (e.g., phonemes, syllables) in an abstract sequence that will be converted into motor commands. These results fit well with (at least) two single cases of language representation deficits following SMA damage (Ziegler et al., 1997) or direct cortical stimulation (Rozanski et al., 2015) with difficulties in linear sequence coding and word selection, respectively.

Literature specifically addressing the use of intraoperative language tasks to target the SMA during ESM remains sparse, as reflected in language mapping protocol reviews (e.g., Martín-Monzón et al., 2022). This is likely due to the traditional view of the SMA as primarily supporting motor aspects of speech. As a result, most intraoperative mapping studies have focused on articulatory functions, and reports describing language-specific mapping within the SMA are limited to isolated case studies highlighting articulatory disruptions. For example, Rutten (2015) examined three patients with tumors near the SMA and found that both counting and object picture naming tasks induced speech rate disruptions—either acceleration or deceleration—during stimulation, rather than the typical speech arrest. These findings, in line with most of the literature on SMA mapping, were interpreted as evidence of the SMA's involvement in motor control of speech. Accordingly, the SMA has often been studied in the context of SMA syndrome, characterized by motor deficits including transient speech initiation difficulties. Consistent with this focus, articulatory-based tasks such as automated counting have been prioritized in many ESM protocols, often in combination with object picture naming (e.g., Duffau et al., 2002; Rutten, 2015). Notably, although object picture naming engages both articulation and lexical retrieval, this task may lack the sensitivity to detect SMA involvement in lexico-semantic processing. In a large retrospective multicenter study, Lu et al. (2021) analyzed data from 598 patients undergoing ESM for epilepsy or tumor resection in frontal regions across four international centers, involving native speakers of English, French, and Mandarin. All patients were tested using counting and object naming tasks. Among 917 stimulation sites associated with speech arrest and 423 with anomia, the SMA was identified as one of the clusters linked to speech arrest but not anomia—suggesting its role was limited to articulation rather than lexical access. Together, these findings support the idea that standard tasks currently used in ESM are effective at detecting articulatory-related language regions in the SMA, but may fail to capture regions involved in lexico-semantic processing.

In light of the challenges posed by task selection in intraoperative language mapping, several authors have recommended the use of verb production tasks—particularly when targeting frontal regions. For example, Havas et al. (2015) found that, during ESM, language-disruptive points in the prefrontal cortex were more frequently identified with verb than with noun production tasks, with 86 % of language-related points affected by verbs compared to only 14 % by nouns. Similarly, Rofes and Miceli (2014), in their review of language mapping tasks, argued that verb production is generally better suited than noun production for identifying eloquent areas in the frontal lobe. Supporting this recommendation, functional neuroimaging studies have consistently shown that several frontal regions exhibit a preference for verbs over nouns (e.g., Shapiro et al., 2006). Importantly, the SMA appears to be among these verb-preferring regions. For instance, Willms et al. (2011) reported greater SMA activation for verbs than for nouns across different languages. Likewise, action-related language processing has been linked to motor circuits—including the SMA—during the effortful retrieval of verb representations from semantic memory (Pavlova et al., 2019). Grèzes and Decety (2007) also proposed that verbalizing action knowledge may rely on internally generated speech mechanisms supported by SMA pathways.

It is important to emphasize that a greater neural response to verbs in frontal regions does not imply verb specificity, as these regions—including the SMA—are also activated by non-verbal or noun-based stimuli. For example, Nelson et al. (2002) reported SMA involvement during antonym generation and phonemic verbal fluency tasks in a preoperative fMRI study, while Rozanski et al. (2015) observed that direct stimulation of the SMA in an epileptic patient prior to surgery elicited anomia during an object picture naming task. Such cases underscore the SMA's broader contribution to language beyond verbs—including noun-related lexico-semantic processes—even though noun production tasks have shown limited reliability in eliciting language-related responses during intraoperative ESM (see, e.g., Ritaccio et al., 2018, for discussion of discrepancies between intraoperative and pre-/extraoperative mapping outcomes).

While some researchers attribute verb preference to the typically greater cognitive demands of processing verbs—due to their abstractness and morphosyntactic complexity (e.g., Vigliocco et al., 2011)—Rofes & Miceli (2014) argue that the observed differences between nouns and verbs may instead reflect fundamentally distinct linguistic operations specific to each grammatical category. For instance, some authors have proposed that a verb's argument structure is lexically encoded and automatically accessed during single-word processing (e.g., Thompson et al., 2007), and that this property may even account for verb preference in certain brain regions (Hernández et al., 2014). Based on the view that nouns and verbs differ not only in processing complexity but also in underlying linguistic operations, Rofes &d Miceli (2014) recommend using both word classes in clinical mapping—though ideally, more ecologically valid sentence-level tasks should be employed. However, when mapping is restricted to single-word tasks, including verbs may offer a methodological advantage due to their higher likelihood of engaging frontal language regions. In this respect, both action naming and verb generation tasks appear suitable for ESM protocols, as they rely on comparable language processes (Rofes & Miceli, 2014). However, verb generation may offer specific practical benefits over action naming. Unlike action pictures, which often suffer from visual ambiguity or complexity, verb generation—particularly in auditory versions—allows for the inclusion of less visually depictable items. In addition, because auditory items lack external visual cues that typically support semantic access (e.g., manipulability features like handles or blades), their retrieval may require deeper motor and conceptual simulation (see Garcea & Mahon, 2012). While verb generation tasks have been incorporated into various preoperative and intraoperative ESM protocols (e.g., Rofes & Miceli, 2014; Salillas et al., 2024), to our knowledge, Rosenberg et al. (2010) is the only study to report its use during intraoperative mapping of the SMA. Language-relevant sites were identified in 10 of the 26 patients tested. However, the verb generation task was administered alongside a counting task, and the authors did not differentiate between the contributions of the two tasks.

Besides missing lexico-semantic sites, another limitation of ESM studies targeting the SMA is the tendency to overlook this region in bilingual or multilingual mapping—likely due to its traditional association with articulation. One might assume that, if the SMA were purely motor, distinct language-specific sites would not be expected there. Indeed, Giussani et al. (2007) suggested that articulatory functions in the precentral gyrus are language-invariant. However, phonetic research shows that even motor planning can be language-specific: bilinguals maintain distinct phonetic categories (Szakay et al., 2016), and exhibit different speech timing patterns across their languages (Redford & Oh, 2017), suggesting that articulatory sites like the SMA may also vary with language. This tendency to overlook multilingualism in SMA mapping may also contribute to the underreporting of potentially relevant findings. For instance, Bello et al. (2006) conducted ESM in seven multilingual patients with left frontal gliomas using object, verb, and famous people naming tasks (without differentiating identified sites by task), and reported both language-common and language-specific frontal sites. Although SMA involvement was not explicitly discussed, their schematic representation of stimulation sites includes markers in the superior medial frontal cortex that may correspond to the pre-SMA—an interpretation further supported by an intraoperative image in a subsequent review by the same group (Giussani et al., 2007) that appears to show distinct language-specific sites within this region.

In the current ESM study, we aimed to provide evidence of multilingual and bilingual language specificity in the SMA for the first time. We report on four single-case patients—two bilingual and two multilingual—who have diverse language dominance profiles. All four patients underwent pre-operative fMRI and intraoperative ESM using a verb generation task to identify language-relevant sites prior to the resection of a lesion located near the SMA.

## 2. Methods

### *2.1. Participants*

The present study included two bilingual and two multilingual right-handed subjects, diagnosed with an expansive brain lesion in the SMA within the left-dominant hemisphere who underwent awake brain surgery, including ESM. All the patients were operated on by the same senior neurosurgeon (AG) at the Department of Neurosurgery of the *Hospital Universitari de Bellvitge* (HUB) following the asleep-awake-asleep sequence.

- **Patient 1** was a 65-year-old multilingual woman (L1: Catalan; L2: Spanish; L3: English; L4: French) with a high educational level (19 years). She was admitted to the neurosurgery ward after debuting with epileptic seizures followed by periods of post-ictal aphasia. She was diagnosed with colorectal adenocarcinoma metastasis (See Fig. 2A), with a complete resection of the lesion.
- **Patient 2** was a 31-year-old bilingual male (L1: Spanish, L2: Catalan) with a medium educational level (12 years). He debuted with epileptic seizures and was diagnosed with anaplastic oligoastrocytoma (Grade 3, see Fig. 2B), with a subtotal resection of the lesion.
- **Patient 3** was a 37-year-old bilingual woman (L1: Catalan; L2: Spanish) with a medium educational level (13 years). She initially presented with an epileptic seizure, which resulted in right hemiparesis, and she was diagnosed with anaplastic astrocytoma, IDH-mutant (Grade 3, see Fig. 2C), following a subtotal resection of the lesion.
- **Patient 4** was a 54-year-old multilingual woman (L1: Polish; L2: Spanish; L3: English; L4: German) with a high educational level (16 years) who was diagnosed with glioblastoma, IDH-WT (Grade 4, see Fig. 2D), after presenting difficulties in writing and language switching, achieving subtotal resection of the lesion.

