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## An advancement of intraoperative language mapping in awake craniotomy

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### ABSTRACT

Direct electrical stimulation (DES) during awake craniotomy is the gold-standard for language mapping; however, conventional tasks (e.g. counting, object naming, reading) provide limited sensitivity to grammatical and sentence-level processes. The present study introduces the first intraoperative application of the English Verb and Noun Test for Perioperative testing (VAN-POP), a sentence-based paradigm designed to probe object and action naming with finite verbs in past and present tense. VAN-POP was administered to four UK English-speaking patients undergoing awake craniotomy for WHO grade II-III gliomas involving frontal, temporal, or parietal regions. Language-positive sites were identified in three patients, and real-time monitoring revealed language disruptions in three patients. DES elicited action naming disruptions in two patients. Middle and inferior frontal stimulation induced tense errors and verbal-visual paraphasias, whilst angular gyrus stimulation induced speech arrest. During resection, three patients exhibited action naming disruptions, including semantic and morphosyntactic errors, anomia, and delays. Postoperatively, no patients showed clinically significant deficits requiring speech and language therapy. These findings demonstrate that VAN-POP is feasible for intraoperative use and increases sensitivity to grammar-related cortical sites beyond conventional mapping approaches. Incorporating finite verb production within DES protocols may improve delineation of language networks, supporting better preservation of function.

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Direct electrical stimulation; glioma; language mapping; action naming; neurosurgery; craniotomy; verbs

### Introduction

Awake craniotomy with direct electrical cortical stimulation (DES) is the gold-standard for language mapping during glioma resection. In addition to being well tolerated by patients (Dziedzic & Bernstein, 2014; Mofatteh et al., 2023), awake surgery offers several advantages over general anesthesia, including greater extent of resection, reduced length of hospitalization, and improved neuropsychological outcomes (Bu et al., 2021; De Witt Hamer et al., 2012). Preservation of language function is supported by performing continuous assessment, whereby tasks are used both to identify functional regions and to monitor performance throughout resection.

Object naming, reading, and counting are the most commonly used intraoperative tasks (De Witte & Marien, 2013; Rofes & Miceli, 2014; Rofes et al., 2019). Object naming is favored due to its ease of administration and sensitivity to a range of language disruptions including speech arrest and lexical retrieval and output difficulties. This sensitivity reflects its engagement of multiple language processes including vision, phonology, and

semantics (Collee et al., 2022, 2023). However, mapping results in glioma patients show considerable variability, and are influenced by factors such as task selection and preoperative neuroplastic reorganization associated with slow-growing gliomas (Duffau, 2015; Ng et al., 2023). This highlights the need for more comprehensive assessment protocols.

Accordingly, incorporating action naming alongside object naming may provide a more comprehensive evaluation of language function. Verb retrieval is generally more cognitively demanding than noun retrieval, reflecting differences in semantic organization, imageability, and morphological complexity, as well as the involvement of motor representations (Chiarello et al., 1999; Cordier et al., 2013; Matzig et al., 2009; Tyler, 2004; Zhang et al., 2018). Consistent with this, despite evidence that nouns and verbs are supported by partially distinct neural networks (discussed in detail below), few studies have investigated action naming during awake craniotomy (Corina et al., 2005; De Witte et al., 2015; Lubrano et al., 2014; Mumtaz et al., 2025; Rofes et al., 2017; Rofes et al., 2015).

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Verb assessment has gained prominence within comprehensive language protocols, with action naming emerging as a key component (De Witte & Marien, 2013; Mumtaz et al., 2025; Rofes et al., 2015). However, most previous studies have employed confrontational action naming tasks requiring production of isolated, uninflected verbs (e.g., [to] eat/eating) to map language functions (Corina et al., 2005; De Witte et al., 2015). Such tasks do not capture grammatical processes beyond basic noun-verb distinctions and fail to assess verb inflection and sentence-level processing, both of which are crucial for functional preservation and everyday language use (Rofes & Miceli, 2014; Rofes et al., 2015).

To address this, more complex sentence-based tasks incorporating action naming with finite verbs have been introduced (Lubrano et al., 2014; Mumtaz et al., 2025; Rofes et al., 2017; Rofes et al., 2015). These require verb production within a sentence context, prompting finite responses (e.g., [he] jumps/jumped), and engaging morphosyntactic processes alongside lexical retrieval. Manipulation of verb tense (“eats” or “ate”; Rofes et al., 2015), further increases grammatical demands and more closely approximates natural speech. Rofes, Capasso and Miceli (2015) demonstrated that finite verb production more accurately reflects real-world language function and can be integrated into intraoperative protocols alongside object naming. Such tasks have successfully mapped frontal regions, including the inferior and middle frontal gyri (IFG, MFG), that are not consistently identified through object naming (Rofes et al., 2017; Rofes et al., 2015). Functional neuroimaging studies similarly demonstrate more widely distributed and bilateral activation during finite verb production compared with standard preoperative tasks (Połczyńska et al., 2017).

Despite this evidence, the clinical application of finite verb production tasks remains limited, with most studies focusing on frontal gliomas and offering minimal exploration of other cortical regions. The rationale for extending their use is supported by the partial anatomical segregation of grammatical processing, with verbs typically associated with the left prefrontal cortex and nouns with the anterior temporal lobe (ATL; Crepaldi et al., 2011; Matzig et al., 2009; Vigliocco et al., 2011). Whilst lesions to left prefrontal and ATL typically result in verb and noun processing deficits, respectively (Damasio & Tranel, 1993; Daniele et al., 1994), this dissociation is not absolute. Posterior temporal and inferior parietal lesions can also disrupt verb retrieval (Aggujaro et al., 2006; Tomasino et al., 2019). Meta-analytic studies in neurotypical participants further indicates activation of the fusiform gyrus for nouns and inferior frontal and middle temporal regions for verbs, with overlapping fusiform engagement for both (Faroqi-Shah et al.,

2018). This suggests that whilst noun and verb networks are primarily frontotemporal, verb processing also extends to the temporal and parietal lobes, supporting the application of finite verb tasks beyond the frontal regions during awake craniotomy.

