Elements of the Neurobiology of Language: A Neurostimulation Model

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Abstract

Models of the neurobiology of language often rely on correlative neuroimaging techniques and ambiguous terminology derived from linguistic theory (e.g., 'semantics') rather than regions' functional profiles. The brain's cytoarchitecture and the capacity to functionally affect cognition via neurostimulation imply greater precision may be possible. We systematically reviewed 221 of tES, TMS, and DES papers modulating linguistic processes and qualitatively analysed by-paper outcomes to infer the specific subprocess actually modulated, which we term an *element*. We uncover 608 distinct elements of the neurobiology of language from 22 different languages and nearly 6,300 participants. These elements apply over a 7-level hierarchy of process specificity, help to redefine the operable terms of language neuroscience, and enable generalised functional characterisation of key nodes of the language network. The model is available for scientific use via an online database (https://www.language-elements.org/) and has clinical applications for planning awake craniotomies with neuro-oncology patients.

Keywords: brain; language; neurostimulation; cognition; neurobiology of language; neurosurgery

Introduction

The history of the study of the neurobiology of language spans over 150 years, with the early clinical neurolinguistic discoveries of Broca (1861) and Wernicke (1881) laying the foundation for future modelling. Later neurosurgical stimulation research (with direct electrical stimulation; DES) also helped map and model the cortical surface of patients for language functions. (Ojemann et al., 1989; Penfield & Rasmussen, 1950). These two sets of research embody a dichotomy between perspectives in modern neurobiology of language. One characterises the *essence* of a region by virtue of its function. The other determines the best explanatory *instrument* for yielding the most data from neurolinguistic substrates. Their extent of (dis)agreement is embodied in positions taken over various theoretical principles and methodological choices. These include how differently neural tissues specialise for language; what (and how many) tasks and pieces of equipment are used to probe neurolinguistic questions; and what can be reasonably inferred from different practice. The tension between these approaches reflects their difficulty in integrating each other's core assumptions. We argue that such congruency is possible within our model: *elementalism*.

The central axiom of essentialism is that specific regions of the brain specialise for some subprocess of language. That neural structures might have a linguistic 'essence' finds primary scientific backing via the study of cytoarchitecture – the many interconnected neuronal layers present in region-specific structured patterns, whose patterns change by-function and thus demarcate functionally relevant regions (Palomero-Gallagher & Zilles, 2019).

Modern essentialist models abound. Broca and Wernicke's early efforts laid the foundation for a production-comprehension binary, such as in the Dual Stream Model (e.g., Hickok & Poeppel, 2007), wherein dorsal and ventral pathways correspond to phonological and semantic functions. This model inspired a more detailed update from evidence in neuro-oncology patients (Duffau et al., 2014). More recently, Lambon-Ralph et al.'s (2017) Hub-and-Spoke Hypothesis follows a trend of honing in on a specific function. They posit a central processing region for composing semantic representations; a concept expanded multimodally in the more recent model proposed by Kuhnke et al. (2023). Grodzinsky et al.'s (2021) review highlights specific syntactic operations and their clustering in frontal regions. Further, a continuing body of work from Chang's laboratory using intracranial recordings identifies specific regional specialisation for lower-level phonetic and phonological functions, such as lexical tone (Lu et al., 2023), phonemic encoding (Leonard et al., 2024), and speech sequencing (Liu et al., 2025). Indeed, for these functions, their approach's soundness is borne out via recent advances in successfully deploying brain-computer interfaces in clinical populations (Silva et al., 2024). Though intracranial recordings have great regional specificity, to-date, no essentialist model has employed causal neural measurement techniques, which more reliably map language in the brain.

The neuroscientific endeavour of the *instrumentalist* instead begins with large-scale observation of whole-brain involvement in general language tasks. Their central axiom is that the best explanatory tool is that which best encapsulates whole-brain analysis data, irrespective of what focusing on some small region entails. These methods