An adapted version of the Bilingual Language Profile (Birdsong et al., 2012) was used to assess each patient's language background, including age of acquisition (AoA), percentage of use, and self-reported proficiency (see Fig. 1). Notably, the first two languages of Patients 1–3 (L1 and L2) and the first language (L1) of Patient 4 were acquired early in immersive, bilingual environments. In contrast, all other languages—including the L2 of Patient 4—were acquired later in life and are classified as non-native. However, as highlighted in previous literature (e.g., Tomoschuk et al., 2019), self-rated proficiency does not always reflect actual performance and may be influenced by factors such as formal education, literacy, and social comparison. For example, Patient 1 rated her L2 proficiency higher than her L1, while Patient 3 reported unexpectedly low proficiency in both L1 and L2 despite early and immersive acquisition (see Fig. 1B). Due to such typical inconsistencies, a non-native language was considered eligible for ESM only if it was relevant to the patient's daily life, as reported in structured interviews about language use in personal and professional contexts. Accordingly, languages were classified as functional if relevant to the patient's everyday life, and non-functional otherwise. This criterion excluded L4 of Patient 1 from intraoperative testing. Language dominance beyond L1 (the earliest acquired language) was determined based on functional relevance in daily life, which in turn guided the order of intraoperative language testing. Notably, this order did not always align with AoA. For instance, although Spanish (L2) in Patient 4 was acquired later than her L3 and L4, it was tested second due to its current primary role in her daily communication (see Fig. 1A). While AoA is commonly used in the literature to determine language dominance, we prioritized functional relevance in this study to reflect the actual order of intraoperative testing.

All patients gave written informed consent to participate, in accordance with the Declaration of Helsinki. The study was approved by the Ethical Committee of the HUB (PR303/12), where all procedures were conducted. As this is a case study, no part of the methodology or analysis was preregistered in a time-stamped institutional registry.

### *2.2. Neuropsychological assessment*

Before surgery, patients underwent a comprehensive cognitive, motor, and language evaluation. Expressive language was assessed using the Cookie Theft picture description from the Boston Diagnostic Aphasia Examination (Kaplan et al., 2001). Semantic (animals) and phonological (letter "p") verbal fluency tasks evaluated lexical retrieval and executive function (Artiola et al., 1999). Motor dexterity and coordination were measured with the Purdue Pegboard test (Tiffin & Asher, 1948). Processing speed (symbol search, coding) and working memory (Digit Span, Letter-Number Sequencing, Arithmetic) were assessed using WAIS-III/IV subtests (Wechsler, 1997, 2008). Premotor functions were evaluated with the Test Barcelona–Revised (Peña-Casanova, 2005), including graphical and gestural sequences and a bimanual coordination test. Handedness was assessed with the Edinburgh Handedness Inventory (Oldfield, 1971). Neuropsychological scores were interpreted using Spanish normative data from WAIS (Wechsler, 1997, 2008) and the NEURONORMA project (Casals-Coll et al., 2013; Peña-Casanova et al., 2009), with values below 1.5 SD (e.g., scalar $< 6$, percentile $< 5$, z $<$

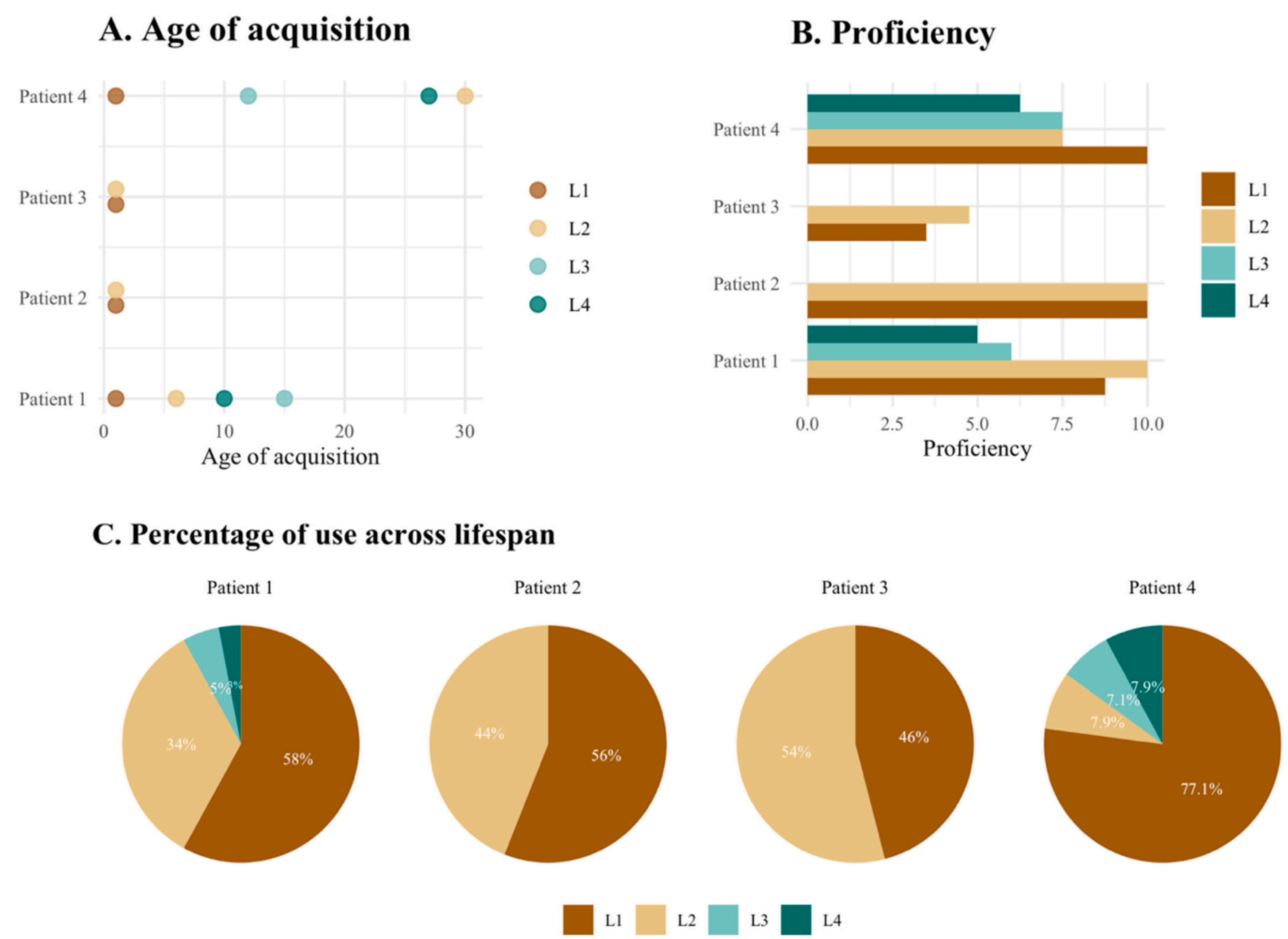


**Fig. 1.** Language profile from the Bilingual Language Profile questionnaire – adapted version. A: age of starting acquisition of each language; B: self-rated level of proficiency in each language; C: medium percentage of use of each language across lifespan considering different periods of life and different contexts (family, friends, etc.). Scores refer to the medium from the rating of proficiency in speaking, understanding, reading and writing each of the languages.

–1.5) considered pathological.

A verb generation task (see Havas et al., 2015; Sierpowska et al., 2015) was included in the neuropsychological assessment and administered in all languages selected for intraoperative testing. Patients heard 33 auditorily presented nouns and were instructed to produce a semantically related verb (e.g., *bed* → *sleep*). Items were selected to evoke prototypical actions and minimize response variability, which is particularly important for ensuring consistency between preoperative and intraoperative performance.

The task was originally developed in Catalan and Spanish, where noun–verb phonological overlap is common due to productive derivational morphology. To reduce this confound, the final lists minimized such overlap: in Catalan and Spanish, most items (22/33 and 24/33, respectively) shared no phonological stem with the target verb. Moreover, although some nouns and verbs showed clear phonological overlap, in several cases the stem required morphological modification before suffixation (e.g., *torradora* → *torrar*; 7/33 and 2/33 in Catalan and Spanish, respectively), rather than simply attaching a suffix to the full noun form (e.g., *escombra* → *escombrar*; 4/33 and 7/33 in Catalan and Spanish, respectively). This means that no systematic strategy of adding a verbal suffix to the noun form could be applied across items. The same items were then used across languages through translation, and such noun–verb phonological overlap was also minimal in the other languages (English: 28/33 items with no overlap; German: 24/33; Polish: 26/33).

This direct translation approach—a standard practice in our hospital—reduces differences in item familiarity, argument structure, and imageability, which are otherwise difficult to control across item sets. Although this approach may raise concerns about language-switching errors or translation-related hesitations, these were minimized by presenting auditory cues in the target language on every trial. Noteworthy, however, the use of the same items across languages inherently assumes morphosyntactic differences between them. For example, English, Polish, and German rely on less predictable derivational patterns compared to Catalan and Spanish. Reflexivity introduces additional complexity, particularly in Polish and Spanish, where reflexive forms are frequently obligatory. Polish requires reflexive clitics and aspectual distinctions that are not present in the source nouns. Moreover, both Polish and German exhibit greater morphological richness, including complex inflectional systems and variable verb stems. Another relevant cross-linguistic factor is the number of cognates—equivalent translations with phonological overlap in the expected verb responses. Cognates were markedly higher between Catalan and Spanish (19 items), but very few or absent in other relevant pairings (Catalan–English: 2; Catalan–Spanish: 1; Spanish–Polish: 1; English–German: 5; all other pairings: 0).