Intraoperative assessment aims to maximize preservation of language function whilst enabling extensive glioma resection. Accordingly, protocols must capture multiple language components yet remain brief to minimize patient fatigue. Sentence-based tasks combining object and action naming with finite verb production offer a more comprehensive approach to mapping, encompassing visual, phonological, semantic, and grammatical processing. Previous research has examined object and action naming with finite verbs in Italian-speaking patients (Rofes et al., 2017; Rofes et al., 2015) and more recently in English-speaking patients using the British Object and Action Naming Test for Intraoperative Mapping (BOATIM; Mumtaz et al., 2025). Italian paradigms were adapted and validated across several languages, including English, Dutch, and German, in the form of the Verb and Noun Test for Perioperative testing (VAN-POP; Ohlerth et al., 2020). In non-English versions, only present tense action naming with finite verbs is administered since this is typically sufficient to capture grammatical processing due to the richer inflectional systems of these languages. In contrast, English verb inflection in the present tense is relatively simple (e.g., walk → walks), and does not adequately probe inflectional complexity, which is better elicited through past tense production (e.g., walk → walked), particularly for irregular forms (e.g., run → ran). Accordingly, the English VAN-POP incorporates an additional past tense condition to probe both regular and irregular verb inflection. The BOATIM, by comparison, assesses only present tense finite verbs.

The present study investigates action naming with finite verbs alongside object naming in patients with gliomas affecting frontal, temporal, and parietal regions. It provides the first intraoperative evaluation of the English VAN-POP in UK English speakers, focusing on finite verb production in the past and present tense.

### *Clinical predictions*

The study aimed to evaluate the feasibility of the VAN-POP and provide preliminary intraoperative mapping data to support its wider clinical application. Based on prior studies, clinical predictions were formulated regarding the functional representation of object and action naming with finite verbs.

For prefrontal glioma patients (RS, JLR), language-positive sites were predicted for both object and action naming within frontal cortex, particularly in the IFG and MFG (predictions one and two). For the inferior parietal patient (GD),



performed the preoperative assessment. The standard protocol included both ad hoc and validated assessments such as counting, object naming (Snodgrass & Vanderwart, 1980), automatic speech (e.g., push and . . . [pull]), word repetition, sentence completion, reading, and calculation. In addition, patients completed the VAN-POP (Figure 1) – a validated language protocol designed to assess noun and verb retrieval in a sentence context. It comprises three sentence-level picture naming tasks: two action naming with finite verbs sets (past tense: 27 items; present tense: 23 items) and one object naming set (50 items). VAN-POP has been normed for perioperative rTMS and intraoperative DES language mapping in multiple languages, including English, Dutch, and German. Each stimulus set includes items exceeding the naming agreement threshold ( $\geq 80\%$ ) and controls for psycholinguistic variables affecting lexical retrieval within and across sets. For nouns and verbs, these include word frequency, age of acquisition, syllable length, and animacy. Verb sets additionally control for past tense regularity, transitivity, argument structure, instrumentality, and noun-relatedness (for details see: Ohlerth et al., 2020).

Each finite verb item consisted of a line drawing depicting an action (e.g., a man eating), paired with a lead-in phrase containing a temporal adverb (“yesterday” or “daily”) and a pronoun (“he”, “she”, or “it”) to indicate the tense and subject, respectively. Patients were instructed to read the phrase and complete it using the target verb in the correct tense (e.g., “Daily, he . . . eats” [present] or “Yesterday, he . . . ate” [past]). Similarly, the object naming task presented a line drawing with a lead-in phrase (e.g., “This is a/an. . .”), prompting patients to read and complete the sentence aloud (e.g., “This is an . . . apple”).

In addition to formal testing, conversation was used throughout surgery, particularly during the monitoring (resection) stage and between tasks, to elicit spontaneous connected speech and ensure patient comfort and alertness. Topics were personalized using biographical information from the initial preoperative session.

### *Intraoperative procedure*

Preoperative MRI and fMRI were performed for all patients to delineate glioma boundaries and identify adjacent language regions. GD additionally underwent cerebral perfusion imaging. All patients received intraoperative MRI-guided awake craniotomy using an asleep–awake–asleep protocol. Following dural opening, patients were awoken and cortical stimulation mapping performed.

DES mapping was conducted using a bipolar stimulator (1–10 mA, 60 Hz, 4 s pulse duration). Mapping began with low demand tasks such as counting or object naming, followed by more complex tasks including action naming with finite verbs, depending on glioma location, intraoperative conditions, and patient tolerance. Stimulation onset was manually synchronized with stimulus presentation to ensure temporal precision. During naming tasks, the SLT presented the stimulus (e.g., an object picture) and instructed the patient to read the lead in phrase (e.g., “This is a . . .”) before naming the picture. The neurosurgeon listened for the introductory phrase and immediately applied cortical stimulation before the patient’s verbal response. Positive language sites were identified when stimulation consistently disrupted performance and were marked with sterile white tags on the cortex. Typically, a site was designated functional if stimulation produced language interference on at least two out of three trials. In



**Figure 1.** Example items from the VAN-POP. Top: object naming tasks where patients read a lead-in phrase and named the pictured object (e.g., “This is a/an. . . apple”). Bottom: action naming with finite verbs in past and present tense, where patients completed a sentence by producing the correctly inflected verb based on the lead-in phrase (e.g., “Yesterday he . . . ate”; “Daily he . . . climbs”).

addition, tasks were also administered during periods without stimulation to establish an intraoperative baseline against which to compare any DES-induced interference. Once the neurosurgeon was satisfied with the mapping, glioma resection proceeded.

Language monitoring continued throughout resection using formal tasks and spontaneous conversation, allowing real-time feedback to be provided to the neurosurgeon in the event of performance deterioration. Upon achieving maximal safe resection, intraoperative MRI was used to detect any residual glioma. Additional resection was considered if functional boundaries permitted. Finally, patients were re-sedated and the craniotomy was closed.

## Results

This section presents detailed case reports and intraoperative DES mapping and monitoring outcomes for RS, GD, MW, and JLR. The results are summarized anatomically by task and error type (Figure 2; Table 2). Due to the exploratory nature of this study amongst a small sample of heterogeneous cases, the mapping and monitoring data provided is observational. The results are therefore reported descriptively, focusing on within and between case patterns rather than statistical differences.

