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REVIEW

Language processing from the perspective of electrical stimulation mapping

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ABSTRACT
Electrical Stimulation (ES) is a neurostimulation technique that is used to localize language functions in the brain of people with intractable epilepsy and/or brain tumors. We reviewed 25 ES articles published between 1984 and 2018 and interpreted them from a cognitive neuropsychological perspective. Our aim was to highlight ES as a tool to further our understanding of cognitive models of language. We focused on associations and dissociations between cognitive functions within the framework of two non-neuroanatomically specified models of language. Also, we discussed parallels between the ES and the stroke literatures and showed how ES data can help us to generate hypotheses regarding how language is processed. A good understanding of cognitive models of language is essential to motivate task selection and to tailor surgical procedures, for example, by avoiding testing the same cognitive functions and understanding which functions may be more or less relevant to be tested during surgery.

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Awake surgery; language; direct electrical stimulation; cognitive neuroscience

Introduction

Electrical Stimulation (ES) is a neurostimulation technique that is typically used to neurally map motor, language, or other cognitive functions in individuals with pharmacologically intractable epilepsy and/or who are undergoing brain tumor surgery (e.g., Duffau et al., 1999; Ojemann, Ojemann, Lettich, & Berger, 2008). It involves the administration of a 4–5 s electric current with an intensity of 1–6 mA and a frequency of 50–60 Hz, while individuals perform cognitive tasks. ES can be administered via subdural grids (SG), with a monopolar/bipolar probe (here, we refer to it as Direct Electrical Stimulation-DES), or with intracerebral electrodes (ICE). The first two techniques allow the application of the electrical current directly to the cortex and subcortical/axonal brain areas (e.g., Bello et al., 2007; Pallud et al., 2017; Roux, Durand, Djidjeli, Moyse, & Giussani, 2017; Szelényi et al., 2010), and the third technique is particularly suited to map subcortical areas (Jonas et al., 2014). Electrical stimulation requires the cooperation of a surgical team and the active collaboration of the patient, who may be asked to respond to a variety of tests during surgery or after the implantation of subdural grids (for reviews, Hamberger, 2007; Rofes, Spena, Miozzo, Fontanella, & Miceli, 2015). The use of this technique is widespread, as it is safe, easy to use, and increases the precision of the surgery while minimizing permanent postoperative impairments (e.g, Borchers, Himmelbach, Logethetis, & Karnath, 2012; Desmurget, Song, Mottolese, & Sirigu, 2013; De Witt Hamer, Robles, Zwinderman, Duffau, & Berger, 2012; Dragoy, Chrabaszcz, Tolkacheva, & Buklina, 2016; Ilmberger et al., 2008; Kayama, 2012; Sanai, Mirzadeh, & Berger, 2008).

ES provides an opportunity to understand cognitive functions in vivo, including language. Ojemann (1983) described a language model that identified language components (whether they are considered tasks or functions, as we explain below) such as “naming, reading, short-term verbal memory, mimicry of orofacial movements, and phoneme identification during neurosurgical operations under local anesthesia”. The model was used to explain how these components occur and overlap in the cortex of the left hemisphere. More than 30 years later, the neurosurgical field has expanded to the point that there is an increasing need of testing tools standardized for clinical practice, as well as an increasingly fine-grained analysis of intraoperative responses in the light of

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current cognitive models. Examples of this increased interest are the numerous studies regarding the neural substrates of many cognitive functions (e.g., Duffau, 2015; Giussani, Roux, Lubrano, Gaini, & Bello, 2007; Mandonnet, 2017; Zanin et al., 2017), descriptions of common practices among expert centres (Mandonnet, Wager, et al., 2017; Rofes, Mandonnet, et al., 2017), discussions of advantages and disadvantages of intraoperative tasks (e.g., Rofes & Miceli, 2014; Rofes, Spena, et al., 2015), the standardization of batteries of tasks to assess patients at different surgical stages (e.g., De Witte et al., 2015; Połczyńska, 2009), ethical considerations (Chiong, Leonard, & Chang, 2017), as well as the advent of neuro-anatomically specified models of language processing (e.g., Bohland & Guenther, 2006; Chang, Raygor, & Berger, 2015; Duffau, 2015; Duffau, Moritz-Gasser, & Mandonnet, 2014; Fernández-Coello et al., 2013; Hickok & Poeppel, 2004; Indefrey & Levelt, 2000; Mandonnet, 2017; Tourville & Guenther, 2011).

Following this interest, here we focus on a subset of studies to highlight how findings from ES can be explained within two cognitive models of language that are not neuro-anatomically specified, and to argue for the value of ES as a method for advancing our understanding of cognitive neuroscience/neuropsychology. Even though some aspects inevitably relate to brain anatomy, it is not our goal to identify which brain areas and networks are recruited to aid in the processing of specific functions (for reviews see Chang et al., 2015; Duffau et al., 2014; Fernández-Coello et al., 2013; Mandonnet, 2017; Selimbeyoglu & Parvizi, 2010). Rather, here we focus on the value of ES as a method to unveil the intricacies of cognitive functions and how these are organized. This is a fundamental topic in cognitive neuroscience, as this knowledge is relevant to issues such as understanding how functions occur (e.g., parallel vs serial), how two or more functions may associate or dissociate, and which functions (if any) are unique to a specific cognitive domain or input modality. This information is also of clinical importance, as it may allow surgical teams to maximize the number of cognitive domains they test and to make decisions regarding which language tasks may be more appropriate to administer. For example, in testing naming, teams may choose to test finite verbs over nouns. This is because naming finite verbs recruits similar perceptual and lexico-semantic functions as object naming, yet, in individuals with post-stroke aphasia it has been shown to correlate more strongly with language abilities in daily life, in comparison to object naming, verb generation, and naming infinitives (Rofes, Capasso, & Miceli, 2015).

This article is structured as follows: first, we provide a short explanation of the role of language tasks and cognitive functions in an ES context; second, we examine two cognitive models that are used in the aphasiological literature and that apply to the ES context; third, we explain how results from tasks used in ES can be used to inform cognitive models of language through the identification of associations, dissociations, and double dissociations between functions; fourth, we review previous ES findings from the perspective of cognitive models of language; and, finally, we draw some parallels between ES findings and classic reports from the aphasiological (stroke, trauma, dementia) literature, and reflect on some of the challenges of interpreting ES data to understand the organization of language functions.