### 2.3. Functional magnetic resonance imaging (fMRI)

MR imaging was performed on a Philips Intera 1.5 T system before

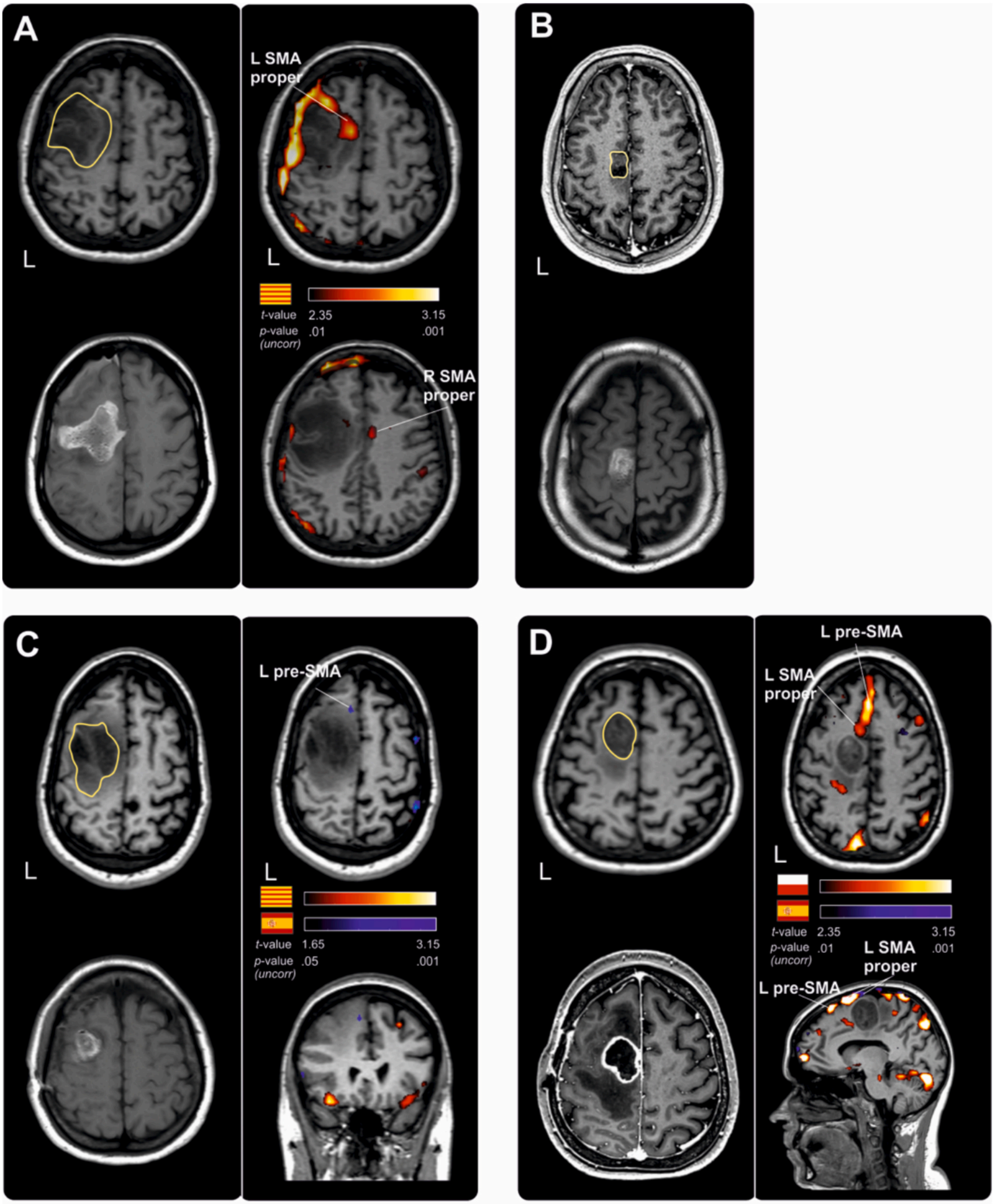


**Fig. 2.** Structural and functional magnetic resonance imaging results before the surgery. A, B, C and D refer to patient 1, 2, 3 and 4, respectively. For each patient, the left panel indicates lesion topography in T1 (top row) and FLAIR (upper row) acquisitions, delineating the tumoral tissue in yellow. The right panel illustrates functional magnetic resonance imaging results with a whole brain event-related analysis for the contrast Active vs Rest condition. Activations are reported at an uncorrected level of $p < 0.01$.

surgery to check language lateralization and localize the brain network associated with the patient's performance of the different cognitive and motor tasks. Due to time constraints in the clinical setting, fMRI was not systematically performed for all languages in every patient. When possible, priority was given to assessing the patient's L1, which is typically the most robustly represented and reliably activated language in the brain (as in Patient 1). In some cases, additional languages, such as L2, were also included (Patients 3 and 4). Notably, Patient 2 did not undergo preoperative fMRI due to these constraints. Functional images were acquired in the axial plane using a single-shot T2⁄-weighted gradient-echo EPI sequence (slice thickness = 3.5 mm; gap = 0.1 mm; number of slices = 35, repetition time (TR) = 3000 ms; echo time (TE) = 50 ms; flip angle = 90°; matrix = 64 × 64; field of view FOV = 230 mm; voxel size = 3.59 × 3.59 × 3.5 mm). In addition to the functional runs, a high-resolution T1-weighted image (slice thickness = 1 mm; number of slices = 160; repetition time (TR) = 8.4 ms; echo time (TE) = 3.9 ms; flip angle = 8°; matrix = 248 × 173; field of view FOV = 246 × 163 mm; voxel size = 1 × 1 × 1 mm) was also acquired.

The verb generation task used during fMRI was the same as in the neuropsychological assessment, but with a more extensive set of items. The fMRI employed a standard block design with alternating active and rest periods. Each of the seven active blocks lasted 30 s (with ten different verbs generated per block, using each noun only once), followed by 30 s of rest, resulting in a total run time of 7 min and 30 s (including an initial 30-second rest).

The fMRI analysis was performed using SPM12 (Friston et al., 2007; https://www.fil.ion.ucl.ac.uk/spm/) from the Wellcome Trust Centre for Neuroimaging, University College London, UK. Preprocessing included realignment, segmentation, normalization, and smoothing with an 8 mm Gaussian kernel. Unified Segmentation (Ashburner & Friston, 2005) with medium regularization and cost function masking (CFM) was applied (Andersen et al., 2010; Brett et al., 2001; Ripollés et al., 2012). Cost function masks were defined individually for each patient by applying a binary mask of the lesioned tissue using the MRIcron software package (Rorden & Brett, 2000). For first-level analysis, a general linear model was created contrasting Active and Rest conditions. Translational and rotational motion parameters extracted from realignment were included as regressors. Statistical parametric maps were generated after model estimation for the noun-based verb generation task comparing Active versus Rest blocks. Presurgical activations are reported at an uncorrected threshold of $p < 0.01$ with a minimum cluster extent of 20 voxels (see Fig. 2).

### 2.4. Electrical stimulation mapping (ESM)

ESM was performed following the methodology described by Ojemann (1979) (see also Fernández-Coello et al., 2017, for a detailed description). In the first stage, motor and sensory cortices were mapped at the cortical level using an Ojemann cortical stimulator under awake conditions. A stimulated site was considered specific to the motor or sensory cortex when stimulation elicited an involuntary motor response or a sensory disturbance reported by the patient.

Specific SMA language functions were then assessed using the same verb generation task employed in the neuropsychological assessment, which was customized to each patient's presurgical performance; only items correctly answered presurgically were used during surgery to ensure errors reflected stimulation effects rather than prior language difficulties. A cortical point was considered positive when speech disturbances occurred in at least two out of three stimulations. Responses were coded as follows: a verb correctly evoked immediately after the noun was classified as a "correct response"; a correct but delayed response was labeled "latency"; failure to produce a response was classified as "speech arrest"; and when a regular morpheme was applied to the noun stem resulting in a non-existent verb, it was classified as "overregularization" (e.g., the Spanish noun *gafas* ["glasses"] triggering the novel verb *gafear* instead of the correct verb *ver* ["to see"]; Sierpowska et al., 2015).

Positive points were labeled intraoperatively with sterile flags for each corresponding language area and numbered tags for the motor and sensory cortices, as well as for the SMA motor area (Fig. 3). The final stimulation map, including the location of each site, was determined from intraoperative photographs. To normalize this map, all information was transferred onto an arbitrary grid (Fig. 3). To evaluate the anatomical distribution of language-positive points, we conducted two-proportion z-tests: one comparing the observed proportions of positive points in the pre-SMA and SMA-proper, and another comparing the proportions of positive points for L1 and L2 within each region.

Languages were tested in order of dominance, starting with L1. This approach aimed to (i) ensure that critical language areas for the primary language were mapped before any potential interruption of the procedure and (ii) minimize inhibitory carryover effects known to occur when less dominant languages are tested first (Misra et al., 2012). Non-functional languages—L4 in Patient 1—were excluded from mapping. This decision was made collaboratively with the patient and applied to languages not actively used in personal or professional contexts. Patient responses were assessed in real time by trained professionals fluent in each tested language. For Catalan and Spanish—the main languages of most local patients—the hospital's senior clinical neuropsychologist administered and interpreted the tasks, both preoperatively and intraoperatively. For other languages, native speakers with formal ESM training (e.g., advanced neuroscience students or clinical neuropsychologists trained at our center) conducted the testing under the supervision of the senior neuropsychologist. When multiple foreign languages were needed for a given patient, different language-specific assessors were present during surgery to ensure accurate real-time interpretation.

## 3. Results

### 3.1. Neuropsychological assessment

Results from the presurgical neuropsychological assessment (Table 1) revealed impaired premotor functions—specifically in gesture sequencing—in most patients (3 out of 4), affecting both the dominant and non-dominant hands. Additionally, half of the patients (2 out of 4) showed pathological scores in fine motor skills and coordination.

One patient (1/4) showed impairment in working memory, and only Patient 3 exhibited deficits in processing speed. Most patients (3/4) had impaired scores in fine motor skills and coordination. In the language domain, the majority (3/4) showed deficits in semantic verbal fluency, with two patients (2/4) also impaired in phonological verbal fluency.

Regarding spontaneous expressive language, as assessed through the Cookie Theft picture description, Patients 1, 2, and 4 demonstrated fluent speech with appropriate content, adequate phrase length, grammatically correct structures, and no paraphasias. In contrast, Patient 3 showed reduced fluency, characterized by bradylalia and some latencies, though speech content remained appropriate.