### Case RS

#### Presentation and diagnosis

RS, a 23-year-old right-handed male with 17 years of education, held a bachelor's degree in graphic design and worked as a retail assistant. Approximately two years prior to surgery, he experienced dizziness, nausea, and vomiting, lasting approximately one week. Although initially diagnosed with labyrinthitis, he later presented to the emergency department with headache and slurred speech. No neurological abnormalities were found at the time. His medical history was notable only for mild anxiety, managed with propranolol. During this period, he also experienced reduced appetite leading to weight loss. MRI revealed a left frontal abnormality consistent with cortical dysplasia, later characterized as a low-grade glioma (Figure 3). RS's condition was monitored with MRI and neurological examinations until referral for surgical resection. Preoperative testing revealed no significant cognitive or language deficits, although mild errors were noted across language domains, including complex grammatical and syntactic abilities (Table 1).

#### Operation

DES (2–5 mA, 60 Hz) applied anterior to the glioma (middle IFG, pars triangularis), elicited speech arrest, semantic paraphasias (e.g., “bolt” for “screw”) and word-finding difficulties (delay and anomia) during object naming. During past tense action naming with finite verbs, stimulation at the same site induced verbal and semantic paraphasias. Stimulation superior to the glioma (posterior IFG, pars opercularis; MFG) produced verbal and visual paraphasias during present tense finite verb production (e.g., “daily she drinks” for “daily she sings”), and tense switching errors (e.g., “daily he shot” for “daily he shoots”). Although tense errors were grammatically correct, they represented task-specific deviations, as performance was accurate during preoperative testing. Semantic and verbal paraphasias were also observed during object naming at this site.

During resection anterior to the glioma, near the middle IFG, RS exhibited incorrect verb production during past tense action naming with finite verbs (e.g., “yesterday she flowered” for “yesterday she watered [the flowers]”) along with semantic and verbal paraphasias, and word-finding difficulties (delay and anomia) during object naming. Reading errors were also observed during sentence completion. Resection at the superior aspect of the glioma (posterior IFG; MFG), elicited speech arrest during recitation of the months of the year. However, no errors were observed on object naming, repetition, or other automatic speech tasks.

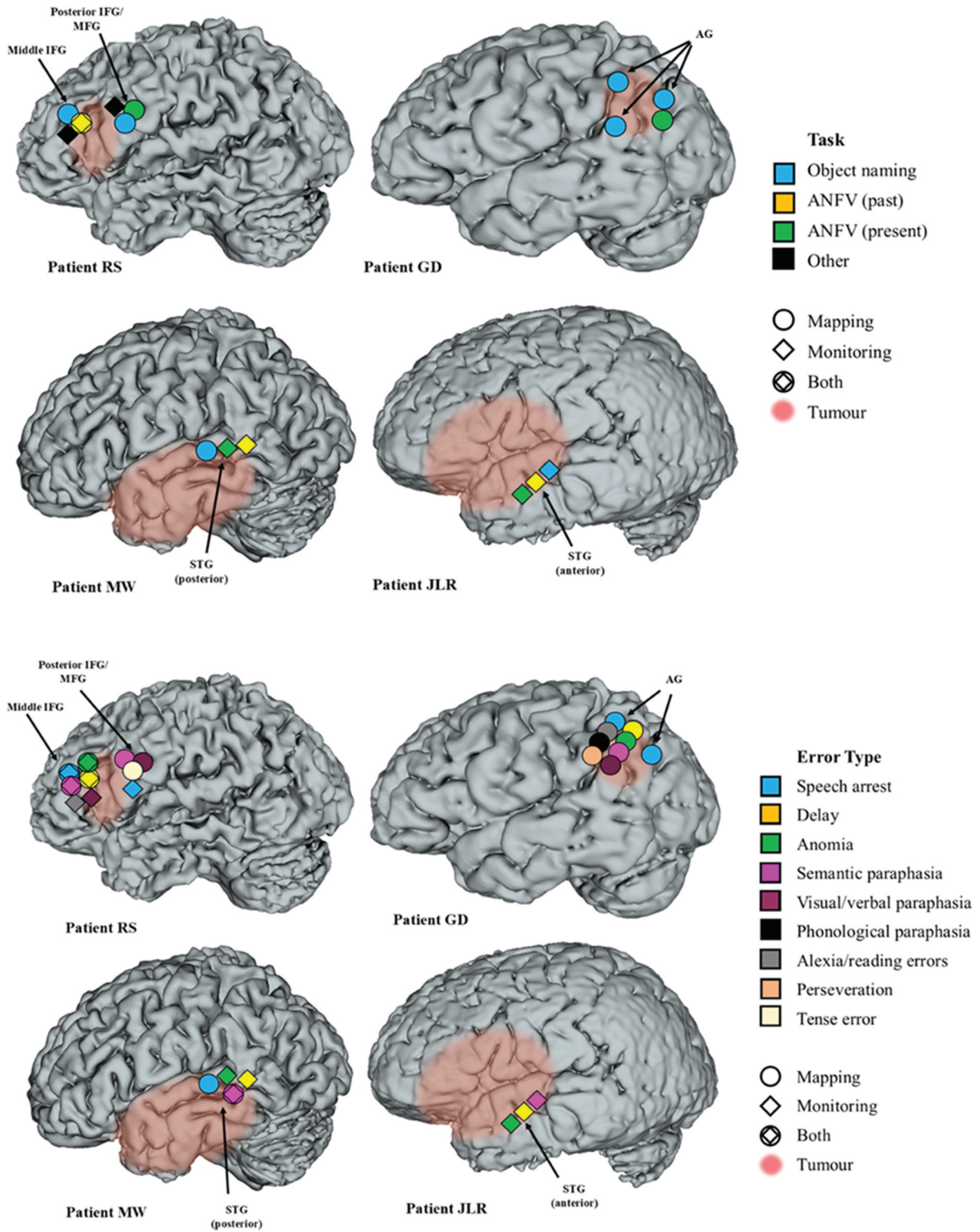
#### Postoperative course

Postoperative imaging revealed residual glioma in the motor cortex, as planned, to preserve function. Histology confirmed a WHO Grade II oligodendroglioma. RS was referred for chemotherapy and radiotherapy. Assessment performed 24 hours postoperatively revealed largely stable performance, with both improvements and new errors in specific domains (Table 1).