Language tasks and cognitive functions

In an ES context, language tasks include sets of images, words, or sentences that patients are asked to respond to before, during, and after surgery. Before surgery, tasks help the surgical team to decide which language functions are impaired and which items should be used for mapping. During surgery, tasks allow the surgical team to find specific brain areas and networks that relate to language processing, thus providing information on the likelihood of postoperative damage. After surgery, tasks are useful to detect the presence of language impairment and optimize rehabilitation. One of the most frequently used tasks in surgical studies is object naming (e.g., Duffau et al., 1999; Ojemann et al., 2008). In this task, a patient is shown a picture of an object and asked to say its name (e.g., for a picture of an apple, a patient is asked to say "apple" or "this is an apple"). This task is also called "picture naming", "confrontation naming", or "noun naming". Many other tasks have been used during surgery, albeit sparingly (see for a review, Rofes, Spena, et al., 2015).

A cognitive function is a mental process or set of mental processes necessary to perform a task. A cognitive function is not unique to a specific task. For example, *accessing spoken word forms* via the phonological output lexicon (a store of spoken word forms) is necessary in tasks such as object naming, reading sentences aloud, sentence completion, and translating paragraphs. Also, tasks require more than one cognitive function. For example, object naming recruits functions that relate to object and picture recognition (i.e., extracting perceptual features, binding features into objects, recognizing objects as familiar, accessing non-verbal conceptual meaning representations) and spoken word production (i.e., accessing word meanings, generating phonemic strings, articulation). Finally, the same brain area(s) may be recruited to perform different tasks. For example, the middle temporal gyrus (MTG) and some of its subcortical pathways have been reported as relevant for word repetition, object naming, and reading (Sarubbo et al., 2015). This could be due to the fact that the same area is involved in a cognitive function shared by all of these tasks (e.g., accessing auditory word forms via the phonological output lexicon).

Cognitive models of language

Models of language specify the cognitive functions involved in language or in specific language domains. An underlying premise of most current models of language is that the cognitive system is composed of independent functions that can be selectively impaired after brain damage (or during ES). No single model explains all cognitive functions necessary to process all aspects of language and specific models differ in several aspects. For example, it is debated whether lexical-phonological and grammatical information are accessed sequentially or in parallel (Miozzo & Caramazza, 1997; Patterson & Shewell, 1987; Roelofs, Meyer, & Levelt, 1998). In sequential processing, one function is engaged only after the previous one has been completed, while in parallel processing both functions can happen at the same time. Another example is the debate regarding whether the interaction between language processing levels is unidirectional (e.g., with conceptual features associated with a word activated prior to their respective lexical units; Bastiaanse & Van Zonneveld, 2004; Miozzo & Caramazza, 1997; Patterson & Shewell, 1987; Levelt, 1999) or bidirectional (e.g., with conceptual and lexical activation influencing each other in an interactive way; Dell, 1988; Rapp & Goldrick, 2000). Despite these differences, word and sentence processing models agree on the existence of conceptual features that generate meaning, syntactic features (including grammatical class, verb argument structure, gender, among others), and phonological representations that specify the segmental and supra-segmental phonological properties of words. Here, we concentrate on cognitive functions for which there is general consensus—detailed discussion of the differences between competing models is outside the scope of this article. We focus on two models of language that are used to study language impairments in people with aphasia (Garrett, 1980; Whitworth, Webster, & Howard, 2014). These models are monolingual models of language processing, at the sentence level and word level, respectively.

Figure 1 depicts a cognitive model for the production and comprehension of single words. The model is based on Whitworth et al. (2014).[1] The model contains cognitive functions that are commonly proposed (in other models) for comprehension and production of written and spoken words, and for picture recognition. A key aspect is a shared lexical-semantic system (central store of meaning, highlighted in grey). This level plays a central role because damage or interruption of this level will impair performance in oral and written word production and comprehension. Hence, information processed through each input modality converges at the lexical-semantic level, where conceptual representations of words are activated. For output modalities, it is the initial activation of the semantic features that prompts subsequent functions. This model features functions for visual object and picture recognition (i.e., extracting perceptual features, binding perceptual features into objects, recognizing objects as familiar, accessing non-verbal conceptual meaning representations), written and spoken word production (i.e., accessing word forms in the output lexica, generating ordered sequences of grapheme/phoneme strings in buffers, motor/articulatory programming), and written and auditory word comprehension (i.e., phonological/orthographic analysis for the discrimination of speech sounds and graphemes, recognition of word forms as familiar in the input lexica). Additionally, it contains non-semantic, sublexical routes that transform auditory and written input into auditory and written output without the involvement of lexical-semantics. In Figure 1, non-semantic routes are indicated with dashed lines. Non-semantic routes

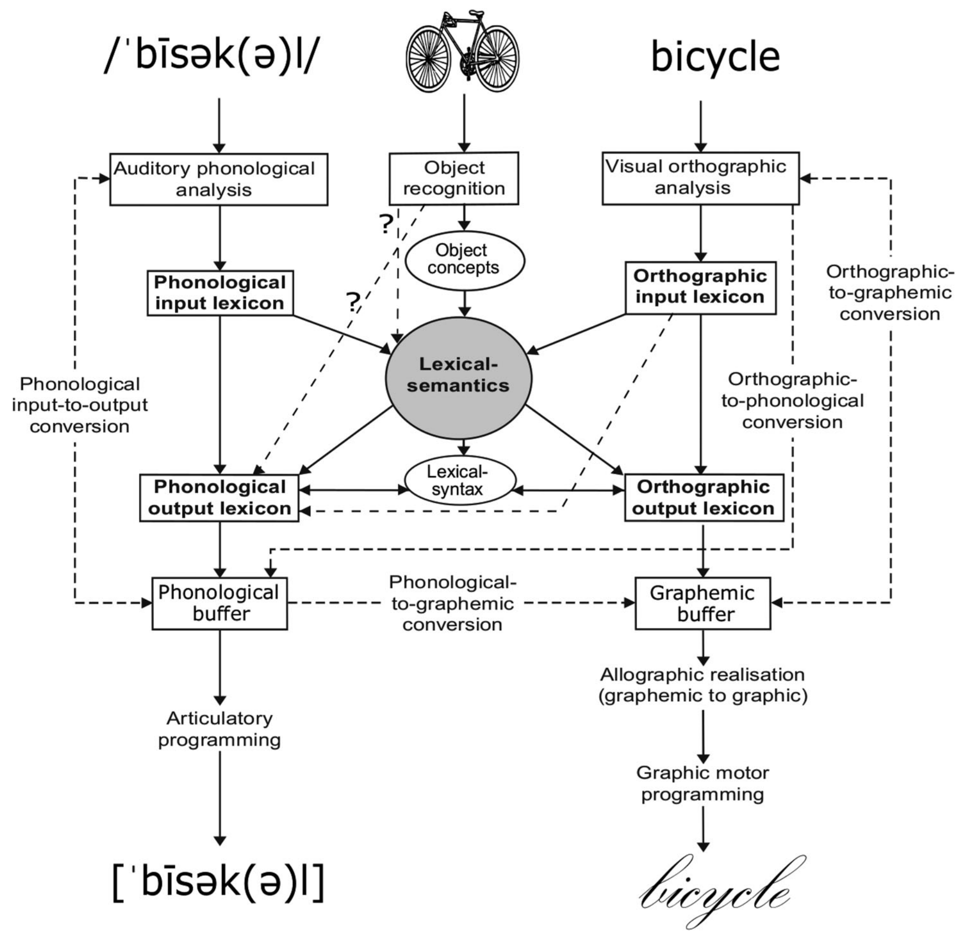

Figure 1. Single-word model of language processing (based on Whitworth et al., 2014). The connection that starts in object recognition and connects with the phonological output lexicon (highlighted in grey) is an addition to the model that can be supported with DES data.