### 3.2. Functional magnetic resonance imaging (fMRI)

The pre-surgical fMRI verb generation task was performed by all patients except Patient 2. In the remaining patients ($n = 3$), the contrast between active verb generation and rest revealed significant activation within the left SMA (see Fig. 2). Specifically, all three patients showed robust activation in the left pre-SMA (3/3), while activation in the SMA-proper was observed in only two of them (2/3)—one of whom exhibited only a small cluster with a tendency toward right lateralization.

Other regions activated during the L1 verb generation task included the left middle frontal gyrus (MFG; 3/3), middle cingulate cortex (3/3), bilateral insular cortex (2/3), and the precuneus (2/3). In contrast, L2 verb generation revealed a more limited activation pattern. In Patient 3, activation was restricted to the right precentral gyrus and inferior

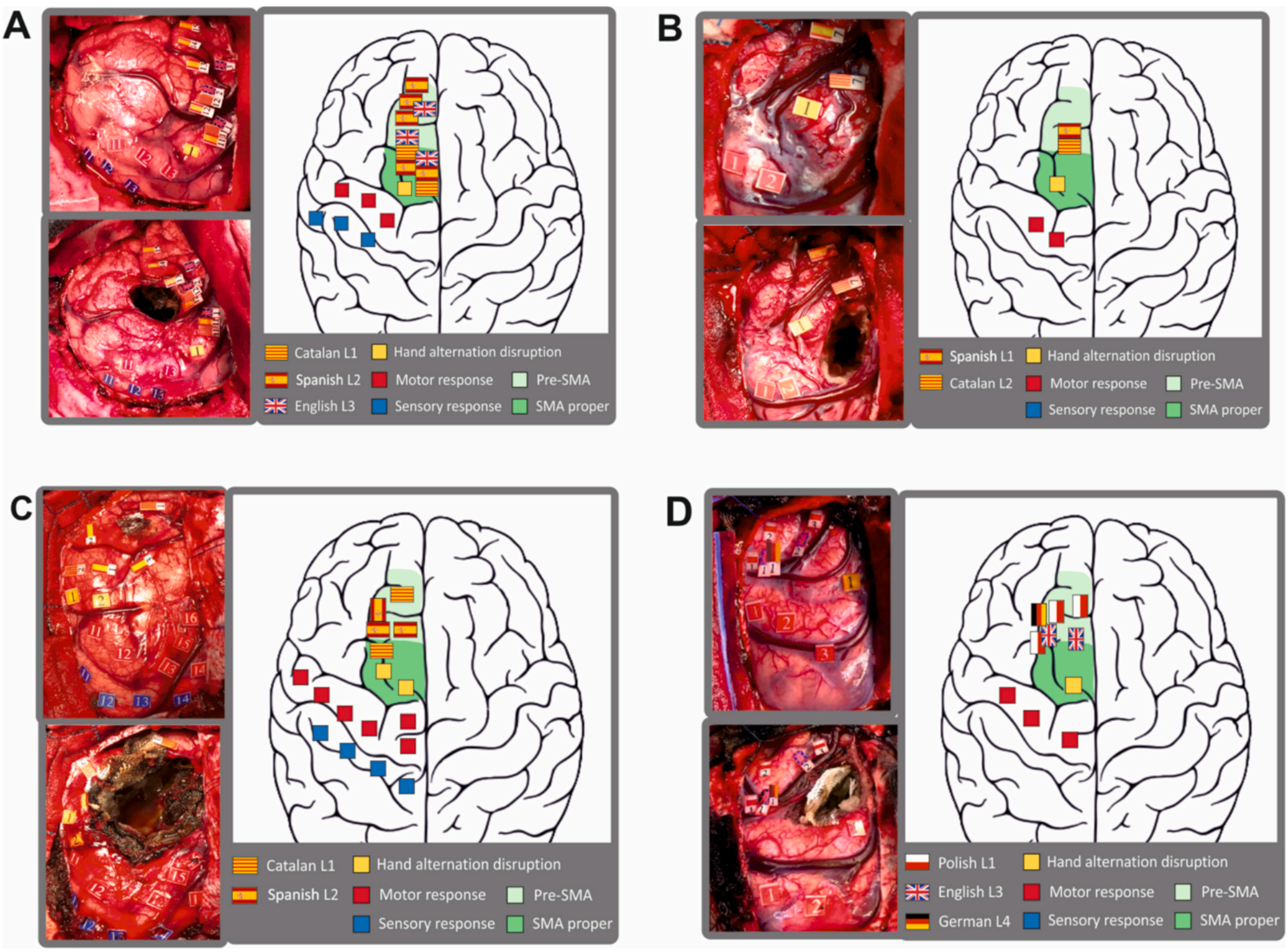


**Fig. 3.** ESM results. A, B, C and D refer to patient 1, 2, 3 and 4, respectively. For each patient, the left-upper panel indicates the ESM intraoperative photograph after the completion of the ESM results at the left SMA region and the left-bottom panel the intraoperative photograph showing the resection cavity at the end of the surgery. The right panel illustrates the cortical ESM results transferred to the anatomical grid to normalize the results.

parietal cortex. In Patient 4, activation was observed in the bilateral MFG, right inferior parietal cortex, and left precuneus.

### *3.3. Electrical stimulation mapping (ESM)*

Initially, ESM of the motor and sensory cortices identified positive points that elicited involuntary movements on the contralateral side and somatosensory sensations reported by the patient, respectively (see blue and red numbered tags in Fig. 3). Subsequently, the left SMA-proper regions were localized using the hand alternation paradigm (see yellow numbered tags in Fig. 3).

Regarding language, ESM using the verb generation task identified language-specific sites within the left SMA, encompassing both the SMA-proper and pre-SMA subregions (see Fig. 3 for detailed intraoperative results). Overall, 23 sites elicited positive language responses, characterized by stimulation-induced latencies or absence of response. A significantly higher proportion of these language sites was located in the pre-SMA (17/23) compared to the SMA-proper (6/23) ($\chi^2 = 8.69$, $p = 0.003$).

More specifically, L1 and L2 were similarly represented within the left SMA ($\chi^2 = 0$, $p = 1$), with 8 out of 23 and 9 out of 23 positive points, respectively. For L1, positive sites were found both in the pre-SMA and SMA-proper, with no significant difference between these regions ($\chi^2 = 0.43$, $p = 0.51$; 5/17 in pre-SMA and 3/6 in SMA-proper). Similarly, L2 mapping revealed functional sites in the left pre-SMA in three patients and in the SMA-proper in one patient, without significant differences in the number of positive points between areas ($\chi^2 < 0.001$, $p = 0.57$; 7/17 in pre-SMA and 2/6 in SMA-proper). Notably, only Patient 4 showed negative L2 verb generation mapping within the left SMA.

## 4. Discussion

This multimodal study combined fMRI and ESM to examine language representation within the SMA using a verb generation task. We aimed to localize potential language sites and explore language-specific patterns in bilingual and multilingual patients. Our findings clearly support the SMA's involvement in lexico-semantic processing and its sensitivity to multiple languages within individuals.

Although not traditionally included in core language models (e.g., Hickok & Poeppel, 2007), the SMA has been linked to language through SMA syndrome—often following left SMA resection—which may result in reduced spontaneous speech (Pinson et al., 2022). fMRI studies have also shown SMA activation during word selection, articulation (Alario et al., 2006), and lexico-semantic processing in verb and adjective generation (Blacker et al., 2006; Chung et al., 2005). Our own fMRI data showed consistent left SMA activation during verb generation across patients. ESM further confirmed this involvement: stimulation disrupted auditory verb generation performance, indicating the SMA's role in language. Verb generation is a dual process involving (1) activation and retrieval of semantic knowledge linking noun concepts and related

**Table 1**
Presurgical neuropsychological assessment results.

| *Days between neuropsychological assessment and surgery* | Case 1 *1d* | Case 2 *47d* | Case 3 *4d* | Case 4 *3d* |
|---|---|---|---|---|
| ATTENTION AND WORKING MEMORY | | | | |
| **Digits (/30)** | 12 (SS 11) | SS 8 | 7 (**SS 4**) | 13 (SS 9) |
| *Forward span (/9) / Backward span (/8)* | 6/3 | 5/4 | 4/2 | 6/4 |
| **Letter-number sequencing (/21)** | 5 (SS 9) | (SS 12) | 2 (**SS 2**) | 9 (SS 10) |
| *Total span (/8)* | 3 | 4 | 2 | 3 |
| **Arithmetic (/22)** | 7 (SS 7) | 9 (SS 7) | 7 (SS 6) | 11 (SS 10) |
| **Working memory IQ** | 86 (Pc 18) | 92 (Pc 30) | 63 (**Pc 0.7**) | 96 (Pc 40) |
| LANGUAGE | | | | |
| **Verb generation (/33) – L1** | 32 | 28 | 33 | 30 |
| **Verb generation (/33) – L2** | 32 | 33 | 33 | 32 |
| **Verb generation (/33) – L3** | 18 | | | 28 |
| **Verb generation (/33) – L4** | 21 | | | 30 |
| **Semantic verbal fluency** | 11(**SS 3**) | 14 (**SS 4**) | 10 (**SS 2**) | 20 (SS 9) |
| **Phonological verbal fluency** | 3 (**SS 1**) | 14 (SS 9) | 2 (**SS 2**) | 11 (SS 7) |
| PROCESSING SPEED | | | | |
| **Coding (/133)** | 36 (SS 10) | 72 (SS 9) | 16 (**SS 1**) | 74 (SS 11) |
| **Symbol search (/60)** | 13 (SS 8) | 34 (SS 10) | 10 (**SS 2**) | 32 (SS 11) |
| PREMOTOR FUNCTION | | | | |
| **Posture sequencing – right hand (/8)** | 5 (**Pc < 5**) | 8 (Pc 95) | 2 (**Pc < 5**) | 6 (Pc 5) |
| Alternate tapping (/2) | 1 | 2 | 0 | 2 |
| Palm-fist-side sequence (/2) | 0 | 2 | 0 | 0 |
| Peak-and-valley pattern (/2) | 2 | 2 | 2 | 2 |
| Serial curl model (/2) | 2 | 2 | 0 | 2 |
| **Posture sequencing – left hand (/8)** | 5 (**Pc < 5**) | 8 (Pc 95) | 3 (**Pc < 5**) | 6 (Pc 5) |
| Alternate tapping (/2) | 0 | 2 | 1 | 2 |
| Palm-fist-side sequence (/2) | 1 | 2 | 0 | 0 |
| Peak-and-valley pattern (/2) | 2 | 2 | 2 | 2 |
| Serial curl model (/2) | 2 | 2 | 0 | 2 |
| **Reciprocal coordination (/4)** | 3 (Pc 30) | 4 (Pc 95) | 0 (**Pc < 5**) | 0 (**Pc < 5**) |
| FINE MOTOR SKILLS AND COORDINATION | | | | |
| **Purdue Pegboard Test** | | | | |
| Right hand (/25) | 13 (**z = −1**) | 15 (**z = −0.2**) | 10 (**z = −3.7**) | 11 (**z = −3**) |
| Left hand (/25) | 12 (**z = 1.3**) | 15 (**z = −0.06**) | 14 (**z = −0.86**) | 8 (**z = −4**) |
| Bimanual (/25) | 10 (**z = −0.6**) | 12 (**z = −0.25**) | 0 (**z = −10**) | 8 (**z = −3.9**) |
| Assembly (/100) | – | 27 (**z = −2.88**) | 26 (**z = −2.69**) | 22 (**z = −3.3**) |