### Case GD

#### Presentation and diagnosis

GD, a 39-year-old right-handed male with 14 years of education, worked as an IT manager. He initially presented with headaches and episodes of expressive aphasia affecting both speech and writing, with reported confusion and transient inability to produce meaningful language despite intact comprehension (Figure 4). MRI revealed a left temporoparietal abnormality consistent with a low-grade glioma (Figure 4), prompting awake craniotomy. As GD experienced intermittent aphasic episodes rather than persistent deficits, preoperative assessment one day prior to surgery revealed largely preserved language function, with only minor errors (Table 1).



**Figure 2.** Anatomical summaries of language mapping and monitoring during glioma resection. 3D reconstructions from patient MRI scans (except GD) display glioma location, DES language sites, and monitored regions. GD's image was generated from a sample MRI due to motion artefacts in the original scan. Images were created using 3D Slicer (version 5.8.1; <https://www.slicer.org/>). Top: mapping and monitoring by task type. Bottom: mapping and monitoring by error type. Note: monitoring regions indicate resection at the time of observed language disturbances and should not be interpreted as precise anatomical localization. ANFV, action naming with finite verbs; IFG, inferior frontal gyrus; MFG, middle frontal gyrus; AG, angular gyrus; STG, superior temporal gyrus.

**Table 2.** DES sites/regions of resection, language tasks, and error types observed during language mapping and monitoring in each patient. Note: monitoring represents general regions of resection at the time language disturbances were observed and do not reflect anatomical localization of function. ANFV, action naming with finite verbs; IFG, inferior frontal gyrus; MFG, middle frontal gyrus; AG, angular gyrus; STG, superior temporal gyrus.

Patient	Stimulation site	Language task	Error type
RS	Middle IFG	Object naming	Semantic paraphasia Delay Anomia
		ANFV (past)	Semantic paraphasia Verbal paraphasia
	Posterior IFG/MFG	Object naming	Semantic paraphasia Visual paraphasia
		ANFV (present)	Verbal/visual paraphasia Tense error
GD	AG (anterior; inferior)	Object naming	Speech arrest Delay Anomia Phonological paraphasia Perseveration Semantic paraphasia Perseveration Alexia
		Object naming ANFV (present)	Speech arrest Speech arrest
	AG (posterior)	Object naming	Speech arrest
	Posterior STG	Object naming	Speech arrest Semantic paraphasia
MW	Posterior STG	Object naming	Semantic paraphasia
Patient	Region of resection	Language task	Error type
RS	Middle IFG	ANFV (past)	Semantic paraphasia
		Object naming	Semantic paraphasia
		Object naming	Verbal paraphasia
		Object naming	Delay
		Object naming	Anomia
		Sentence completion	Alexia
MW	Posterior IFG/MFG Posterior STG	Automatic speech (months)	Speech arrest
		ANFV (past)	Semantic errors
		ANFV (present)	Delay Semantic errors
		ANFV (present)	Delay Anomia
JLR	Anterior STG	Object naming	Delay Anomia Semantic paraphasia
		ANFV (past)	Semantic paraphasia
		ANFV (present)	Semantic paraphasia
		ANFV (present)	Semantic paraphasia

### Operation

Two sites in the AG, one anterior inferior to the glioma (Figure 5), elicited language disruptions upon stimulation. During object naming, stimulation induced expressive and receptive difficulties including speech arrest, word-finding (delay and anomia), complete alexia, and inability to comprehend simple instructions (e.g., “squeeze my hand”). Multiple paraphasic errors were observed including phonological, semantic, and verbal, as well as perseverative errors (e.g., repeated use of “omelet”) during sentence attempts. Further stimulations of AG posterior-superior to the glioma (Figure 5) produced speech arrest during object naming and present tense action naming with finite verbs. No intraoperative deterioration in language occurred during resection.

### Postoperative course

GD recovered quickly and was discharged four days postoperatively with no observable deficits. Histology confirmed a WHO Grade II oligodendroglioma. Residual glioma remained adjacent to functional regions, and the patient was referred for chemotherapy. Assessment on postoperative day three revealed both improvements and new errors across language domains (Table 1).

### Case MW

#### Presentation and diagnosis

MW, a 47-year-old right-handed male with 12 years of education, worked as a primary school site manager. He presented with a first seizure one month prior to diagnosis and was started on antiepileptics and steroids, with no subsequent seizures. His history included hypertension,

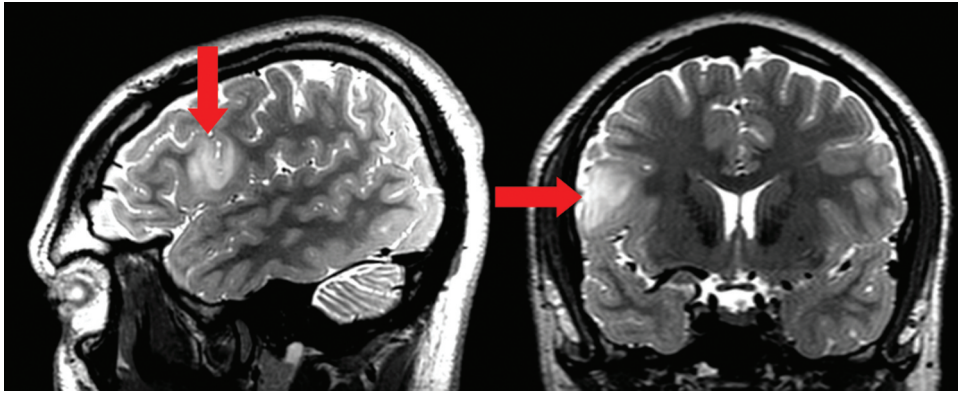


Figure 3. Sagittal and coronal MRI of RS, displaying a left frontal mass in the IFG involving the pars triangularis/opercularis.