contribute to different language processes, including the repetition/transcription of real words, the production of strings that are plausible but have no meaning (e.g., "buttle" in English or "naçon" in French), and, possibly, the learning of new words (e.g., Papagno, Valentine, & Baddeley, 1991). In this article, we use the term lexical-syntax to refer to agreement processes such as those that occur between the determiner and the noun in object-naming tasks introduced by a lead in sentence (e.g., "this is … "). This latter aspect is particularly relevant in languages such as French, where the determiner and the noun share agreement features (*Ceci est *un*$_{MASCULINE.SINGULAR}$ *vache* $_{FEMININE.SINGULAR}$ vs *Ceci est *une*$_{FEMININE.SINGULAR}$ *vache* $_{FEMININE.SINGULAR}$ [This is a cow]).

In Figure 2, we present a model for sentence production and comprehension. According to Garrett's model (Garrett, 1980), generating a sentence for speech includes at least three separate levels of representation: the message level, the functional level, and the positional level. The message level entails a speaker's communicative goals and the non-linguistic representation of the message that is to be conveyed, and therefore requires perspective taking, selection of content to transmit, and understanding of causality, agency, and temporal ordering of events. Subsequently, functional-level processing entails three operations: (1) semantic search (activation of meaning-related representations of the ideas to be conveyed and grammatical categories associated with corresponding concepts), (2) creation of the predicate-argument structure (determining the number of arguments associated with the main verb, and the thematic role of each argument), and (3) assignment of each semantic representation activated in (1) to a thematic role in the predicate argument structure created in (2). Finally, three other processes take place to form the positional level representation: (1) selection of an ordered sequence of syntactic features and slots for insertion of syntactic morphemes and

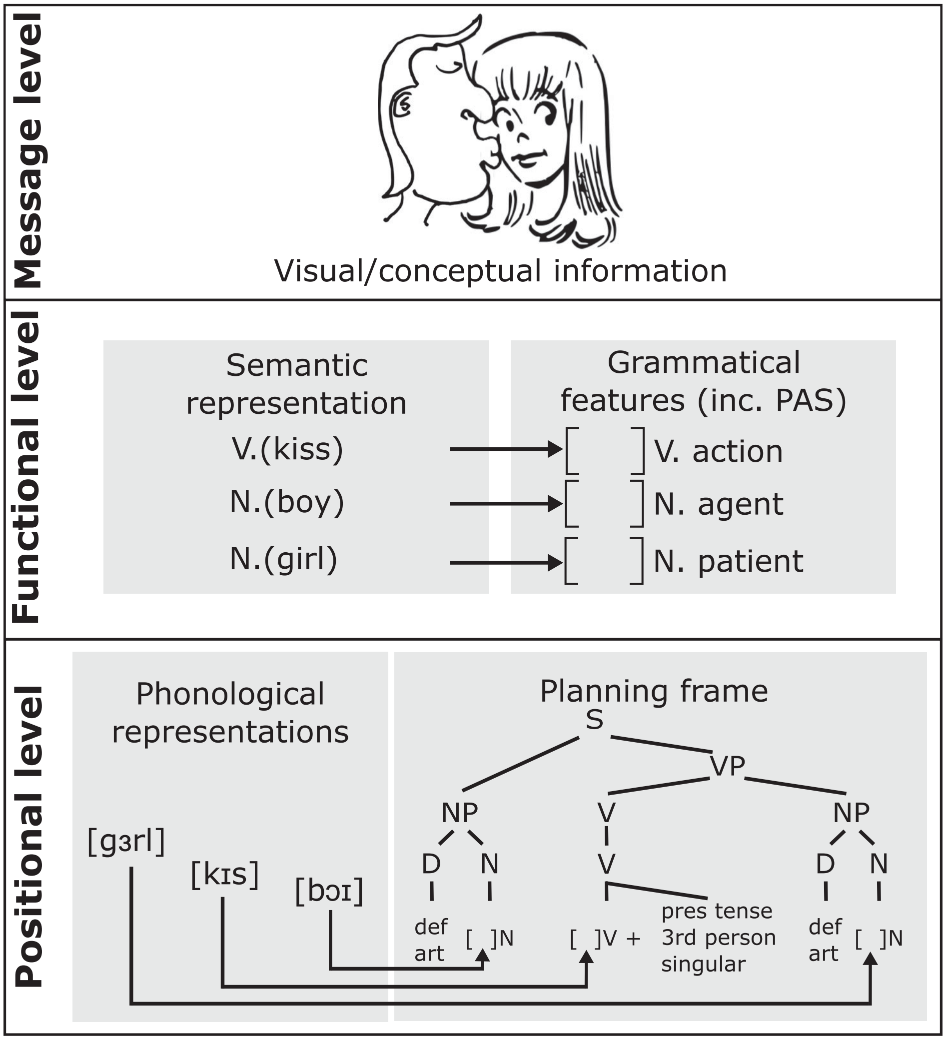

Figure 2. Sentence model of language processing (based on Garrett, 1980).

phonologically specified lexical representations (the planning frame), (2) retrieval of said phonological representations, and (3) insertion of each lexeme retrieved in (2) into a designated slot in the planning frame created in (1). Models of sentence processing agree on these levels of representation. It should be noted, however, that there is a long-running debate on whether or not the functions operate in parallel or serially and whether or not there is interaction between them. This discussion is beyond the scope of this paper (for a review, Thompson, Faroqui-Shah, & Lee, 2015).