Numbers indicate raw scores followed by the normative score between parentheses. SS: scalar score; Pc: percentile; z = z score. Pathological (below-norm) scores are indicated in bold.

attributes, and (2) optimal selection among competing alternatives (Martin & Byrne, 2006; Thompson-Schill et al., 1998). Importantly, these processes are not unique to verbs and similarly occur in noun-generation tasks requiring lexico-semantic retrieval. As noted in the Introduction, our choice of a verb generation task was not based on an assumption of verb-specific processing in the SMA, but on prior research suggesting that verb production may better identify language-eloquent sites within this region—future studies could directly compare verb and noun generation tasks during ESM to clarify whether verb production identifies more lexico-semantic sites than noun production within the SMA, as reported in other frontal regions (e.g., Havas et al., 2015). Lexico-semantic processing, a core feature of single-word production, involves retrieving the correct lexical representation among competing alternatives (Dell et al., 1997; Levelt, 1989). Taken together with our results, this supports the hypothesis that the SMA participates in language processing, particularly lexical selection. This linguistic role is often attributed to the anterior SMA (pre-SMA), which is involved in lexical disambiguation, context-tracking, monitoring, and inhibition of erroneous language representations (Hertrich et al., 2016). In simple terms, the pre-SMA is more language-related, while the SMA proper is more involved in speech production.

This involvement of the SMA in lexical competition and decision-making processes is further supported by its established role in bilingual language control. Bilingual language control refers to the ability to manage and select the appropriate language based on the communicative context (Calabria et al., 2018). In this regard, Luk et al. (2011) identified a consistent network involved in bilingual language control that includes the dorsolateral prefrontal cortex, the basal ganglia, and the SMA—specifically the pre-SMA. Supporting this, Rodriguez-Fornellset al. (2005) reported significant SMA activation during a language-switching task, highlighting its involvement in interlinguistic competition and selection. Furthermore, the role of the SMA in lexical competition and disambiguation has been demonstrated in word learning tasks, where participants selected among competing lexical candidates to infer the meaning of novel words (Mestres-Missé et al., 2008). Thus, the SMA's involvement in lexical decision-making, as suggested by our findings, may be shaped by the multilingual backgrounds of our patients, engaging language control processes during verb generation.

Building on this, it is worth noting that language-specific frequency effects could potentially influence lexical retrieval. However, in our cohort, where Spanish and Catalan are the dominant languages for most participants and are co-official in Catalonia, both languages are used extensively across all domains of daily life (educational, professional, social, and recreational). Participants typically display near-native proficiency in both, even if one language is slightly more dominant. As a result, frequency-related confounds are likely minimized, at least for these two languages. Additionally, the verb generation task was based on prototypical actions, reducing the likelihood of substantial frequency variation across languages, whether more or less dominant, as such differences are more typical of domain-specific vocabulary. Still, subtle effects of language control arising from cross-linguistic item frequency variations cannot be entirely ruled out, highlighting the need for better item control in this regard in future studies. This concern further raises the possibility that the SMA's role in multilingual language control may also extend to within-language control, including in monolingual contexts. In this context, it would be particularly interesting to test whether SMA engagement increases when response selection is more competitive—especially considering that lexical selection under competition has been strongly associated with the inferior frontal gyrus (IFG) (Thompson-Schill, et al. 1997), a region structurally connected to the SMA via the frontal aslant tract (FAT). Importantly, Salillas et al. (2024) recently showed that the verb generation task is particularly well suited to examining lexical selection demands. Using neuroimaging, they parametrically modulated selection load by manipulating the number and strength of competing lexical candidates across items and showed that activity in the IFG scaled accordingly. This not only confirms the task's sensitivity to lexical competition demands but also provides a framework to systematically tailor the task in this respect in future ESM studies targeting the SMA.

Consistent with the distinctive selection demands attributed to the IFG, Thompson-Schill et al. (1998) demonstrated that lesions in the IFG led to errors during a verb generation task, particularly for items with high selection demands. The SMA is directly connected to this region via the frontal aslant tract (FAT) (Vergani et al., 2014), and lesions in this tract have been linked to poor performance in verb generation tasks, affecting morphological derivation and lexical retrieval (Sierpowska et al., 2015). Additionally, Fontaine et al. (2002) showed that language representation within the SMA occurs at the boundary between pre-SMA and SMA proper, corresponding to the cortical termination of the FAT. Furthermore, the role of the FAT in language has been highlighted by correlations between its integrity and verbal fluency performance in patients with primary progressive aphasia (Catani et al., 2013). Thus, both the SMA and its white matter connectivity contribute to lexico-semantic retrieval and selection processes.

From an anatomical perspective, the SMA has been subdivided into two regions: the caudal part (SMA-proper) and the rostral part (pre-SMA) (Tanji, 1994). Generally, the pre-SMA's role in language and speech processing has been characterized as supporting "domain-general processing," involving cognitive functions not directly related to articulation, such as "lexical disambiguation, context-tracking, monitoring, or inhibition of erroneous language representations" (Hertrich et al., 2016). In this context, Bathla et al. (2019) evaluated resting-state functional connectivity of the SMA in patients with brain tumors and found lower connectivity between the pre-SMA and motor areas compared to the SMA-proper. Additionally, evidence suggests stronger connectivity between perisylvian language areas (e.g., Broca's area) and the pre-SMA than with the SMA-proper (Jenabi et al., 2014). Taken together, the pre-SMA may be considered language-related, whereas the SMA-proper is more speech-related (Ardila, 2020). Applying this parcellation to our ESM results, a higher proportion of language sites were found in the pre-SMA, confirming its greater language specialization. Moreover, visual inspection of our ESM results (see Fig. 3) showed no motor sites in the pre-SMA, whereas motor sites were present in the SMA-proper, emphasizing a stronger motor component in SMA-proper and a greater language role in pre-SMA. Our findings align with Alario et al. (2006), who highlight the specific involvement of the pre-SMA in lexical selection. Overall, lexico-semantic retrieval and selection processes can be attributed to the SMA, but more prominently to the pre-SMA.

Importantly, our sample includes both bilingual and multilingual participants, providing a unique opportunity to examine how linguistic profiles influence language-related functions in the SMA. The number of languages acquired is known to affect language localization in the brain. For example, bilinguals may have overlapping but also distinct cortical sites for each language within perisylvian areas (Lucas et al., 2004; Roux & Trémoulet, 2002). Similarly, in multilinguals, second and subsequent languages tend to be more widely distributed, potentially extending beyond classic perisylvian regions (Bello et al., 2006). Moreover, it is not only the number of languages but also factors such as age of acquisition and exposure level that shape the cortical organization of language (Fernández-Coello et al., 2017). In our study, however, we found no significant differences in the cortical localization of L1 versus L2 within the left SMA or its subregions (SMA-proper and pre-SMA).

Interestingly, only Patient 4′s L2 (Spanish) showed a negative response during verb generation mapping within the left SMA, suggesting that this site was not eloquent for that language. Importantly, this cannot be attributed to reduced use: despite Polish being her L1, she reported using it only sporadically, whereas Spanish (her dominant L2) is employed extensively in daily life. The absence of a positive mapping site for this language may instead reflect the influence of AoA, as Spanish was the latest acquired (at age 30). Patient 4′s distribution of eloquent sites followed a clear gradient with increasing AoA—three sites for L1 (Polish), two for L3 (English, adolescence), one for L4 (German, adulthood), and none for L2 (Spanish)—which may indicate that later-acquired languages are integrated into the network differently than earlier ones. By contrast, Patient 1—who also spoke a late-acquired language—did not show this gradient, suggesting that in her case the SMA may not have been AoA-sensitive. This variability is consistent with Fernández-Coelloet al. (2017), who reported that AoA is a powerful factor but that its expression differs across patients: some sites were sensitive to early-acquired languages, others to late-acquired ones, and others to both. Because their classification relied on a categorical cut-off at 6 years, without more precise information on the timing of late acquisitions, their data could not reveal a gradient pattern like the one observed in Patient 4. Alternatively, Patient 4′s SMA may reflect a specific manifestation of the AoA effect, expressed as a graded presence/absence of sites across her languages rather than a simple early–late site distinction. Although tentative, this interpretation underscores the need to further investigate AoA as a key factor in multilingual brain organization and how it interacts with sociolinguistic (e.g., exposure, context of use) and linguistic (e.g., typological similarity) variables.