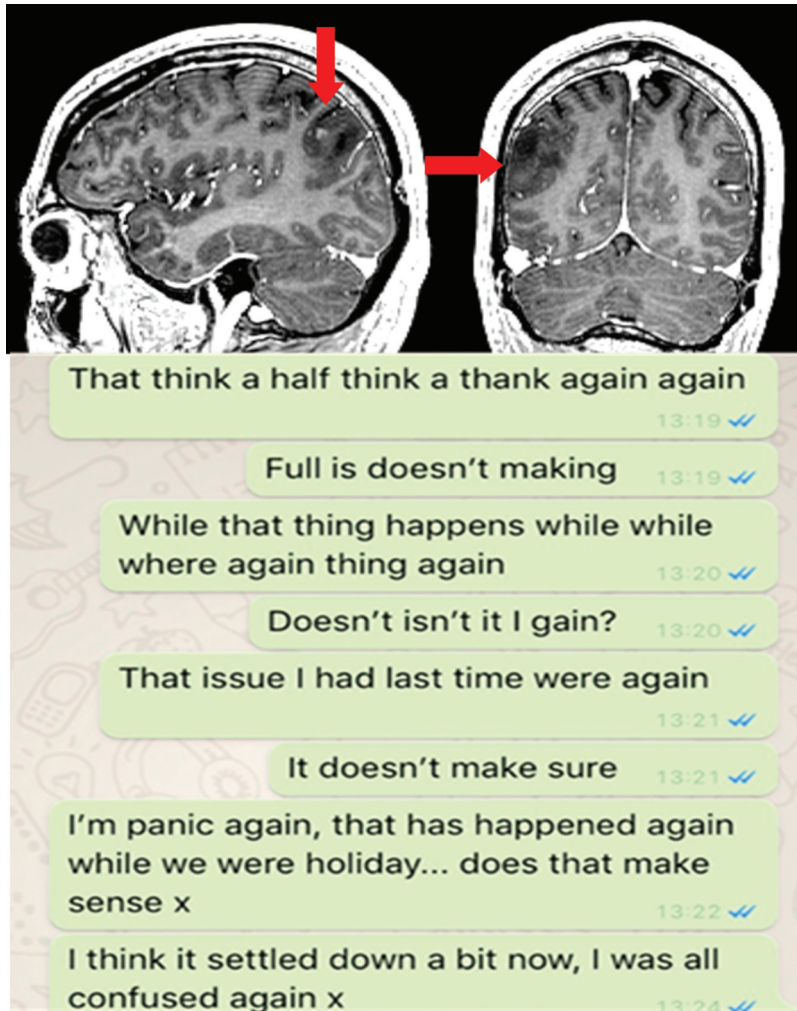
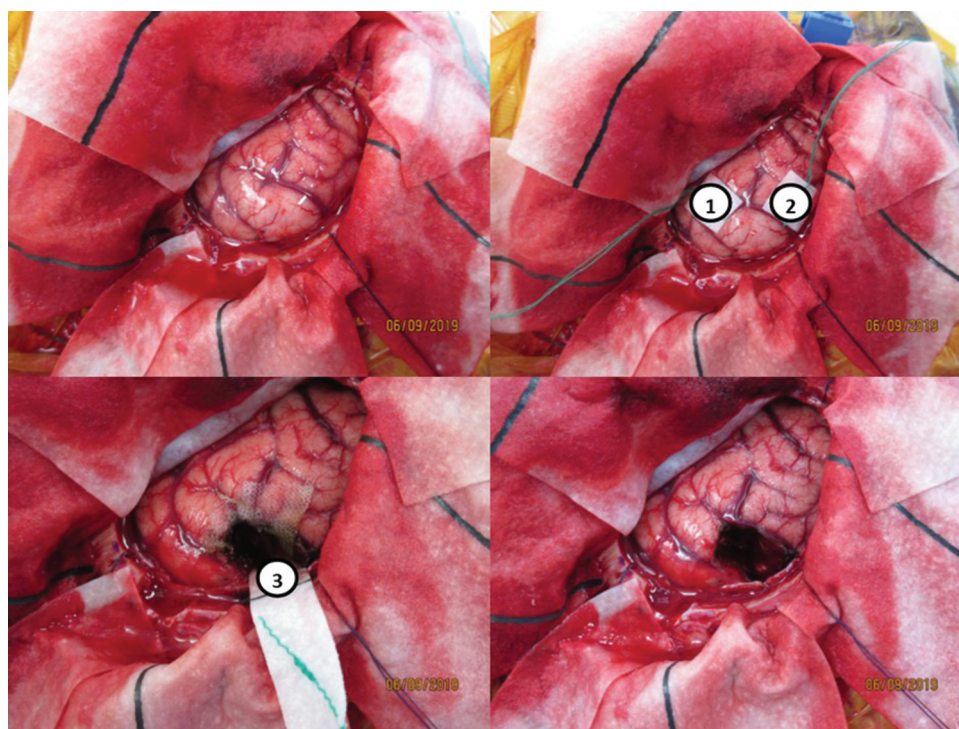
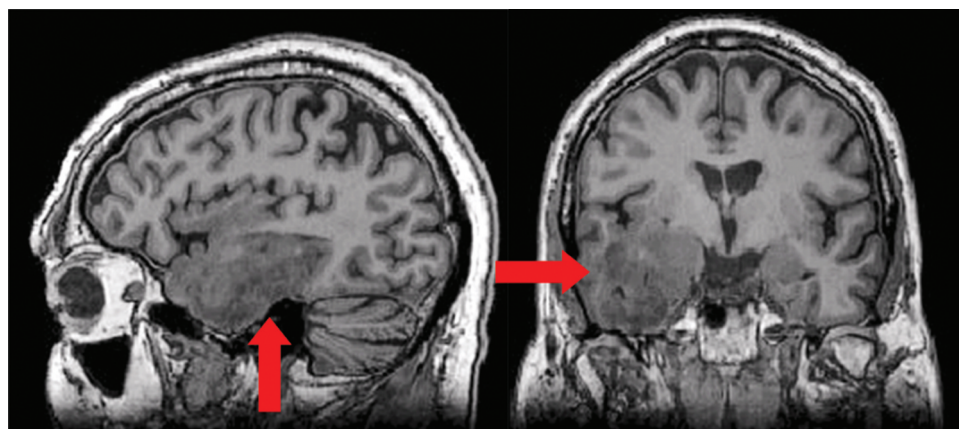


Figure 4. Top: sagittal and coronal MRI of GD, displaying a left temporoparietal mass involving the angular gyrus. Bottom: text messages sent by GD to his partner during a transient aphasic episode, describing confusion and impairments in verbal and written expression, which resolved spontaneously within minutes.