Associations, dissociations, and double dissociations

Deciding which cognitive functions are required to perform a given task and how they relate to other cognitive functions are heavily debated topics (e.g., Hillis, 2015; Kemmerer, 2015; Pulvermüller, 2002; Stemmer & Whitaker, 2008). Some of these questions can be answered by studying the errors and error types of people with different neurological disorders (e.g., Mandonnet, Sarubbo, & Duffau, 2017; Rapp, 2001; Whitworth et al., 2014). By looking at the performance of patients during tasks that share cognitive functions, it is possible to individuate specific functions of interest. For example, if we administer a spoken object-naming task and a written object-naming task, we are assessing the same functions for object recognition and semantic processing. Yet, the functions engaged to produce the word are different, as the spoken visual object-naming task requires functions for spoken production (e.g., phonological output lexicon, phonological buffer, articulatory planning), while the written object-naming task requires functions for written production (e.g., orthographic output lexicon, graphemic buffer, graphic motor programming). By looking at the performance of patients, it is also possible to test whether functions can be teased apart (dissociation) or not (association) from other functions. For example, finding that a subject is impaired in spoken object naming and also in written object naming indicates that object recognition and access to semantics may be shared, regardless of whether the final output is a spoken or a written word. Also, finding that a subject performs well on spoken object naming and poorly in written object naming provides evidence that cognitive functions for written production are separate from functions needed for spoken production.

In an ES context, an area is deemed necessary for (or participating in) a language function when stimulation to that area systematically induces errors (e.g., often operationalized as two of three non-consecutive stimulations). Chi-squared tests comparing numbers of correct and incorrect responses during stimulation vs no-stimulation and other statistics can also be used to determine this (e.g., Herbet, Moritz-Gasser, & Duffau, 2017). Thus, two language functions *X* and *Y* are considered to be associated when ES to a brain area induces errors for both functions (*X*+, *Y*+). Contrary to an association, a dissociation between two language functions is attested when ES to a brain area systematically disrupts performance on cognitive function *X*, while leaving cognitive function *Y* unaffected (*X*+, *Y*–). Finally, a double dissociation is finding a brain area in one patient where ES induces errors during cognitive function *X* and not *Y*, and another brain area in the same (or in another) patient where ES induces errors during cognitive function *Y* and not *X* (brain area *A* = *X*+, *Y*–; brain area *B* = *X*–, *Y*+). Double dissociations rule out simple explanations of differences on the basis of task difficulty. Indeed, it has been argued that they are the strongest evidence to separate two cognitive functions (Ellis & Young, 1988). Note, however, that some authors have argued that single functions can give rise to double dissociations (Plaut, 1995).

Method

MEDLINE, PubMEd, and Web of Science records were searched for articles discussing aspects of the cognitive neuroscience of language using ES. The following search terms were used: awake surgery, (direct) electrical stimulation, electrocorticography, language, language mapping, neurosurgery, processing, comprehension, production, naming, repetition, reading, writing, syntax, grammar. Reference sections and citations of each of the ES articles were scrutinized to identify further topics and studies. In each study, the following aspects were considered: type of task and its cognitive components, stimulation sites, and ES method. We included studies where ES was used in people with brain tumors and epilepsy in the intraoperative setting (awake surgery) and some studies where stimulation was delivered with subdural gird implants outside the surgery. In total, 25 manuscripts regarding ES and language processing were identified. We organized the discussion according to auditory/ written comprehension and or spoken/written production. We focused on specific dissociations and associations reported by the authors or on our own interpretations based on their results and the two cognitive models we outlined above. The results are organized according to components indicated in the two models.[2]

Results

A summary of the studies according to the specific cognitive components reported can be found in Table 1.

Auditory comprehension

Dissociation between vowels and consonants within auditory phonological analysis

Auditory phonological analysis allows for the discrimination of speech sounds and distinguishes environmental and speech sounds (Auerbach, Allard, Naeser, Alexander, & Albert, 1982; Denes & Semenza, 1975; Whitworth et al., 2014). DES studies suggest that discrimination functions for vowels and consonants occurring during auditory phonological analysis dissociate from one another and that both rely on the superior temporal gyrus (STG). Boatman et al. (1995) implanted a subdural grid in the left temporal lobe of three people with epilepsy. The authors found specific sites where stimulation of the STG induced errors in vowel and consonant–vowel discrimination and in vowel and consonant–vowel identification, and other sites in the STG where stimulation

Table 1. Summary of the papers per modality and dissociation, including information on the method, tasks used and regions stimulated.

Modality	Dissociation	Paper	Method	Tasks	Regions stimulated
Auditory comprehension	Between vowels and consonants within auditory phonological analysis	Boatman, Lesser, and Gordon (1995)	SG	Phoneme identification and discrimination	Left STG
		Boatman, Hall, Goldstein, Lesser, and Gordon (1997)	SG	Phoneme identification and discrimination	Left STG
	Between auditory comprehension of single words and sentences	Malow et al. (1996)	SG	Naming to definition, object naming, auditory word-to-picture matching	Left STG
		Hamberger, Goodman, Perrine, and Tamny (2001)	DES	Naming to definition	Left ATL
		Matsumoto et al. (2011)	SG	Auditory sentence comprehension	Left STG
Spoken production	Between lexical and sublexical pathways in word and pseudoword repetition	Sierpowska et al. (2017)	DES	Auditory word repetition, auditory pseudoword repetition	Left MTG, left AF
	Between object concepts and lexical-semantics in object naming and nonverbal picture association	Herbet et al. (2017)	DES	PPTT, object naming	Left and Right IFOF
		Herbet, Moritz-Gasser, and Duffau (2018)	DES	PPTT, object naming	Left and Right dorsolateral prefrontal cortex
		Moritz-Gasser, Herbet, and Duffau (2013)	DES	PPTT, object naming	Left IFOF
		Gatignol, Capelle, Le Bihan, and Duffau (2004)	DES	PPTT, object naming	Left STG
	Between lexical-semantic processes involving nouns and verbs	Lubrano, Filleron, Démonet, and Roux (2014)	DES	Object naming, action naming	Left MFG
		Havas et al. (2015)	DES	Object naming, action naming	Left STG
	Between lexical-semantics/phonology and lexical syntax in nouns, verbs, and sentences	Vidorreta, Garcia, Moritz-Gasser, and Duffau (2011)	DES	Object naming	Left IFG, left MFG, left STG, left SMG
		Corina et al. (2005)	DES	Object naming, action naming (videos)	Left STG, left SMG, left MTG
		Rofes, Spena, Talacchi, Santini, Miozzo, and Miceli (2017)	DES	Object naming, naming finite verbs	Left IFG, left MFG
		Chang, Kurteff, and Wilson (2018)	DES	Sentence production	Left IFG
	Between lexical-semantic processes involving living and non-living things	Ilmberger, Rau, Noachtar, Arnold, and Winkler (2002)	SG	Naming animals, naming tools	Left frontal lobe, left STL
	Between lexical-semantic processes involving common and proper nouns	Giussani et al. (2009)	DES	Object naming, naming faces	Left STG, left MTG, right MFG, right SMG
		Glosser, Salvucci, and Chiaravalloti (2003)	SG	Naming faces	Left temporal lobe
		Allison, McCarthy, Nobre, Puce, and Belger (1994)	SG	Object naming, Naming faces	Left fusiform, left ITG
		Parvizi et al. (2012)	SG	Naming faces, naming scenes	Left fusiform
		Jonas et al. (2014)	ICE	Object naming, naming faces	Right OG
Written comprehension	Between lexical and sublexical pathways in word and pseudoword reading	Zemmoura, Herbet, Moritz-Gasser, and Duffau (2015)	DES	Reading regular words, reading irregular words, reading pseudowords	Left posterior inferior temporal cortex
Written production	Between reading writing and speaking	Lesser, Lueders, Dinner, Hahn, and Cohen (1984)	SG	Reading sentences, writing sentences	Left MTG, left IFG, left SMG
		Roux et al. (2014)	DES	Reading single words, writing to dictation, object naming	Left postcentral gyrus, left SMG, left STG, left MTG