Importantly, we acknowledge several limitations that warrant caution in interpreting our results and highlight directions for future research. Some caveats relate to the cognitive mechanisms underlying SMA involvement in multilingual language processing. For example, our data do not allow firm conclusions about whether the language-specific SMA sites observed reflect true language identity or language-specific morphosyntactic demands. This distinction is crucial: certain sites may preferentially respond to particular morphosyntactic operations common in one language (e.g., reflexivity, derivational morphology) rather than to the "language" per se. Nonetheless, even in such cases, these sites should be considered eloquent and preserved to avoid selective multilingual aphasia. While the issue remains subject to debate (see Rofes & Miceli, 2014, for recommendations on cross-language stimulus matching in ESM using sentence-level materials), it is worth noting that equating morphosyntactic demands across languages may be infeasible—not necessarily due to differences in difficulty, but because the underlying processes often differ qualitatively across languages. Along similar lines, it is unclear how the number of cognates between each patient's pair of languages, as well as the varying number of cognates across different language combinations, may affect the language map. Psycholinguistic research shows that cognates facilitate lexical access in language production—a "cognate effect"—which particularly benefits the less dominant language (e.g., Costa et al., 2000). How this facilitatory effect interacts with site identification remains difficult to determine. Admittedly, these cross-linguistic differences may be somewhat exacerbated by the direct translation approach we used. Nevertheless, they also reflect inherent typological properties of the languages, and differences in morphosyntax and cognate status constitute important issues to address in future research.

Another important caveat concerns the heterogeneity and size of our sample. The small sample size and diversity of multilingual profiles constrain the generalizability of our findings. While language-specific activation patterns within the SMA are suggested, we cannot determine whether they are driven by age of acquisition, current proficiency, frequency of use, or combinations thereof. For instance, a factor classically associated with nativeness, such as proficiency, may modulate SMA's preferential responsiveness to different languages, similarly to the age-of-acquisition effects reported by Fernández-Coello et al. (2017) in perisylvian regions. Larger cohorts with systematically controlled linguistic variables—ideally isolating one factor at a time—are necessary to clarify which aspects of multilingualism most strongly influence SMA involvement. A further consideration is the use of a relatively simple verb generation task, which limits our ability to identify which specific lexico-semantic operations drive SMA engagement. Finally, patients presented with different types of brain lesions, potentially associated with distinct neuroplasticity patterns, which may have variably impacted the results. In addition, the SMA's role in bilingual and multilingual language control (e.g., Abutalebi & Green, 2007; Hervais-Adelman et al., 2011) represents another factor that may contribute to observed activation patterns. Future studies should aim to isolate the contributions of control processes alongside linguistic variables such as AoA, proficiency, and frequency of use, particularly in regions where language representation and control may converge.

Finally, a more conceptual caveat—applicable not only to our study but to the broader field of SMA research—concerns the functional specificity of this region. Cona and Semenza (2017) reviewed evidence implicating the SMA in a wide range of high-level cognitive functions, including language, music, motor control, numerical cognition, and writing. Given this functional diversity, they argue that the SMA is unlikely to subserve domain-specific mechanisms. Instead, they propose that the SMA's core role lies in domain-general sequential processing—that is, managing the hierarchical and temporal structure of complex, goal-directed behaviors. From this perspective, an important future direction for language research in the SMA will be to determine whether regions labeled as "language-specific" are truly exclusive to language, or whether they also participate in non-linguistic tasks that share similar demands for sequencing and control.

Despite these acknowledged limitations, our findings support the relevance of multilingual testing within the SMA. The verb generation task, which is easy to implement intraoperatively and avoids confounds such as visual complexity (unlike picture naming), offers a practical mapping tool. It also allows for the inclusion of blocks manipulating lexical demands or association strength (e.g., Salillas et al., 2024), making it suitable for investigating SMA involvement in lexical selection, even in monolinguals.

## 5. Conclusions

The present study specifically addresses the involvement of the SMA in language processing. Using a verb generation task, we demonstrated that the SMA—particularly the pre-SMA—contains language-specific sites in multilingual patients. Although the exact role of language experience in shaping these sites remains unclear, our findings support the use of multilingual language testing in SMA mapping.

## 6. Data statement

In line with Bellvitge University Hospital's Clinical Research Ethics Committee guidelines, patient data cannot be publicly shared. Access is restricted and granted only upon request following committee review to ensure ethical and legal compliance.

## Funding sources

This work was supported by the Spanish Ministry of Science, Innovation, and Universities (RYC-2016-19477 and PGC2018-094891-A-100 to M.H. and predoctoral FPI grant BES-2016-078889 awarded to A.G-A). ARF has been suported by the FIAS fellowship Program, co-funded by the European Commission, Marie-Skłodowska-Curie Actions – COFUND Program, Grant n°945408.

## CRediT authorship contribution statement

**Mireia Hernández:** Writing – original draft, Resources, Formal analysis, Conceptualization. **Anna Gasa-Roqué:** Writing – original draft, Software, Formal analysis. **Alba Gómez-Andres:** Writing – original draft, Software, Formal analysis. **Ruth Lau:** Writing – original draft, Methodology. **Inmaculada Rico:** Investigation. **Montserrat Juncadella:** Investigation. **Àngels Camins:** Methodology, Investigation. **Antoni Rodríguez-Fornells:** Supervision, Conceptualization. **Andreu Gabarrós:** Supervision, Resources, Methodology, Investigation, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The data that has been used is confidential.

## References


Abutalebi, J., & Green, D. (2007). Bilingual language production: The neurocognition of language representation and control. *Journal of neurolinguistics, 20*(3), 242–275.

Ardila, A. (2020). Supplementary motor area aphasia revisited. *Journal of Neurolinguistics, 54*.

Alario, F. X., Chainay, H., Lehericy, S., & Cohen, L. (2006). The role of the supplementary motor area (SMA) in word production. *Brain Research, 1076*(1), 129–143. https://doi.org/10.1016/j.brainres.2005.11.104

Andersen, S. M., Rapcsak, S. Z., & Beeson, P. M. (2010). Cost function masking during normalization of brains with focal lesions: Still a necessity? *NeuroImage, 53*(1), 78–84. https://doi.org/10.1016/j.neuroimage.2010.06.003

Artiola, L., Hermosillo, D., Heaton, R., Pardee, R. E. (1999) Manual de normas y procedimientos para la batería neuropsicológica en español [Manual of norms and procedures for the Spanish neuropsychological battery] Tucson, AZ: M Press.

Ashburner, J., & Friston, K. J. (2005). Unified segmentation. *NeuroImage, 26*(3), 839–851. https://doi.org/10.1016/j.neuroimage.2005.02.018

Bello, L., Acerbi, F., Giussani, C., Baratta, P., Taccone, P., Songa, V., Fava, M., Stocchetti, N., Papagno, C., & Gaini, S. M. (2006). Intraoperative language localization in multilingual patients with gliomas. *Neurosurgery, 59*(1), 115–125. https://doi.org/10.1227/01.NEU.0000219241.92246.FB

Birdsong, D., Gertken, L.M., & Amengual, M. *Bilingual Language Profile: An Easy-to-Use Instrument to Assess Bilingualism.* COERLL, University of Texas at Austin. https://sites.la.utexas.edu/bilingual/>.

Blacker, D., Byrnes, M. L., Mastaglia, F. L., & Thickbroom, G. W. (2006). Differential activation of frontal lobe areas by lexical and semantic language tasks: a functional magnetic resonance imaging study. *Journal of Clinical Neuroscience: Official Journal of the Neurosurgical Society of Australasia, 13*(1), 91–95. https://doi.org/10.1016/j.jocn.2005.02.009

Bathla, G., Gene, M. N., Peck, K. K., Jenabi, M., Tabar, V., & Holodny, A. I. (2019). Resting state functional connectivity of the supplementary motor area to motor and language networks in patients with brain tumors. *Journal of Neuroimaging: Official Journal of the American Society of Neuroimaging, 29*(4), 521–526. https://doi.org/10.1111/jon.12624

Bleasel, A., Comair, Y., & Lüders, H. O. (1996). Surgical ablations of the mesial frontal lobe in humans. *Advances in Neurology, 70*, 217–235.

Brett, M., Leff, A. P., Rorden, C., & Ashburner, J. (2001). Spatial normalization of brain images with focal lesions using cost function masking. *NeuroImage, 14*(2), 486–500. https://doi.org/10.1006/nimg.2001.0845

Calabria, M., Costa, A., Green, D. W., & Abutalebi, J. (2018). Neural basis of bilingual language control. Annals of the New York Academy of Sciences, 10.1111/nyas.13879. Advance online publication. Doi: 10.1111/nyas.13879.

Cargnelutti, E., Tomasino, B., & Fabbro, F. (2019). Language brain representation in bilinguals with different age of appropriation and proficiency of the second language: A meta-Analysis of functional imaging studies. *Frontiers in Human Neuroscience, 13*, 154. https://doi.org/10.3389/fnhum.2019.00154

Catani, M., Mesulam, M. M., Jakobsen, E., Malik, F., Martersteck, A., Wieneke, C., Thompson, C. K., Thiebaut de Schotten, M., Dell'Acqua, F., Weintraub, S., & Rogalski, E. (2013). A novel frontal pathway underlies verbal fluency in primary progressive aphasia. *Brain: A Journal of Neurology, 136*(Pt 8), 2619–2628. https://doi.org/10.1093/brain/awt163

Casals-Coll, M., Sánchez-Benavides, G., Quintana, M., Manero, R. M., Rognoni, T., Calvo, L., Palomo, R., Aranciva, F., Tamayo, F., & Peña-Casanova, J. (2013). Spanish normative studies in young adults (NEURONORMA young adults project): norms for verbal fluency tests. *Neurologia (Barcelona, Spain), 28*(1), 33–40. https://doi.org/10.1016/j.nrl.2012.02.010

Chan, H. M., Loh, W. N., Yeo, T. T., & Teo, K. (2019). Awake craniotomy and excision of a diffuse low-grade glioma in a multilingual patient: Neuropsychology and language. *World neurosurgery, 128*, 91–97.