**Figure 5.** Intraoperative photographs from GD. Top left: craniotomy exposing the parietal cortex, including the angular gyrus. Top right: two language-positive sites identified near the angular gyrus – (1) inferior and (2) anterior to the glioma – eliciting expressive and receptive language disturbances during object naming. Bottom left: language-positive site (3) angular gyrus, posterior-superior to glioma, where stimulation induced speech arrest during object naming and present tense action naming with finite verbs. Bottom right: glioma cavity following resection, with boundaries defined by functional mapping.

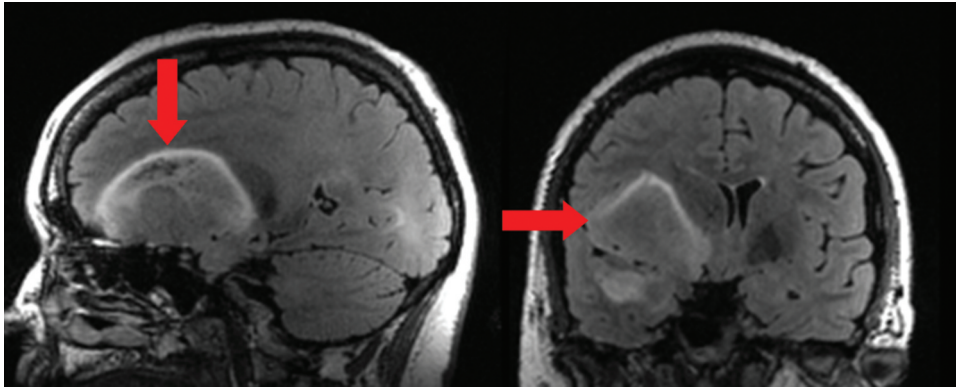


**Figure 6.** Sagittal and coronal MRI of MW, displaying a left anterior temporal mass.

e-cigarette use, and high alcohol consumption (~100 units/week). MRI revealed a left anterior temporal glioma (Figure 6), and MW was referred for awake craniotomy. Preoperative assessment three weeks prior to surgery (due to surgery postponement) revealed no major deficits, though minor language and cognitive errors were noted (Table 1).

### Operation

Stimulation (2–8 mA; 60 Hz) of posterior STG during object naming elicited speech arrest, and semantic paraphasias (e.g., “emu” for “kangaroo”), and incorrect color naming despite correct object naming (i.e., “red pepper” for “green pepper”). No language-positive sites were observed in MTG.



**Figure 7.** Sagittal and coronal MRI of JLR, displaying a left superior frontotemporal mass.

During dissection of the posterior superior aspect of the glioma, past and present tense action naming with finite verbs prompted semantic errors (i.e., “yesterday she flowered” for “yesterday she watered [the flowers]”), and delayed responses. On present tense trials, MW reported word-finding difficulties despite intact conceptual knowledge such that he recognized the action but struggled to recall the verb. Automatic speech remained unaffected. Resection of anterior temporal lobe proceeded, preserving the posterior portion to avoid language impairment.

#### **Postoperative course**

Postoperative imaging indicated 85–90% resection rate. Histology revealed a WHO Grade III anaplastic oligodendroglioma, and the patient was referred for chemotherapy and radiotherapy. Assessment 24 hours postoperatively revealed no major impairments, and largely stable performance relative to preoperative assessment. MW improved in arithmetic, and spoken language comprehension of words and sentences, but exhibited new errors on written language comprehension of words and sentences (Table 1).

#### **Case JLR**

##### **Presentation and diagnosis**

JLR, a 28-year-old right-handed female with 14 years of education, worked as a barista and was on maternity leave at the time of surgery. Following childbirth, she developed seizures, prompting neurological investigation. MRI revealed a large left frontotemporal glioma (Figure 7), and awake craniotomy was scheduled. Preoperative language assessment one week prior to surgery revealed mild aphasia (Table 1) with deficits in object naming (requiring phonological cues), and reduced informational content with repetition during picture description.

##### **Operation**

Stimulation of STG and MTG during counting elicited no interference. Due to fatigue and sedative effects, further mapping was not possible. During resection near anterior STG, JLR produced word-finding difficulties (delays and anomia) and semantic errors (e.g., “ostrich” for “peacock”; “mustache” for “beard”) during object naming. Additional semantic errors were observed during both past and present tense action naming with finite verbs (e.g., “he raises his hands” for “he waves”; “yesterday he sailed” for “yesterday he surfed”).

##### **Postoperative course**

Postoperative assessment revealed mixed outcomes, with some improvements and persistent difficulties across domains, particularly in object naming (Table 1). Histology revealed a WHO Grade III oligodendroglioma, and the patient was referred for chemotherapy and radiotherapy.

#### **Discussion**

Cortical DES mapping produces variable results depending on task selection and interindividual differences. This study presents the first intraoperative application of the VAN-POP alongside established tests in English-speaking glioma patients. Unlike other test batteries such as BOATIM (Mumtaz et al., 2025), VAN-POP incorporates past tense finite verb production, capturing complex inflectional processes not assessed by present tense tasks. Mapping and monitoring were achieved across patients with frontal, temporal, and parietal gliomas, with VAN-POP revealing novel stimulation-induced disruptions to tense and syntax. Postoperative language deficits were minimal, and no patients required speech and language intervention. These findings support and extend prior work (Bello et al., 2008; Havas et al., 2015;

Lubrano et al., 2014; Rofes et al., 2017; Rofes et al., 2015), revealing the functional significance of higher-order language regions during awake craniotomy.

VAN-POP was administered during DES mapping and monitoring. In all but one case (JLR), at least one language-positive site was successfully identified using action naming with finite verbs (RS, GD) or object naming (RS, GD, MW). Language deterioration during resection, detected via monitoring, was observed in three out of four cases (except GD). Mapping the IFG through both object and action naming was consistent with predictions one and two, whilst language-positive sites in the AG during object and finite verb naming supported predictions three and four. Additional sites in the STG (but not MTG), identified through DES or dissection, corresponded to predictions five and six. Overall, these findings corroborate prior studies incorporating object naming and finite verb production into intraoperative protocols. The study further highlights the added value of VAN-POP for assessing grammatical and morphosyntactic processes, supporting more precise identification and preservation of language function during glioma resection.