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are particularly prevalent in Fedorenko and Huth's work (Fedorenko et al., 2024; Huth et al., 2016; Pereira et al., 2018). Both typically leverage whole-brain analyses in tasks that demonstrate the selectivity of regions' activation to meaningful linguistic stimuli. In the former's, for example, a sentence vs. non-sentence passive listening task during fMRI (Fedorenko et al., 2010) is frequently used to define language-eloquent cortex (Malik-Moraleda et al., 2025) and/or contrast non-linguistic task performance (Kean et al., 2025). In the latter's, highly general podcast/story listening is preferred (Hamilton & Huth, 2020) for understanding activity response patterns to vector-semantic properties to generalise and even decode regional specifics of semantics (Tang et al., 2023). From these, it appears very difficult to generalise subregions' functional specialisation; Fedorenko et al. converge on the idea that much of the left hemisphere specialises at maximal specificity for 'language' (Fedorenko et al., 2024) and Huth et al. converge on the idea that response to semantics is a whole-brain activity (Huth et al., 2012). However, to-date, no instrumentalist approach has yet leveraged their whole-brain analyses with many heterogenous tasks to address the entailment of cytoarchitecture structures (sub-region functional specificity) and its consequences for constructing the ontology of the neurobiology of language, a theoretical endeavour based in terminological precision.

We position elementalism as an approach that bridges essentialism and instrumentalism. On one hand, we argue that high process specificity is the gold standard for determining the true functional character of a region – an essentialist tenet. On the other, we also advocate the practice of post hoc inference over whole-brain analyses – *qua* instrumentalism. However, elementalism differentiates itself in two ways. First, it prefers causal mechanisms for studying language neurobiology over correlative: neuromodulation. As the gold standard for determining function, DES, transcranial magnetic stimulation (TMS), and perhaps transcranial electrical stimulation (tES) techniques have directly probed functional involvement compared with magnetic resonance imaging (MRI; Chang et al., 2015), for example. This is a methodological, rather than a theoretical, differentiation, but to start with neurostimulation as the tool of choice represents a theoretical commitment to scrutinising region-specific functional responsibilities. Second, it prefers task heterogeneity in defining regions of language neurobiology, not only on different levels of neuroanatomical (sub-)region(s) – from by-coordinate to by-lobe levels – but then amalgamating across the brain to generalise by-level functional characteristics. This approach advocates that to know a region's functional character, one must probe its involvement in responses to many unrelated tasks and qualitatively account for its individual responsibility (Genon et al., 2018); one that contrasts the instrumentalist perspective of unconstrained tasks (Hamilton & Huth, 2020) and homogeneous definition of the language network (Fedorenko et al., 2010; 2012). The elementalist ambition is that this pursuit leads to tighter terminological precision in the definition of the language neurobiology ontology.

To substantiate this approach, we completed an exhaustive preregistered systematic review of papers evidencing neuromodulation of specific linguistic (sub)processes. We then conducted a qualitative analysis to more precisely characterise the process(es) or function(s) targeted by modulation by the authors. To achieve these outcomes, we apply our approach: *elementalism*. Elementalism specifies that the building blocks of general, traditional constructs in the neurobiology of language can be defined by the subprocesses that compose them: *elements* (see Table 1). We then conduct a qualitative analysis – with a novel framework inspired by a *super*model of language as told by neuroimaging – to most precisely characterise what function authors modulated. Here, we report answers to two key questions. First, to what extent do neurostimulation outcomes support the use of traditional terms from linguistic study ('semantics', 'syntax', etc.) in delimiting functional neuroanatomy? Second, contrasting essentialist and instrumentalist MRI models of language, what could an elementalist TMS model of the neurobiology of language be like?

Methods

The systematic review was preregistered on PROSPERO, a link to which can be found here: https://www.crd.york.ac.uk/PROSPERO/view/CRD42024602006. Stages of the review are detailed schematically in Figure 1.

Search, selection, and screening

Database search lasted between October 2024 and January 2025, which utilised four databases and returned 12,763 records, of which 932 were from PubMed (819/11,600), Scopus (15/432), Embase (40/179), PsychInfo (58/552). After checking for duplicates, 554 papers remained. The abstracts of these were then screened using Rayyan according to four exclusion criteria: wrong publication type (e.g., conference paper), wrong population type (e.g., not healthy – for TMS and or neuro-oncology patients), wrong outcome (e.g., no process specificity; authors only report modulation of 'language'), and wrong study design (e.g., not using neuromodulation). Papers with gesture as the explanandum were excluded as it is not clear what its separation from language is neurobiologically (Hagoort & Özyürek, 2024), and embodied cognition papers were excluded as the status of sensorimotor systems' functional vs. epiphenomenal contributions to linguistic processing is a matter of academic debate (Mahon & Caramazza, 2008; Pulvermüller et al., 2005). Abstract screening returned 350 papers for data extraction.