Chauvel, P. Y., Rey, M., Buser, P., & Bancaud, J. (1996). What stimulation of the supplementary motor area in humans tells about its functional organization. *Advances in Neurology, 70*, 199–209.

Chung, G. H., Han, Y. M., Jeong, S. H., & Jack, C. R., Jr (2005). Functional heterogeneity of the supplementary motor area. *AJNR. American Journal of Neuroradiology, 26*(7), 1819–1823.

Cona, G., & Semenza, C. (2017). Supplementary motor area as key structure for domain-general sequence processing: A unified account. *Neuroscience and biobehavioral reviews, 72*, 28–42. https://doi.org/10.1016/j.neubiorev.2016.10.033

Costa, A., Caramazza, A., & Sebastian-Galles, N. (2000). The cognate facilitation effect: implications for models of lexical access. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 26*(5), 1283–1296. https://doi.org/10.1037//0278-7393.26.5.1283

Dell, G. S., Schwartz, M. F., Martin, N., Saffran, E. M., & Gagnon, D. A. (1997). Lexical access in aphasic and nonaphasic speakers. *Psychological Review, 104*(4), 801–838. https://doi.org/10.1037/0033-295x.104.4.801

Duffau, H., Lopes, M., Denvil, D., & Capelle, L. (2002). Delayed onset of the supplementary motor area syndrome after surgical resection of the mesial frontal lobe: a time course study using intraoperative mapping in an awake patient. *Stereotactic and Functional Neurosurgery, 76*(2), 74–82. https://doi.org/10.1159/000056496

Garcea, F. E., & Mahon, B. Z. (2012). What is in a tool concept? Dissociating manipulation knowledge from function knowledge. *Memory & Cognition, 40*(8), 1303–1313. https://doi.org/10.3758/s13421-012-0236-y

Fernández-Coello, A., Havas, V., Juncadella, M., Sierpowska, J., Rodríguez-Fornells, A., & Gabarrós, A. (2017). Age of language acquisition and cortical language organization in multilingual patients undergoing awake brain mapping. *Journal of Neurosurgery, 126*(6), 1912–1923. https://doi.org/10.3171/2016.5.JNS152791

Fontaine, D., Capelle, L., & Duffau, H. (2002). Somatotopy of the supplementary motor area: evidence from correlation of the extent of surgical resection with the clinical patterns of deficit. *Neurosurgery, 50*(2), 297–305. https://doi.org/10.1097/00006123-200202000-00011

Freedman, M., Alexander, M. P., & Naeser, M. A. (1984). Anatomic basis of transcortical motor aphasia. *Neurology, 34*(4), 409–417. https://doi.org/10.1212/wnl.34.4.409

Friston, K., Ashburner, J., Kiebel, S., Nichols, T., & Penny, W. (2007). *Statistical Parametric Mapping. The Analysis of Functional Brain Images* (1st ed.). London, UK: Academic Press.

Giussani, C., Roux, F. E., Lubrano, V., Gaini, S. M., & Bello, L. (2007). Review of language organisation in bilingual patients: what can we learn from direct brain mapping? *Acta Neurochirurgica, 149*(11), 1109–1116. https://doi.org/10.1007/s00701-007-1266-2

Grèzes, J., & Decety, J. (2001). Functional anatomy of execution, mental simulation, observation, and verb generation of actions: a meta-analysis. *Human Brain Mapping, 12*(1), 1–19. Doi: 10.1002/1097-0193(200101)12:1<1::aid-hbm10>3.0.co;2-v.

Havas, V., Gabarrós, A., Juncadella, M., Rifa-Ros, X., Plans, G., Acebes, J. J., de Diego Balaguer, R., & Rodríguez-Fornells, A. (2015). Electrical stimulation mapping of nouns and verbs in Broca's area. *Brain and Language, 145–146*, 53–63. https://doi.org/10.1016/j.bandl.2015.04.005

Hernández, M., Fairhall, S. L., Lenci, A., Baroni, M., & Caramazza, A. (2014). Predication drives verb cortical signatures. *Journal of Cognitive Neuroscience, 26*(8), 1829–1839. https://doi.org/10.1162/jocn_a_00598

Hertrich, I., Dietrich, S., & Ackermann, H. (2016). The role of the supplementary motor area for speech and language processing. *Neuroscience and Biobehavioral Reviews, 68*, 602–610. https://doi.org/10.1016/j.neubiorev.2016.06.030

Hervais-Adelman, A. G., Moser-Mercer, B., & Golestani, N. (2011). Executive control of language in the bilingual brain: integrating the evidence from neuroimaging to neuropsychology. *Frontiers in psychology, 2*, 234. https://doi.org/10.3389/fpsyg.2011.00234

Hickok, G., & Poeppel, D. (2007). The cortical organization of speech processing. Nature reviews. *Neuroscience, 8*(5), 393–402. https://doi.org/10.1038/nrn2113

Jenabi, M., Peck, K. K., Young, R. J., Brennan, N., & Holodny, A. I. (2014). Probabilistic fiber tracking of the language and motor white matter pathways of the supplementary motor area (SMA) in patients with brain tumors. *Journal of neuroradiology, 41*(5), 342–349. https://doi.org/10.1016/j.neurad.2013.12.001

Kaplan, E., Goodglass, H., & Weintraub, S. (2001). *Boston naming test*. Philadelphia, USA: Lea and Febiger.

Krainik, A., Lehéricy, S., Duffau, H., Capelle, L., Chainay, H., Cornu, P., Cohen, L., Boch, A. L., Mangin, J. F., Le Bihan, D., & Marsault, C. (2003). Postoperative speech disorder after medial frontal surgery: Role of the supplementary motor area. *Neurology, 60*(4), 587–594. https://doi.org/10.1212/01.wnl.0000048206.07837.59

Laplane, D., Talairach, J., Meininger, V., Bancaud, J., & Orgogozo, J. M. (1977). Clinical consequences of corticectomies involving the supplementary motor area in man. *Journal of the Neurological Sciences, 34*(3), 301–314. https://doi.org/10.1016/0022-510x(77)90148-4

Lau, H. C., Rogers, R. D., Haggard, P., & Passingham, R. E. (2004). Attention to intention. *Science (New York, N.Y.), 303*(5661), 1208–1210. https://doi.org/10.1126/science.1090973

Levelt, W. J. M. (1989). *Speaking: From intention to articulation*. The MIT Press.

Lu, J., Zhao, Z., Zhang, J., Wu, B., Zhu, Y., Chang, E. F., Wu, J., Duffau, H., & Berger, M. S. (2021). Functional maps of direct electrical stimulation-induced speech arrest and anomia: A multicentre retrospective study. *Brain: A Journal of Neurology, 144*(8), 2541–2553. https://doi.org/10.1093/brain/awab125

Lubrano, V., Prod'homme, K., Démonet, J. F., & Köpke, B. (2012). Language monitoring in multilingual patients undergoing awake craniotomy: A case study of a German–English–French trilingual patient with a WHO grade II glioma. *Journal of Neurolinguistics, 25*(6), 567–578. https://doi.org/10.1016/j.jneuroling.2011.08.002

Lucas, T. H., 2nd, McKhann, G. M., 2nd, & Ojemann, G. A. (2004). Functional separation of languages in the bilingual brain: a comparison of electrical stimulation language mapping in 25 bilingual patients and 117 monolingual control patients. *Journal of Neurosurgery, 101*(3), 449–457. https://doi.org/10.3171/jns.2004.101.3.0449

Luk, G., Green, D. W., Abutalebi, J., & Grady, C. (2011). Cognitive control for language switching in bilinguals: A quantitative meta-analysis of functional neuroimaging studies. Language and Cognitive Processes, 27(10), 1479–1488. Doi: 10.1080/01690965.2011.613209.

Martin, R. C., & Byrne, M. D. (2006). Why opening a door is as easy as eating an apple: A reply to Thompson-Schill and Botvinick (2006). *Psychonomic Bulletin & Review, 13*, 409–411. https://doi.org/10.3758/BF03193861

Martín-Monzón, I., Rivero Ballagas, Y., & Arias-Sánchez, S. (2022). Language mapping: A systematic review of protocols that evaluate linguistic functions in awake surgery. *Applied Neuropsychology. Adult, 29*(4), 845–854. https://doi.org/10.1080/23279095.2020.1776287

Mestres-Missé, A., Càmara, E., Rodriguez-Fornells, A., Rotte, M., & Münte, T. F. (2008). Functional neuroanatomy of meaning acquisition from context. *Journal of Cognitive Neuroscience, 20*(12), 2153–2166. https://doi.org/10.1162/jocn.2008.20150

Misra, M., Guo, T., Bobb, S. C., & Kroll, J. F. (2012). When bilinguals choose a single word to speak: Electrophysiological evidence for inhibition of the native language. *Journal of Memory and Language, 67*(1). https://doi.org/10.1016/j.jml.2012.05.001

Nelson, L., Lapsiwala, S., Haughton, V. M., Noyes, J., Sadrzadeh, A. H., Moritz, C. H., Meyerand, M. E., & Badie, B. (2002). Preoperative mapping of the supplementary motor area in patients harboring tumors in the medial frontal lobe. *Journal of Neurosurgery, 97*(5), 1108–1114. https://doi.org/10.3171/jns.2002.97.5.1108

Oldfield, R. C. (1971). The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia, 9*(1), 97–113. https://doi.org/10.1016/0028-3932(71)90067-4

Ojemann, G. A. (1979). Individual variability in cortical localization of language. *Journal of Neurosurgery, 50*(2), 164–169. https://doi.org/10.3171/jns.1979.50.2.0164

Pai, M. C. (1999). Supplementary motor area aphasia: a case report. *Clinical Neurology and Neurosurgery, 101*(1), 29–32. https://doi.org/10.1016/s0303-8467(98)00068-7

Paradis, M. (1990). Language lateralization in bilinguals: Enough already! *Brain and Language, 39*(4), 576–586. https://doi.org/10.1016/0093-934x(90)90163-b

Pavlova, A. A., Butorina, A. V., Nikolaeva, A. Y., Prokofyev, A. O., Ulanov, M. A., Bondarev, D. P., & Stroganova, T. A. (2019). Effortful verb retrieval from semantic memory drives beta suppression in mesial frontal regions involved in action initiation. *Human Brain Mapping, 40*(12), 3669–3681. https://doi.org/10.1002/hbm.24624

Peña-Casanova, J. (2005). *Test Barcelona Revisado [revised Barcelona Test]*. Barcelona: Masson.