Note: AF = Arcuate Fasciculus; ATL = Anterior temporal lobe; DES = Direct Electrical Stimulation, ICE = Intracerebral electrodes; IFOF = Inferior frontal occipital fasciculus; MFG = Midfrontal gyrus; MTG = Middle temporal gyrus; OG = Occipital gyrus PPTT = Pyraminds and Palm trees test; SG = Subdural grids, SMG = Supramarginal gyrus; STG = Superior temporal gyrus.

induced errors only during identification and not during discrimination. The identification tasks required participants to point to the target they heard when given four orthographic choices (/pa/ *pa*, ta, ba, ga) or four pictures, including three phonological distractors and one semantic distractor (/bi:/

pea, *bee*, key, ant). The discrimination task consisted in responding "same or different" when listening to two vowels or two consonant–vowel pairs (same /pa/-/pa/; different /pa/-/ba/). Boatman et al. (1997) provided converging evidence using a syllable discrimination task in which patients heard a consonant–vowel or vowel–consonant pair and were asked to indicate whether the pair was the same (e.g., /pa/-/pa/; /ap/-/ap/; /poi/-/poi/) or different (e.g., /pa/-/ta/; /ap/-/at/, /poi/-/pai/). Boatman et al. (1997) found a site in the posterior part of the STG where patients had more difficulty identifying consonants than vowels in syllable pairs (in both consonant–vowel and vowel–consonant pairs), hence finding a dissociation between discrimination of vowels and consonants during auditory phonological analysis. This dissociation indicates that consonant and vowel perception require different functional resources. However, as there was some degree of impairment for both consonants and vowels, it could also be argued that the posterior part of the STG is actually relevant for both functions, and that differences were due to greater task difficulty for discriminating consonants than for discriminating vowels. A double dissociation would be especially helpful in distinguishing between these two alternatives. The dissociation between vowels and consonants is also supported in studies using high-density direct cortical surface recordings (Mesgarani, Cheung, Johnson, & Chang, 2014).

Dissociations between auditory comprehension of single words and sentences

Single-word comprehension is different from sentence comprehension, as the former does not require the range of grammatical functions and working memory needed for the latter (Garrett, 1980). This distinction is illustrated with DES. Malow et al. (1996) implanted a subdural grid in the temporal lobe of people with epilepsy. The authors used three tasks: naming to definition (participants are given a short oral description of an object [Tell me what's a barking pet] and are asked to produce the name of the object [DOG]), object naming (participants are shown the drawing of an object and asked to produce its name), and auditory word-to-picture matching (participants are given four drawings and are asked to point to a word they hear). These authors found seven sites in the middle and posterior STG where only naming to definition was impaired. One distinctive feature of naming to definition in relation to the other tasks is that auditory comprehension of sentences is required. Hence, these data may indicate that the STG plays a role in sentence comprehension, which is functionally different from the auditory word comprehension required for word-to-picture matching or the comprehension of visual stimuli required in word-to-picture matching and object naming. According to Garrett's (1980) model, sentence comprehension required for naming to definition involves functions engaging all levels of sentence processing (positional, functional, and message level). Word-to-picture matching, while a single word and not a sentence task, requires lexical-phonological knowledge that Garret describes at the positional level and lexical-semantic knowledge represented at the functional level. Furthermore, given that in word-to-picture matching an auditory word is matched with a picture, non-linguistic, conceptual information like that represented at the message level is also engaged by this task. Hence, a comparison between word-to-picture matching and sentence comprehension required by naming to definition does not allow studying dissociations between the message, functional, and positional levels described by Garrett (1980). At the same time, the comparison shows that auditory comprehension of single words and sentences is dissociable.

Other studies have shown that sentence comprehension requires a broader neuroanatomical network. For example, Hamberger et al. (2001) reported that naming to definition was poor and object naming was spared when DES was applied in the anterior temporal lobe of 20 people with epilepsy. Further evidence comes from Matsumoto et al. (2011) where it is indicated that stimulation to the anterior STG in a person with epilepsy induced errors in auditory comprehension of sentences with preserved perception of environmental and music sounds and visual sentence comprehension.

Spoken production

Dissociation between lexical and sublexical pathways in word and pseudoword repetition

Word repetition can make use of functions that are not available for pseudoword repetition. Repeating words can engage the phonological input and output lexica (to find the lexical item to access meaning and to retrieve its phonological form) and lexical-semantics (the store of word meanings). Pseudoword repetition is different because, by virtue of not involving real words, it cannot engage the phonological input and output lexica or lexical-semantics. Pseudoword repetition can only utilize a phonological input-to-output conversion route that connects the auditory phonological analysis and the phonological buffer, with no intervention of the lexica or semantics (McCarthy & Warrington, 1984; Whitworth et al., 2014). DES studies shed light onto potential differences between functions involved in word and pseudoword repetition. Sierpowska et al. (2017) reported the intraoperative results of 12 individuals with brain tumors where resection posed a risk for the arcuate fasciculus. The authors used a word repetition task and pseudoword repetition task and reported more errors during pseudoword repetition than during word repetition when stimulation was applied in the arcuate fasiculus. In sum: the dissociation between word and pseudoword repetition by Sierpowska et al. (2017) implicates a distinction between lexical and sublexical processes used in word repetition—that is, the presence of the phonological input-to-output conversion route that connects the auditory phonological analysis and the phonological buffer without accessing the input/output lexica and lexical-semantics.