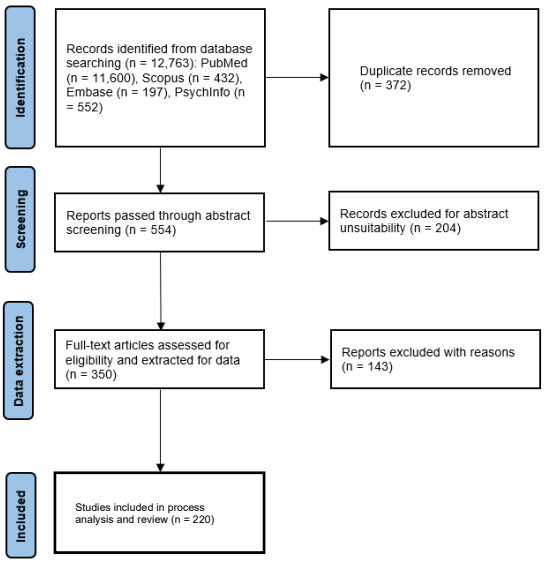

Figure 1: Methods stages in PRISMA Flow Diagram

Data extraction

Data extraction was completed for 44 different datapoints per paper, which constituted categories of: participant/patient information, stimulation methods (equipment, timing, settings, brain regions), materials methods (task, stimuli), analysis methods, and results (of stimulation, take-home finding(s)). Importantly, a subset of these were particularly critical for the later qualitative analysis step: task demands, stimuli contents, reported effects of stimulation, and stimulation site[1]. Papers excluded at this stage were for primarily due to a lack of spatial precision during site targeting (e.g., use of EEG scalp locations for TMS, given MNI- or Talairach-level coordinate specificity possible[2]) and a lack of significant outcome. On the latter, while we acknowledge that null results still confer inferential benefits for determining functional specialisation, a data-driven model that includes true negatives cannot prove true positives. Our worry with including null outcomes in our model is that their inclusion might facilitate inferences that yield false positives, as a null result can only tell you what is not true, not what is. Future work developing the Elementalist approach to language neurobiology, however, may plausibly include an additional aspect that specifies which regions are *not* implicated in specific sub-processes of language. Other reasons included an insufficiently clear link between dependent measure and linguistic effect of neuromodulation (e.g., motor evoked potentials, neural oscillations, cortical silent periods, event related potentials), and lack of a sufficient outcome (e.g., not targeting a linguistic process). Completion of data extraction yielded 221 papers, published between 1999 and 2025.

Element analysis

Novel as an approach to our knowledge, we completed a further qualitative step in our review. This was motivated by the high level of process generality uncovered during data extraction for the datapoint 'reported process implicated'. One paper might say they implicate 'semantic processing', while another could detail 'taxonomic relations processing', for example. To ensure generalisations over papers yielded reliable comparisons, we documented reported or inferred process specificity at three levels of depth (i.e., process, sub-process, sub-sub-process). Importantly, entries into these different depth levels variably constituted items within a 7-level hierarchy of process specificity. This hierarchy is multidimensional and reflects the levels of specificity reported in papers rather than being a precise neurocognitive ontology per se, although it serves as a useful first step to determining the levels of specificity at which analysed processes may reside. This was defined within an internally consistent logic for key terms (e.g., activity, task, neuron, object), and it was ordered in such a way that, as far as possible, items of more specificity on the hierarchy might represent smaller subregions of neuromodulated tissue, although the determination of a process as pertaining to a particular level involved consulting all datapoints collected in our review per paper outcome (see below). We acknowledge that this hierarchical organisation is rudimentary, and future work will be required to make it more valid and applicable. We iteratively codified these into a latent thematic analysis framework (Braun & Clarke, 2006) for inference over extracted datapoints. The levels and examples from each are detailed in Table 1.