### **Prefrontal cortex**

Stimulation of the IFG and MFG elicited noun and verb retrieval errors, consistent with prior studies demonstrating that both regions can be mapped using object naming or finite verb tasks (Havas et al., 2015; Lubrano et al., 2014; Rofes et al., 2017; Rofes et al., 2015). Action-specific sites are typically located in middle and posterior MFG, whereas the IFG supports object and action naming (Havas et al., 2015; Lubrano et al., 2014). In RS, posterior IFG/MFG stimulation produced a novel grammatical tense error during action naming, in which semantically correct verbs were produced in the incorrect tense, a phenomenon not previously reported for this task (Rofes et al., 2017; Rofes et al., 2015). This finding suggests that posterior IFG/MFG supports not only verb retrieval but also morphosyntactic processes critical for finite verb production, consistent with its involvement in agrammatic aphasia (Druks & Carroll, 2005; Valinejad et al., 2022).

Action naming interference following IFG stimulation is consistent with previous findings (Rofes et al., 2017; Rofes et al., 2015). Lesions in the IFG are typically associated with agrammatic aphasia (Shapiro & Caramazza, 2003), and grammatical processing has been consistently linked to IFG activation (Bulut, 2022; Crepaldi et al., 2013; Rogalski et al., 2011). White matter tracts connecting IFG with

supplementary motor areas, particularly the frontal aslant tract, are thought to support grammatical functions during verb and sentence production (Akinina et al., 2019; Chernoff et al., 2019; Sierpowska et al., 2015). These data further substantiate the role of IFG in grammatical processing.

However, not all verb task interferences can be attributed solely to IFG stimulation. During anterior resection near the middle IFG, RS correctly produced the past tense inflection but substituted a semantically incorrect verb (“she flowered” for “she watered [the flowers]”). Whilst morphosyntactic processes were preserved, semantic retrieval was disrupted (watered). This disturbance likely reflects disconnection of the inferior fronto-occipital fasciculus (IFOF) which links the IFG to temporoparietal regions and supports semantic processing (Duffau, 2005a; Nogueira et al., 2025). DES of the IFOF has been associated with semantic paraphasia, and, in some cases, jargonaphasia, where grammar is preserved but speech becomes meaningless (Duffau et al., 2008; Giampiccolo et al., 2022; Moritz-Gasser et al., 2013; Zemmoura et al., 2015). The IFOF is thought to contribute to top-down control within the visual-semantic network, connecting posterior (temporal, parietal, and occipital) with prefrontal regions for language production (Giampiccolo et al., 2025). In this case, semantic control may have been disrupted in RS due to competing object (the flowers) and action (the watering) representations, preventing the correct verb selection and subsequent frontal processing (Lambon Ralph et al., 2017).

Substitution and inflection errors may reflect impaired access to verb argument structure, necessary for constructing phrases with transitive verbs (Thompson & Meltzer-Asscher, 2014), a process attributed to the IFG (Friederici, 2017). Transcranial direct current stimulation (tDCS) of the inferior frontal cortex has been demonstrated to improve transitive verb production under high cognitive load (den Ouden & Zhu, 2022), and lesions in agrammatic aphasia disproportionately affect transitive and ditransitive verbs relative to intransitive verbs, particularly as argument complexity increases (Dragoy & Bastiaanse, 2010; Kim & Thompson, 2000, 2004; Thompson et al., 1997). Navigated transcranial magnetic stimulation (nTMS) targeting the arcuate fasciculus (AF; Ntemou et al., 2023) has also been linked to syntactic production deficits, although phonological errors often predominate during intraoperative AF stimulation (Maldonado, Moritz-Gasser, & Duffau, 2011; Maldonado, Moritz-Gasser, de Champfleury, et al., 2011; Mandonnet et al., 2007; Matsuda et al., 2014). AF damage has further been associated with syntactic deficits in more complex production tasks, such as picture description and spontaneous speech, in primary progressive

aphasia (Wilson et al., 2011). Together, these findings suggest that disruption of the AF may disconnect the IFG from posterior regions, resulting in sentence-level production difficulties that emerge under increased cognitive demands, such as those imposed by complex argument structure generation during finite verb production.

Within the neurocomputational framework proposed by Matchin and Hickok (2020), finite verb production requires hierarchical information from temporal regions to be linearized into sequential morphemes, a process attributed to the middle IFG due to its role in sentence production (for a review see Meyer & Friederici, 2016). Damage to IFOF or AF fibers beneath IFG may disrupt transmission of verb semantic or structural information, preventing correct linearization, and, in some cases, leading to noun or substitution errors. Whilst the precise mechanism cannot be confirmed here, these interpretations provide a basis for future investigation.

### *Parietal cortex*

The left AG has been mapped using a range of language and cognitive tasks, although finite verb production has not previously been examined in this region (Martino et al., 2018; Roux et al., 2003, 2014). This study is the first to demonstrate that AG stimulation during action naming with finite verbs can induce speech arrest and other language disruptions, with error patterns consistent with those reported using other tasks.

Evidence suggests that the AG plays a role in verb processing (Crepaldi et al., 2011; Matzig et al., 2009; Vigliocco et al., 2011). Neuroimaging studies reveal greater activation for verbs than nouns in this region (Berlingeri et al., 2008; Fujimaki et al., 1999; Perani et al., 1999; Saccuman et al., 2006; Shapiro et al., 2006), and lesion studies report verb-specific deficits following inferior parietal damage (Aggujaro et al., 2006; Tomasino et al., 2019; Tranel et al., 2008). Furthermore, nTMS studies in neurologically intact participants elicit a higher error rate for transitive versus intransitive verbs following left parietal stimulation (Ntemou et al., 2021). These findings reinforce the functional contribution of the inferior parietal cortex to verb production and provide a strong rationale for incorporating finite verb production tasks in parietal mapping.