Peña-Casanova, J., Quiñones-Ubeda, S., Gramunt-Fombuena, N., Quintana-Aparicio, M., Aguilar, M., Badenes, D., Cerulla, N., Molinuevo, J. L., Ruiz, E., Robles, A., Barquero, M. S., Antúnez, C., Martínez-Parra, C., Frank-García, A., Fernández, M., Alfonso, V., Sol, J. M., Blesa, R., & NEURONORMA Study Team. (2009). Spanish Multicenter Normative Studies (NEURONORMA Project): norms for verbal fluency tests. *Archives of Clinical Neuropsychology: The Official Journal of the National Academy of Neuropsychologists, 24*(4), 395–411. https://doi.org/10.1093/arclin/acp042

Picard, N., & Strick, P. L. (2001). Imaging the premotor areas. *Current Opinion in Neurobiology, 11*(6), 663–672. https://doi.org/10.1016/s0959-4388(01)00266-5

Pinson, H., Van Lerbeirghe, J., Vanhauwaert, D., Van Damme, O., Hallaert, G., & Kalala, J. P. (2022). The supplementary motor area syndrome: A neurosurgical review. *Neurosurgical Review, 45*(1), 81–90. https://doi.org/10.1007/s10143-021-01566-6

Redford, M. A., & Oh, G. E. (2017). The representation and execution of articulatory timing in first and second language acquisition. *Journal of Phonetics, 63*, 127–138. https://doi.org/10.1016/j.wocn.2017.01.004

Ripollés, P., Marco-Pallarés, J., de Diego-Balaguer, R., Miró, J., Falip, M., Juncadella, M., Rubio, F., & Rodriguez-Fornells, A. (2012). Analysis of automated methods for spatial normalization of lesioned brains. *NeuroImage, 60*(2), 1296–1306. https://doi.org/10.1016/j.neuroimage.2012.01.094

Ritaccio, A. L., Brunner, P., & Schalk, G. (2018). Electrical stimulation mapping of the brain: Basic principles and emerging alternatives. *Journal of Clinical Neurophysiology: Official Publication of the American Electroencephalographic Society, 35*(2), 86–97. https://doi.org/10.1097/WNP.0000000000000440

Rofes, A., & Miceli, G. (2014). Language mapping with verbs and sentences in awake surgery: a review. *Neuropsychology Review, 24*(2), 185–199. https://doi.org/10.1007/s11065-014-9258-5

Rorden, C., & Brett, M. (2000). Stereotaxic display of brain lesions. *Behavioural Neurology, 12*(4), 191–200. https://doi.org/10.1155/2000/421719

Rodriguez-Fornells, A., van der Lugt;, A., Rotte, M., Britti, B., Heinze, H. J., & Münte, T. F. (2005). Second language interferes with word production in fluent bilinguals: brain potential and functional imaging evidence. *Journal of Cognitive Neuroscience, 17*(3), 422–433. https://doi.org/10.1162/0898929053279559

Rosenberg, K., Nossek, E., Liebling, R., Fried, I., Shapira-Lichter, I., Hendler, T., & Ram, Z. (2010). Prediction of neurological deficits and recovery after surgery in the supplementary motor area: a prospective study in 26 patients. *Journal of Neurosurgery, 113*(6), 1152–1163. https://doi.org/10.3171/2010.6.JNS1090

Roux, F. E., & Trémoulet, M. (2002). Organization of language areas in bilingual patients: a cortical stimulation study. *Journal of Neurosurgery, 97*(4), 857–864. https://doi.org/10.3171/jns.2002.97.4.0857

Rozanski, V. E., Peraud, A., & Noachtar, S. (2015). Anomia produced by direct cortical stimulation of the pre-supplementary motor area in a patient undergoing preoperative language mapping. *Epileptic Disorders: International Epilepsy Journal with Videotape, 17*(2), 184–187. https://doi.org/10.1684/epd.2015.0750

Rutten, G. J. (2015). Speech hastening during electrical stimulation of left premotor cortex. *Brain and Language, 141*, 77–79. https://doi.org/10.1016/j.bandl.2014.11.014

Salillas, E., Luisi, C., Arcara, G., Varlı, E. N., d'Avella, D., & Semenza, C. (2024). Verb generation for presurgical mapping: Gaining specificity. *Journal of Neuropsychology, 18*(Suppl 1), 183–204. https://doi.org/10.1111/jnp.12355

Sebastian, R., Laird, A. R., & Kiran, S. (2011). Meta-analysis of the neural representation of first language and second language. *Applied Psycholinguistics, 32*(4), 799–819. https://doi:10.1017/S0142716411000075.

Shapiro, K. A., Moo, L. R., & Caramazza, A. (2006). Cortical signatures of noun and verb production. *Proceedings of the National Academy of Sciences of the United States of America, 103*(5), 1644–1649. https://doi.org/10.1073/pnas.0504142103

Sierpowska, J., Gabarrós, A., Fernandez-Coello, A., Camins, À., Castañer, S., Juncadella, M., de Diego-Balaguer, R., & Rodríguez-Fornells, A. (2015). Morphological derivation overflow as a result of disruption of the left frontal aslant white matter tract. *Brain and Language, 142*, 54–64. https://doi.org/10.1016/j.bandl.2015.01.005

Szakay, A., Babel, M., & King, J. (2016). Social categories are shared across bilinguals' lexicons. *Journal of Phonetics, 59*, 92–109. https://doi.org/10.1016/j.wocn.2016.09.005

Tanji, J. (1994). The supplementary motor area in the cerebral cortex. *Neuroscience Research, 19*(3), 251–268. https://doi.org/10.1016/0168-0102(94)90038-8

Tiffin, J., & Asher, E. J. (1948). The Purdue Pegboard: Norms and studies of reliability and validity. *Journal of Applied Psychology, 32*(3), 234–247. https://doi.org/10.1037/h0061266

Thompson, C. K., Bonakdarpour, B., Fix, S. C., Blumenfeld, H. K., Parrish, T. B., Gitelman, D. R., & Mesulam, M. M. (2007). Neural correlates of verb argument structure processing. *Journal of Cognitive Neuroscience, 19*(11), 1753–1767. https://doi.org/10.1162/jocn.2007.19.11.1753

Thompson-Schill, S. L., D'Esposito, M., Aguirre, G. K., & Farah, M. J. (1997). Role of left inferior prefrontal cortex in retrieval of semantic knowledge: a reevaluation. *Proceedings of the National Academy of Sciences of the United States of America, 94*(26), 14792–14797. https://doi.org/10.1073/pnas.94.26.14792

Thompson-Schill, S. L., Swick, D., Farah, M. J., D'Esposito, M., Kan, I. P., & Knight, R. T. (1998). Verb generation in patients with focal frontal lesions: a neuropsychological test of neuroimaging findings. *Proceedings of the National Academy of Sciences of the United States of America, 95*(26), 15855–15860. https://doi.org/10.1073/pnas.95.26.15855

Tomoschuk, B., Ferreira, V. S., & Gollan, T. H. (2019). When a seven is not a seven: Self-ratings of bilingual language proficiency differ between and within language populations. *Bilingualism: Language and Cognition, 22*(3), 516–536. https://doi.org/10.1017/S1366728918000421

Vergani, F., Lacerda, L., Martino, J., Attems, J., Morris, C., Mitchell, P., Thiebaut de Schotten, M., & Dell'Acqua, F. (2014). White matter connections of the supplementary motor area in humans. *Journal of Neurology, Neurosurgery, and Psychiatry, 85*(12), 1377–1385. https://doi.org/10.1136/jnnp-2013-307492

Vigliocco, G., Vinson, D. P., Druks, J., Barber, H., & Cappa, S. F. (2011). Nouns and verbs in the brain: A review of behavioural, electrophysiological, neuropsychological and imaging studies. *Neuroscience & Biobehavioral Reviews, 35*(3), 407–426. https://doi.org/10.1016/j.neubiorev.2010.04.007

Wechsler, D. (1997). *Wechsler Adult Intelligence Scale* (3rd ed.). San Antonio, TX: The Psychological Corporation.

Wechsler, D. (2008). *WAIS-IV Administration and scoring manual.* San Antonio, TX: The Psychological Corporation.

Willms, J. L., Shapiro, K. A., Peelen, M. V., Pajtas, P. E., Costa, A., Moo, L. R., & Caramazza, A. (2011). Language-invariant verb processing regions in Spanish-English bilinguals. *NeuroImage, 57*(1), 251–261. https://doi.org/10.1016/j.neuroimage.2011.04.021

Ziegler, W., Kilian, B., & Deger, K. (1997). The role of the left mesial frontal cortex in fluent speech: evidence from a case of left supplementary motor area hemorrhage. *Neuropsychologia, 35*(9), 1197–1208. https://doi.org/10.1016/s0028-3932(97)00040-7