Table 1: Hierarchy of process specificity

Hierarchy of specificity for defining modulated elements		*Example from a paper*	*Citation*
An **activity,** which is defined with respect to either of:	**Objects** of internal capacities of the **neuron**	Articulation of /i/	Borodkin et al., 2022
	Objects of properties of the **task**	Heterophonic homograph polysemous association	Raviv et al., 2024
An **object,** over which one of several possible **activities** may operate		Grammatical gender	Cattaneo et al., 2009
A **circuit,** characterised by multiple possibly related **activities**		Lexical access	Brückner & Kammer, 2017
An **error** associated with some **activity** made in a **response**		Neologism	Sollmann et al., 2014
A **super-activity**, many unrelated/without a specific **circuit**, **object**, **activity**		Word learning	Farcy et al., 2024
A **discipline** dedicated to the study of the kind of **response**		Morphosyntax	Carreiras et al., 2012

[1] We concede that to attempt to derive functions from regions by using regions' perceived functional characters is circular; however, in cases of, e.g., differentiating identical task effects in by region, this data is helpful.

[2] Many older (i.e., pre-2010) TMS papers utilised this method. Our exclusion of these does not imply criticism; maximal precision in a systematic review is not aided by different specificity levels for the same device.

For clarity, operative (i.e., internally defined) terms are bolded. We define the possibly ambiguous ones for clarity. First, an element was contextually defined as one constituent activity implicated to perform a task coordinated by certain neurons within an entire response. Then, an activity was understood as a neuropsychological event (electrical or haemodynamic) coordinating neurons specialised for certain objects either as internal capacities or external properties of the task to deliver a response. A task is defined as a behavioural prompt that demands a response that coordinates a possibly unconstrained set of activities, coordinated into objects for specialised neurons (Makin & Krakauer, 2023) to react to. And, importantly, an 'object' is understood in the context that a neuron may be specialised in respect to internal capacities of the neuron (e.g., coordinating certain bodily systems, containing certain kinds of knowledge) or may correspond with certain neuron-external properties of the task (e.g., variables of stimuli, modes of presentation). These capacities and properties are considered objects. In spite of this neuropsychological technicality, it is important to note that the hierarchy is a descriptive tool for analysing process specificity generated over levels of (im)precision existing literature. Thus, it reflects apparent hierarchical organisation of neuropsychological processing in as much as stimulation papers' specificity can permit.

To enable robustness in any inference to function from the extracted stimulation site targeted datapoints, we compiled function-region claims from six different neuroimaging-based models of language (Hickok & Poeppel, 2007; Kuhnke et al., 2023; Matchin & Hickok, 2020; Lambon-Ralph et al., 2017; Turker et al., 2023; Voets et al., 2025) and one from DES (Duffau et al., 2014). This, a '*super*model' of the neurobiology of language, covers 42 distinct brain regions for language and maps equally onto the same levels of depth as the hierarchy of process specificity. Table 2 exemplifies this specificity in cases where two layers of depth is reached for four traditionally delimited areas of inferior frontal gyrus (IFG).

Table 2: *Super*model of language in the IFG[3]

Region	*Process*	*Sub-process*	*Model*
Op.	Phonological processing	Articulatory control	[1]
Op.	Semantic processing	Action concepts	[5]
Tri.	Semantic processing	Semantic control	[1] [3]
Tri.	Semantic processing	Motion concepts	[5]
Tri.	Syntactic processing	Linear morpho-syntactic processing	[4]
Orb.	Semantic processing	Semantic retrieval	[1]
Orb.	Semantic processing	Multimodal semantic integration	[5]
Orb.	Semantic processing	Smell/taste concepts	[5]
Vent.	Articulation	Speech motor planning	[1] [2]
Vent.	Semantic processing	Emotion concepts	[5]

[3] Op. = Pars opercularis, Tri. = Pars triangularis, Orb. = Pars orbitalis, Vent. = ventral premotor cortex. [1] Turker et al., 2023, [2] Duffau et al., 2014, [3] Lambon-Ralph et al., 2017, [4] Matchin & Hickok, 2020, [5] Kuhnke et al., 2023.