### *Posterior temporal cortex*

MW exhibited the same semantic error as RS during past tense action naming with finite verbs (“she flowered” for “she watered [the flowers]”) despite resection occurring in posterior STG rather than IFG. Semantic paraphasias

are commonly reported during object naming when mapping the posterior STG (Chan-Seng et al., 2014; De Benedictis et al., 2014; Duffau et al., 2004; Lubrano et al., 2014; Mandonnet et al., 2007; Robles et al., 2008; Sarubbo et al., 2012; Tate et al., 2014) and have also been observed during action naming (Lubrano et al., 2014), supporting the present findings. Such errors may reflect deficits in semantic control (Lambon Ralph et al., 2017), or impaired access to verb argument structure, especially for transitive verbs (Thompson & Meltzer-Asscher, 2014). Indeed, neuroimaging implicates posterior perisylvian regions, including the STG, in processing transitive verbs and supporting argument structure during sentence production (Meltzer-Asscher et al., 2013; Shetreet et al., 2007).

These findings challenge a strict noun-verb fronto-temporal dichotomy (Crepaldi et al., 2011) and support a distributed, interacting network for sentence production integrating noun and verb arguments (Matchin & Hickok, 2020; Walenski et al., 2019). Whilst syntactic linearization and hierarchical phrase structuring are typically attributed to the posterior MTG and the IFG via the AF (Yagmurlu et al., 2016), the posterior STG may contribute to comprehension by relaying phonological representations to the MTG for decoding (Hickok & Poeppel, 2007) and may also support phrase-structure processing through interactions with the IFG (Lopopolo et al., 2021; Meyer & Friederici, 2016). Given that slow-growing gliomas may provoke functional reorganization, neuroanatomical models may need to be applied more flexibly (Duffau, 2005a; Ho et al., 2021; Piai, 2019).

MW's glioma extended beyond the STG into the MTG and inferior temporal lobe, potentially driving neuroplastic reorganization. As a result, the posterior STG may have assumed a greater role in hierarchical lexico-syntactic processing. Although speculative, posterior temporal damage has been associated with grammatical deficits (Wilson, Eriksson, et al., 2018; Wilson, Yen, et al., 2018; Yagata et al., 2015), and disruption of the shared lexico-syntactic networks (Matchin & Hickok, 2020) supported by AF and IFOF pathways, may explain the semantic substitution errors, as also observed in the paragrammatical speech of fluent aphasics (Bastiaanse et al., 1996; Casilio et al., 2019).

Consistent with previous studies (Lubrano et al., 2014; Martino et al., 2018; Roux et al., 2014), object naming elicited speech arrest and semantic paraphasia. An additional finding was MW's color anomia, which, although rarely reported during awake craniotomy, has been associated with posterior STG stimulation (Roux et al., 2003) and occipital-temporal lesions (Damasio & Damasio, 1983). This suggests that object naming tasks incorporating colored stimuli may probe color semantics,

providing opportunities to expand intraoperative assessment to identify and preserve networks critical for color processing in temporal surgeries.

### Anterior temporal cortex

The ATL is considered a transmodal semantic hub integrating conceptual information across modalities (Farahibozorg et al., 2022; Frisby et al., 2025; Lambon Ralph et al., 2017; Patterson & Ralph, 2016). In JLR, dissection near the anterior STG elicited word-finding difficulties and semantic errors during object naming (De Witte & Marien, 2015; Riva et al., 2016; Rosenberg et al., 2008; Roux & Tremoulet, 2002). Similar semantic disruptions also occurred during finite verb production, with impaired verb selection but preserved grammatical structure (e.g., tense), similar to the patterns observed in MW. In contrast, RS demonstrated impaired tense morphology with intact semantic access following IFG/MFG stimulation. These complimentary patterns support a model in which morphosyntactic processing (e.g., tense errors) is predominantly frontally mediated via regions such as the IFG (van der Burght et al., 2023), whilst semantic processing (e.g., semantic paraphasias) is temporally mediated via the ATL (Henderson et al., 2025; Visser et al., 2010).

Although no overt grammatical disruptions were observed during ATL resection, its role in morphosyntax cannot be excluded. Prior studies report selective delays in producing irregular past tense verbs following ATL-targeted rTMS stimulation (Holland & Lambon Ralph, 2010). Since regular and irregular forms were not directly contrasted here, this aspect remains to be explored.

### Conclusions

This study is the first to demonstrate the feasibility of incorporating the English VAN-POP into awake craniotomy protocols for gliomas affecting frontal, temporal, and parietal language networks. By enabling mapping and monitoring of grammatical and verb-related functions not routinely assessed by conventional tasks, VAN-POP supports improved preservation of postoperative language abilities. Although constrained by sample size and experimental control, these findings provide a strong basis for further validation in larger cohorts. VAN-POP represents a promising tool for comprehensive intraoperative language assessment in English-speaking patients, and broader adoption across centers will be critical to establish its specificity, reliability, and clinical utility for mapping and preserving functional outcomes. In this context, the integration of virtual and augmented reality technologies could further enhance task delivery

and patient engagement, particularly for complex protocols (Mofatteh et al., 2022).

### Limitations

The findings should be interpreted within the context of several limitations. The sample was small and heterogeneous, with non-overlapping lesions of different grades, reflecting its exploratory nature and COVID-19 recruitment constraints. Experimental task comparisons were not possible, and conclusions regarding the efficacy of VAN-POP or its regional specificity should be exercised with caution. Stimulation timing may also have been suboptimal, since it was delivered during a lead-in phrase rather than at stimulus onset, potentially allowing lexical retrieval to begin before disruption. The patient-cue method may have introduced variability in timing across trials and patients. Whilst this approach reflects typical intraoperative mapping practice within our collaborating neurosurgical center, it is not currently optimized for experimental manipulation. Despite these constraints, mapping data were successfully obtained, and the combined use of VAN-POP with existing tasks contributed to favorable postoperative outcomes.

Subcortical mapping and postoperative diffusion imaging were not performed, restricting validation of white matter tract involvement. Errors observed during resection may reflect subcortical disconnection rather than purely cortical effects and may have been influenced by brain shift, fatigue, or sedation. These errors should not be interpreted as strictly localizable to cortical regions.

Long-term outcomes were not systematically assessed. Although immediate postoperative deficits were minimal, delayed impairments may emerge within three months (Lemaitre et al., 2022). In the NHS, follow-up evaluations on the CAT are not routinely conducted for patients with mild deficits, though our ongoing work is examining longitudinal VAN-POP outcomes and subtle impairments within the glioma language profile not captured by standard assessments (Zyryanov et al., 2022).

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## Data availability statement

No additional research data are associated with this article as they are case reports.

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