Double dissociation between object concepts and lexical-semantics in object naming and nonverbal picture association

Among different authors, the terms “object concepts” and “lexical-semantics” have sometimes been used interchangeably or with different meanings—this discussion is described in Bierwisch and Schreuder (1992, p. 31) and Nickels (2001, pp. 293 294, table 12.2). In this article, by “object concepts” we mean non-verbal conceptual meaning representations (including familiarity, relationships with other objects, use, context in which the object is found …) that go beyond what is strictly needed to define a word or retrieve it from the output lexica. In contrast, the term “lexical-semantics” refers to a store of word meanings that are necessary to define a word and that are activated in response to an idea or to an external stimulus. The distinction between these two functions is consistent with the observation that “people with intact object concepts but with a lexical semantic impairment will perform poorly in tasks involving words, but may perform well in non-verbal semantic tasks—for example, three-picture Pyramids and Palm Trees” (Whitworth et al., 2014, p. 28). DES studies have examined this issue.

Herbet et al. (2017) assessed 13 people with brain tumors in the right hemisphere (frontal, temporal, or parietal area) with the Pyramids and palm trees test (PPTT, Howard & Patterson, 1992) and an object-naming task. The authors used a three-picture version of the PPTT in which participants see three black-and-white drawings and are asked to match the drawing on top of the image with the drawing that is most associated (e.g., a drawing of a pyramid is associated more with a drawing of a palm tree than with a drawing of a pine tree). In ten patients, DES induced an inability to respond when applied to the right inferior frontal occipital fasciculus (IFOF) during the PPTT, while no errors were elicited during object naming. In three patients, stimulation induced non-responses during PPTT and semantic paraphasias during visual object naming. Similar findings to Herbet et al. (2017) were reported in an earlier study from the same group during stimulation of the left IFOF (Moritz-Gasser et al., 2013), where stimulation to the superficial level of the left IFOF generated semantic paraphasias during object naming and no errors in the PPTT, and stimulation to a deeper level of the left IFOF elicited disturbances of both object naming and PPTT. Similar findings to these have been reported in a recent study of the right and left dorsolateral prefrontal cortex (Herbet et al., 2018). At a functional level, inability to respond only during the PPTT can be understood if we assume disruption to object concepts, while the inability to respond to the PPTT and semantic paraphasias in object naming more likely corresponds to problems in lexical-semantics or with problems in both lexical-semantics and object concepts.

In agreement with these results, Gatignol et al. (2004) reported data of one right-handed male with a left temporal low-grade glioma who presented two cortical areas in the posterior part of the left STG where DES induced errors during object naming and not during PPTT. Importantly, Gatignol et al. (2004) reported another area, also in the posterior part of the left STG, where the patient produced errors during the PPTT and not during naming. This latter finding is more rarely described in the aphasiological literature (e.g., Ferrand, 1997; Kremin, 1986; Silveri & Colosimo, 1995) and raises interesting discussion points regarding the structure of the single-word model we proposed. If we consider that object naming and PPTT both require processing of object concepts and utilize the same functions for picture recognition (e.g., perception of low level features like luminance or orientation, grouping of features and parts into a 2D object, and building a 3D representation of the visual stimulus) to be able to name an object while being impaired on the PPTT, we would have to draw a direct connection between object recognition and the phonological output lexicon, bypassing object concepts or bypassing both object concepts and lexical-semantics (in Figure 1, see dashed arrows with question marks).

In sum, finding that DES induces errors during object naming and not the PPTT and vice versa indicates that there is a distinction between object concepts and lexical-semantics. Also, further work is needed to elucidate the existence of a direct route that can be used for naming without accessing object concepts or lexical-semantics. One possible argument against the direct routes is that PPTT may require different operations than object naming, such as high-level reasoning or attentional/executive function (Silveri & Colosimo, 1995) and a failure of these high-level processes may account for the specific difficulties with PPTT and not object naming.

Dissociations between lexical-semantic processes involving nouns and verbs

Retrieving a word for production requires a combination of functions occurring at the semantic and lexical levels (Whitworth et al., 2014). Picture naming is a task often used to assess the integrity of such functions. However, different grammatical word categories may functionally dissociate at either or both the lexical-semantic and lexical levels (e.g., Mätzig, Druks, Masterson, & Vigliocco, 2009; Miceli, Silveri, Nocentini, & Caramazza, 1988; Rapp & Caramazza, 2002; Shapiro & Caramazza, 2003c; Tsapkini & Rapp, 2010). Grammatical category effects have also been reported in DES research, illustrating differences in the processing of verbs and nouns. Lubrano et al. (2014) tested 41 people with a brain tumor undergoing awake surgery and tested naming of verbs and nouns. The difference between this task and the one used by Corina et al. (2005) is the use of picture stimuli instead of videos. This involves differences in object-recognition processing, but it is unlikely that it involves differences at the semantic level or other levels of spoken production. Lubrano et al. (2014) suggested a partial segregation of processing involved in noun and verb naming with noun-specific naming sites in the temporal cortex, and verb naming sites in the posterior midfrontal gyrus (MFG). Havas et al. (2015) reported the results of 10 people with brain tumors during awake surgery. The authors used a similar procedure as Lubrano et al. (2014). They showed black-and-white drawings of objects or actions to patients and asked them to say the corresponding noun (e.g., hat) or verb in the infinitival form (e.g., to dance). Havas et al. (2015) indicated a partial segregation of nouns and verbs in the brain. In the inferior/middle frontal cortex, they found that DES selectively disrupted verb naming in 45% of the language-related stimulation sites, while noun naming was selectively disrupted in 14% of the language-related sites. Additionally, the authors found more noun than verb-specific sites in the posterior part of the STG.

In sum, studies that have examined noun and verb naming have reported brain areas selectively involved in object naming compared to action naming and also other areas responding to both tasks. This suggests a potential dissociation of functions needed for the production of nouns and verbs in the brain, as well an association of functions that are shared by both tasks. Indeed, in the two studies we reviewed in this section the authors reported specific sites for the production of verbs in the MFG. However, the current ES evidence does not point clearly to a double dissociation between noun and verb production. Therefore, further work is needed to understand where processing for these word categories diverges. One possibility is to study whether differences between nouns and verbs may originate at either a lexical-semantic or lexical-syntactic/grammatical level (e.g., Shapiro & Caramazza, 2003c).