Results

Statistical overview

The 220 papers yielded on average 2.75 outcomes each, for a total of 608; that is, each paper reported nearly three significant effects of neuromodulation on a specific linguistic process. Outcomes refer to reported significant neuromodulation effects; elements refer to inferred (sub)processes. Population statistics are less consistently reported, owing to (a) occasional within-study ambiguity about which groups received which exposures and (b) the inclusion of both healthy participants and neuro-oncology patients, whose aphasic status is not always clearly specified (see Zyryanov et al., 2022). Under conservative inclusion rules, the dataset comprises approximately 6,500 unique participants. Counting by outcome, however (where the same participant features within different measurements in the same study), the number of people comes closer to 18,000. Across 22 reported languages, the most frequently tested by participant number were English (n = 1,789), German (n = 964), and Italian (n = 471) – though alphabetic and non-alphabetic as well as spoken and signed language were included in the dataset. Each significant outcome was powered by a mean sample size of 31.08 participants (SD = 29.39). The participant-weighted mean age was 24.3 years (range = 17–71).

The 608 outcomes were distributed across 311 from TMS, 173 from tES, and 113 from DES. The most common type of task involved picture naming (e.g., object naming, action naming, etc.), with 141 papers. Sentence-level tasks occurred in 56 papers, while semantic judgement/association tasks appeared in 38. The IFG was the most frequently targeted region, followed by parietal sites like supramarginal gyrus and angular gyrus as well as temporal sites like middle temporal gyrus, superior temporal gyrus, and anterior temporal lobe.

We prioritise two discussions of the data to exhibit its utility for reshaping practice in language neuroscience and modelling the neurobiology of language.

Discussion

Traditional linguistics terms and the brain

We briefly motivate our approach using prior philosophical and neuroscientific critiques of linguistic terminology. Wittgenstein made the early claim that many philosophical problems often boil down to issues around the vagueness of the terms being analysed (e.g., free will, morality, meaning, etc.; Wittgenstein, 1922). Then, Churchland's eliminative materialism argued that the understanding of the mind one gets from folk psychological terms (e.g., emotions, perceptions, desires, etc.) constitutes a false theory that would be properly replaced with complete neuroscientific understanding (Churchland, 1981). Instrumentalists Fedorenko et al. identify how concepts from linguistics like 'syntax', and 'pragmatics' often do not neatly correspond to neural architecture, and call for a

realignment of the 'cognitive ontology' (Fedorenko et al., 2024, p. 296).

If it is right that ordinary terms like 'semantics' (Reilly et al., 2023) and 'syntax' (Fedorenko et al., 2024) are poorly defined for scientific study, then an argument can be made that cognitive neuroscience might benefit from such a realignment (Petersen et al., 2024, p. 13). To introduce the elementalist approach, we answer the first of our two questions: to what extent do neurostimulation outcomes support the use of traditional terms from linguistic study ('semantics', 'syntax', etc.) in delimiting functional neuroanatomy? From our data, 388 outcomes were neatly determinable as implicating traditional linguistic areas of study: semantics (n = 176), phonology (n = 74), syntax (n = 33), phonetics (n = 30), language acquisition (21), and pragmatics (n = 20) – many of the rest were at interfaces. Of these 217 were reported with coordinate-level site targeting specificity (i.e., with TMS). For visualisation purposes, we select only those that apply to the left hemisphere (LH; n = 140); see Figure 2.

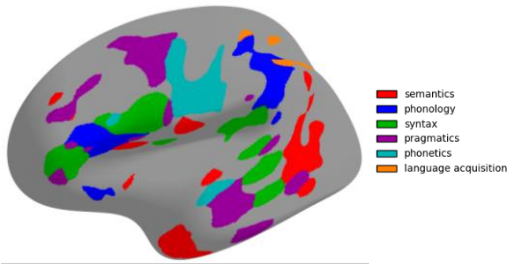

Figure 2: Traditional linguistics terms in LH

Visual inspection of Figure 2 helps to confirm different findings from neuroimaging models of language. A complicated picture of the IFG is painted, with syntactic (as in Matchin & Hickok, 2020), semantic (as in Kuhnke et al., 2023), and phonological (as in Turker et al., 2023) tripartite load share, plus pockets of pragmatic function too. Pragmatic functions also dominate middle and superior frontal gyrus, suggesting a kinship with executive functions like task switching (as in Duffau et al., 2014; Turker et al., 2023) The anterior temporal lobe is clearly established as semantic (as in Lambon-Ralph et al., 2017). Syntactic functions dominate strips of the temporal lobe (as in Matchin & Hickok, 2020), with perhaps further conceptual features' representations distributing amongst posterior temporal regions (as in Kuhnke et al., 2023). Phonetic function dominates (supplementary/sensori-) motor areas, highlighting articulatory capacities of neurons (as in Duffau et al., 2014; Matchin & Hickok, 2020; Turker et al., 2023; Voets et al., 2025).

Critically, however, visual inspection also reveals very few areas that functionally delimit in a way that respects terms from traditional linguistic study. This is exhibited in functions' *degeneracy* (Price & Friston, 2002) – there is no one semantics or one phonology area. These functions are often described as distributed, but this reflects the imprecision of the terms rather than clear functional boundaries. Perhaps these terms are useful in capturing neural network interactions that certain tasks' demands elicit, but they bring us no closer to characterising regions' specific properties (Genon et al., 2018). And then on, their usage over the characterisation of grey *and* white matter (Duffau et al., 2014) misses the kinds of specialisation that these different neural structures may favour. The neural degeneracy of traditional linguistic categories is especially relevant to white matter because it is through white matter that *networks* connect, and it is only really at the level of specificity of the network that traditional linguistics terms appear neurobiologically valid. Indeed, this may be why characterising the functional reorganisation of linguistic abilities post-stroke/-glioma is so scientifically complex (Makin & Krakauer, 2023; Ng et al., 2023; Nieberlein et al., 2023) – while the white matter tracks may show from where to where a function reorganises, precisely *what* reorganises, and thus *what* a patient may be able to recover, is the hard problem. It is on this point that the elementalist perspective aims to contribute: bottom-up functional recharacterisation over large participant samples and heterogenous tasks to specify neurolinguistic elements at the sub-region level with causal methods. Mapping on this level of specificity – beyond imprecise terminology – may permit a more detailed understanding of the compounding of elements that network interconnectivities yield.

With the example at hand, the IFG, one step in this elementalist direction could be to conceptualise the region as a 'language control' hub, thematically in keeping with the frontal gyrus' executive, attentional control functions. Though speculation, this would confirm sub-region specialisations observed for Op. and articulatory control (Turker et al., 2023) and for Tri. and semantic control (Lambon-Ralph et al., 2017). Further by-region generalisations within the elementalism framework may be required for other brain regions, perhaps with support from methods involved in cytoarchitectural analysis (Fedorchenko et al., 2025).

A TMS model of the IFG

The IFG has been of fascination to language neuroscience since Broca's original case work (Broca, 1861). On the theoretical side, Chomskyan interest in a 'language acquisition device' (Chomsky, 1965; Musso et al., 2003) and in finding a core linguistic computational function, perhaps also represented neurobiologically (e.g., 'Merge'; Chomsky, 2014; Friederici et al., 2017), have profiled a possible role for the IFG as a core linguistic region. Further, neuro-oncology cases of complete IFG resection without language deficit (Plaza et al., 2009) spark fascination in the brain's capacity for functional reorganisation, especially in low-grade glioma patients (Hartwigsen, 2018; Nieberlein et al., 2023). To exemplify the specificity possible in the elementalist approach, here we attempt to answer the second of our two questions: contrasting essentialist and instrumentalist MRI models of language, what could an elementalist TMS model of the neurobiology of language be like? While our data may enable a fine-grained functional characterisation of many brain regions, in keeping with the prior discussion of its functionality, we use TMS studies of the IFG as a proof of concept for the elementalist approach for future work.

In our data, 33 papers across 36 different stimulation sites targeted the IFG with TMS. From these, we were able to find sufficient process specificity within 29 papers

(minding the spatial clustering of the corresponding 31 stimulation sites) to generalise three (theory-neutral) plausible thematic groupings. We choose a qualitative approach here, rather than a quantitative (e.g., with a principal component analysis) as these thematic groupings are untested in experimental contexts and these suggestions are most robustly positioned as speculative. We also pitch our analyses at the level of an activity defined with respect to the objects of the properties of the task, as specified in our hierarchy (see Table 1). Thus, three possible core elements of *non-local feature combination*, *temporal sequencing of speech units*, and *executive control over language* may feasibly emerge – see Figure 3.