Dissociations between lexical-semantics/phonology and lexical syntax in nouns, verbs, and sentences

Vidorreta et al. (2011) studied the responses of nine people undergoing surgery for the removal of a brain tumor in the left hemisphere. The authors used an object-naming task including a lead-in sentence (*Ceci est …* [This is …]) to elicit a determiner together with the corresponding noun. This task is particularly relevant in languages such as French, where the determiner agrees in number and gender with the noun, as agreement errors can occur during DES (e.g., *Ceci est *un*$_{MASCULINE.SINGULAR}$ *vache* $_{FEMININE.SINGULAR}$ vs *Ceci est *une*$_{FEMININE.SINGULAR}$ *vache* $_{FEMININE.SINGULAR}$ [This is a cow]). In comparison to an object-naming task where patients are required to say only a noun, this object-naming task engages lexical syntactic processes, picture recognition, and spoken word production. Vidorreta et al. (2011) found areas where participants said the correct object but used an incorrect article when stimulation was delivered in the inferior frontal gyrus and the posterior middle temporal gyrus. Additionally, the authors reported other areas where patients produced the correct article but did not produce the noun. These areas were in the MFG, the pars opercularis of the IFG, the posterior part of the STG, and the SMG. Vidorreta et al. (2011) argued that these results showed that retrieving lexical-syntactic information related to a noun (through the article) is not a prerequisite for accurate noun retrieval. Finding areas where agreement errors occur in the absence of naming errors and vice versa suggests a double dissociation between lexical-phonology and lexical-syntax where the syntactic function of deciding how a determiner and a noun match in gender is separate from the lexical retrieval functions needed to name an object. It is worth noting that the authors do not report any instances in which patients said the name of the object without the corresponding article (e.g., *Ceci est _ vache* [This is _ cow]) or the definite instead of the indefinite article (e.g., "*la vache*" vs "*une vache*"). These types of errors could indicate grammatical difficulties explained in models of sentence production (Figure 2). That is, omissions of this sort could result from disruption in selecting of a sequence of sentence slots in the planning frame, retrieval of phonological representations, or lexeme insertion into a designated slot.

Dissociations have also been reported when comparing nouns and verbs in finite and non-finite form. Corina et al. (2005) assessed 13 people with subdural grids undergoing surgery for epilepsy and/or tuberous sclerosis. The authors elicited production of either a verb or a noun, both of which appeared in a video, with participants cued to respond to one or the other. Corina et al. (2005) performed two analyses: (1) considering all off-target responses as errors (e.g., no response, delay, paraphasia); (2) considering responses correct if participants used the correct grammatical category (e.g., for "a man peeling a banana", the unrelated response "dialing" was correct because a verb was used, while "banana" or "apple" would have been counted as incorrect if the participant was asked to produce a verb). Analysis (1) revealed areas were only nouns could be disrupted during stimulation (anterior part of the STG) and areas where both nouns and verbs could be disrupted (posterior STG and posterior MTG)—these results are similar to other studies looking at lexical-semantic dissociations (Havas et al., 2015; Lubrano et al., 2014). Analysis (2) revealed that errors during noun naming could be triggered when stimulating the anterior and middle STG, while errors during verb naming could be triggered when stimulating the SMG and the posterior MTG. Analysis (2) is relevant to the study of lexical-semantic and lexical-syntax dissociations, as it showed a dissociation between areas in which disruption resulted in inability to produce the correct grammatical category, regardless of whether or not participants produced the correct lexical item.

Rofes, Spena, et al. (2017) assessed 6 people with brain tumors. The researchers asked patients to say the name of an object, followed by the correct inflected article (*Ecco la mela* [Here (is) the apple]) and to say the name of an action in its correct inflected form (*Lei pettina* [She paints]). Differently from Corina et al. (2005), these authors asked subjects to use finite verbs, as opposed to infinitives. Hence, they used a verb task that overtly required the production of grammar in a short sentence. Rofes, Spena, et al. (2017) induced errors during the noun naming in the posterior part of the MFG and inferior frontal gyrus (IFG), and in subcortical sites corresponding to the middle and posterior sections of the arcuate fasciculus. They also induced errors in the production of finite verbs when stimulating the posterior part of the MFG and the posterior part of the IFG (in two patients, separately). The authors found common areas for the two tasks in the posterior part of the MFG and in the anterior part of the arcuate fasciculus. By testing finite verbs in addition to nouns and instead of gerunds, the authors were able to map cognitive functions necessary for sentence formation (e.g., subject-verb agreement, inflectional morphology). These functions are not testable (at least not overtly) with an object-naming task or with verb tasks that use non-finite forms such as infinitives or gerunds. Finally, Chang et al. (2018) assessed 14 individuals with epilepsy or a brain tumor with a sentence production task. Patients were required to describe a picture with a short declarative sentence (e.g., the boy is pushing the girl). The authors identified specific sites in the IFG where stimulation induced errors during the sentence production task and not during counting, naming, or repetition. Some of these errors could arise from disruption in lexical syntax. For example, in "girl is … kiss a … kiss a boy" the participant dropped the gerund morphological marker (-ing), as the correct sentence would be "the girl is kissing a boy". Another example is "the girl is being kissed by the girl" where the participant assigned the subject to the sentence incorrectly, as the correct response was "the girl is being kissed by the boy".

In sum: ES data suggests that grammatical category information may be represented separately from the phonological form of a word. These data are supported by studies such as Shapiro and Caramazza (2003a, 2003b), where people with post-stroke aphasia showed selective deficits with noun or verb morphology when using words. For example, subjects may be more impaired producing words and pseudowords when they are used as verbs than when used as nouns. Following this line of work, it may be possible to implement paradigms that elicit morphological processes in words and pseudowords. For example, participants hear the sentence "*These people sail, this person* … " and are asked to complete it with verb form "*sails*". Another sentence frame could be "*This is a sail, these are* … " where the participant would say the noun "*sails*". The same sentences could be used to elicit pseudowords (e.g., *These people wug, this person* … [*wugs*], *This is a wug, these are* … [*wugs*]).

Dissociations between lexical-semantic processes involving living and non-living things

The production of the names of living and non-living things has been studied in ES. Ilmberger et al. (2002) implanted subdural electrodes in the frontal and/or superior temporal lobe of five German-speaking individuals with epilepsy. The authors asked patients to name drawings of animals (living) and of tools (non-living), inducing significantly more errors when patients named tools than when they named animals. They also looked at error types and indicated that "patients reported that during stimulation they recognized the object but just could not find the right name" (p. 700). This latter aspect suggests that the difference between processing living and non-living things took place subsequent to the recognition of visual features of an object. That is, ES data indicates that differences between living and non-living objects can emerge at the lexical-semantic level.