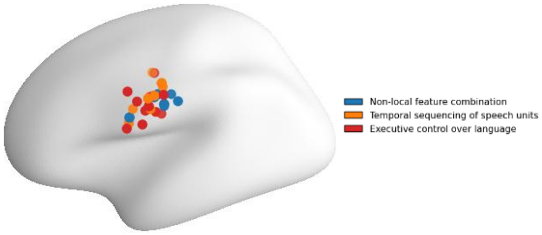

Figure 3: Possible elements of the IFG

It is important to stress that visual inspection of this atlas represents an average (through our own observational clustering) of an average (in that papers' reported MNI targets, e.g., are over their entire participant pool). However, these possible elements do somewhat cluster in an interesting fashion. Executive control, made of studies investigating language switching (Wu et al., 2024), demanding semantic retrieval (Klaus & Hartwigsen, 2019; Whitney et al., 2011), and lexical selection (Krieger-Redwood & Jefferies, 2014; Zhang et al., 2019), for example, take anterior and slightly superior positions. The temporal sequencing of speech units, which concerned more syllabification (Schuhmann et al., 2012; Shinshi et al., 2015) and phonological encoding (Zhang et al., 2018) are more central and also extend superiorly. And non-local feature combination, which included processing non-adjacent (Uddén et al., 2017) and long-distance dependencies (Lauro et al., 2010; Meyer et al., 2018) as well as learning morphological rules (Ren et al., 2024), mostly preserves a posterior position.

The purpose of such a recharacterising exercise is not simply to replace one term with another. It is to provide a more precise description of the region's function, which entails postulating a reduced set of contexts – i.e., specific task demands – in which sub-regions are implicated. To say that posterior IFG does *non-local feature combination* and not "syntax" necessarily precludes it from other "syntactic" operations as the term traditionally entails – e.g., agreement (Vidorreta et al., 2011) and transitivity (Ntemou et al., 2024), both of which also attested in our model in non-IFG regions. We do not attempt to position this idea as conclusive, as it may well be the case that non-*non-local feature combination* syntactic functions are implicated in the IFG. What we profile, however, is that constraining the set of operations specified by a region enables greater neurobiological precision.

And so, as per our conclusion in the previous section, we suggest that these data give rise to the possibility to characterise, at least in part, and bottom-up (Genon et al., 2018), the IFG as a general 'language control' region. All these three thematic groupings, which could feasibly occupy differing sub-regions of the IFG, demonstrate some kind of cognitive control over the objects of language – speech sounds, lexemes, and the selection of features to combine.

Conclusion, outlook, and limitations

Modelling the neurobiology of language has fascinated scientists for decades. Advances in neuroimaging technology have allowed those interested in the functional character of specific regions (essentialists) and the discovery of the best tools to elicit the strongest haemodynamic responses (instrumentalists) to probe the language-eloquent cortex. In clinical circles, neurostimulation has been accepted as gold standard for mapping linguistic functions for over 70 years. Yet, no neuromodulation approach to modelling language in the brain has yet been offered that can exploit its spatial precision whilst leveraging the advantage of a whole-brain approach. In our offer of elementalism, we wish to provide not only a scientific framework for establishing neurolinguistic structure-function relationships.

We also aim to catalyse a global effort for data collection in the elementalist pursuit. Our systematic review has been compiled into an aggregated, AI-powered data platform that is free and open-access, viewable at www.language-elements.org. It has two core functionalities: the Elements tab, which provides detailed neuroscientific breakdown for elements of the neurobiology of language by region, task, stimuli, etc; and the Tasks tab, which returns summaries of regional characteristics in language and suggests tasks that could be suitable for deployment intraoperatively by-region. This resource has similarities to Neurosynth (Yarkoni et al., 2011), but differs in its use of neurostimulation methods over neuroimaging (which better probe functional involvement in processes) and its emphasis on terminological specificity of elements (where Neurosynth only uses one-word entries as processes). This resource can enable scholars to investigate past research and also submit published work to update its contents, and thus precision, indefinitely. We also plan to integrate it with neurosurgical tools currently in development (Jamjoom et al., 2024; Veljanoski et al., 2024) to facilitate ease of access, exploration, and care for neuro-oncology patients.

With all approaches, ours too suffers limitations. We currently operate at best from a coordinate-based understanding of the data: stimulation site and outcomes determine element assignment and functional grouping. But this presumes that superficial interpretations of task demands adequately specify the neuropsychological constructs tapped into by that task. Furthermore, our modelling also presumes that neurostimulation data is reproducible (cf. Bergmann & Hartwigsen, 2021) and reliable (cf. Picht et al., 2013) – both of which are not guaranteed.

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