Dissociations between lexical-semantic processes involving common and proper nouns

Producing a common noun by naming a picture of an object requires functions for picture recognition (extracting perceptual features, binding perceptual features into objects, recognizing objects as familiar, accessing non-verbal conceptual meaning representations), activation of semantic features, and finding the appropriate lexical label in the phonological output lexicon. Likewise, producing a proper noun by naming a picture of a person requires specific functions of face recognition that require a separate visual system for face processing (e.g., Semenza & Zettin, 1989; Warrington & McCarthy, 1987; for a review Haxby, Hoffman, & Gobbini, 2000). Differences between producing common nouns and proper nouns may arise in object recognition, object concepts, lexical-semantic or the phonological output lexicon. For example, for a picture of the singer Madonna, difficulties identifying features of the picture may point to disruption to the object recognition process (e.g., saying that the picture depicts a man, when it is a woman; or the presence of phosphenes or a distorted image). At the same time, difficulties knowing who the person is may point to problems with object concepts and/or lexical-semantic impairment. Finally, knowing that the person in the picture was an American singer and actress but not knowing the word or producing a phonological error during stimulation ("Mabonna" for "Madonna") may point to a phonological output-level impairment. ES studies provide can contribute to identifying the specific loci of functional disruption and in understanding the disrupted functions.

Giussani et al. (2009) mapped 56 people with a brain tumor (39 left, 17 right hemisphere) with object naming and naming faces of famous people. Results showed 26 sites in the left hemisphere (superior, middle, and inferior frontal gyrus, and anterior part of the STG and MTG) and 4 sites in the right hemisphere (MFG and SMG) where only face naming induced errors. In 28 sites, only object naming induced errors (locations not specified). In 42 sites, both object and face naming induced errors (locations not specified). In other studies, Glosser et al. (2003) and Seidenberg et al. (2002) used subdural grids in people with epilepsy and indicated that the left temporal lobe is needed to correctly access/ retrieve names of faces. It is important to highlight that in studies such as Giussani et al. (2009), patients did not show difficulties with the perception of faces. Rather, when stimulation was delivered, they were able to recognize the person but unable to remember the name corresponding to face. At the same time, when stimulation was delivered in the same area during object naming, participants had no difficulty naming the object. This is in contrast to other work, where the difficulties that were reported most likely affected perceptual processes.

Allison et al. (1994) used subdural grids to stimulate the left fusiform, lateral lingual gyrus, and inferior temporal gyrus of 14 individuals with intractable epilepsy. The researchers used object naming and naming faces of famous people. During stimulation of the left fusiform gyrus, individuals were unable to say the name of the face or made substitution errors (e.g., misnaming the state governor as President Bush, despite having named him correctly when no stimulation was applied). Also, stimulation to the inferior temporal gyrus induced face-naming difficulties and desaturation of colour, and stimulation of the lateral lingual gyrus generated mild difficulties in face naming and phosphenes. Desaturation of colour and seeing phosphenes may point to low-level visual impairments. However, during stimulation of both locations, patients had no difficulty with object naming. Parvizi et al. (2012) asked one individual with epilepsy to name photographs of famous faces and famous scenes/monuments. Stimulation to specific sites in the right lateral fusiform gyrus did not elicit significant differences between the two tasks. However, the patient reported issues with face perception (e.g., the pictures were a little bit rough, lines on them?). The role of the right and left fusiform gyri in face perception was reiterated in two other reports of the same group (Rangarajan & Parvizi, 2016; Rangarajan et al., 2014). However, none of these papers used naming tasks during ES. Jonas et al. (2014) showed coloured pictures of famous faces, famous scenes, and objects to one individual with epilepsy. The authors used intracerebral electrodes to stimulate the right inferior occipital gyrus. During stimulation the patient was able to name all the stimuli correctly and reported perceptual difficulties only with the faces (e.g., "I did not process the face as a whole; my brain had to process the different facial elements simultaneously").

In sum: the findings of Giussani et al. (2009) suggest a dissociation between functions required in naming common nouns and proper nouns. This dissociation is in line with perioperative findings, strengthening a possible lexical-semantic (Papagno et al., 2011, 2016) and perceptual origin (e.g., Allison et al., 1994; Parvizi et al., 2012; Rangarajan & Parvizi, 2016).

Written comprehension

Dissociation between lexical and sublexical pathways in word and pseudoword reading

Models of language processing posit the existence of lexical and sublexical routes for word reading (Whitworth et al., 2014). Known words can be read correctly using lexical routes, where the phonological word forms corresponding to known words are retrieved and activated. However, novel/unfamiliar words need to be read using mechanisms of conversion of graphemes to phonemes—the sublexical route that encodes the systematic mappings between letters and sounds needed to provide a plausible pronunciation for novel word strings (e.g., Funnel, 1983; McCarthy & Warrington, 1986; Whitworth et al., 2014).

Dissociations found in the DES literature illustrate the independence of these routes and the relevance of testing their functional integrity. Zemmoura et al. (2015) operated on seven people with brain tumors in the left lateral and basal temporo-occipital lobe. The authors used three reading tasks: reading regular words (*bilatéral*—bilateral), reading irregular words (*oignon*—onion), and reading pseudowords (*bafiko*) from a French battery (Nespoulous, Joanette, & Lecours, 1992). Reading regular and irregular words engages the orthographic input lexicon (recognition of words as familiar), the semantic system and the phonological output lexicon. In contrast, reading pseudowords necessarily engages sub-lexical, non-semantic routes (orthographic-to-phonological conversion). Regular words can also be correctly read via the sub-lexical route since they have predictable pronunciations, while irregular words cannot, as they require access to the orthographic input lexicon and the phonological output lexicon. Irregular words read via non-lexical processes will result in plausible but incorrect responses (e.g., "yacht" read as /jætt/ instead of /jɑt/ or "sew" read as /sue/ instead of /soʊ/). Results indicated reading disturbances in three patients when stimulating the left posterior inferior temporal cortex (which word types were affected was not specified). Difficulties reading irregular words only (patients read the words via non-lexical processes, examples of the errors are not provided) occurred when stimulating subcortical areas underneath the anterior portion of the visual word form area (system that connects extrastriate occipital cortex to the left lateral occipitotemproal sulcus cortex, at the anterolateral aspects of the left fusiform gyrus). These results illustrate the involvement of this area in the identification of the orthographic forms of known words. The results also denote a dissociation between sublexical processes needed to read pseudowords (orthographic-to-phonological conversion) and processes needed to read irregular words (for a cognitive and anatomical account of reading errors under intraoperative DES, see Mandonnet & Duffau, 2016).

Written production

Dissociations between reading, writing, and speaking

Differences in oral reading and writing[3] are well attested, and most word processing models separate the visual orthographic analysis and the orthographic input lexicon used in reading from the orthographic output lexicon and letter production processes used in writing (Whitworth et al., 2014; although see Rapp & Dufor, 2011 and Tainturier & Rapp, 2003 for arguments that specific orthographic processes are shared in word reading and writing). However, these models do not indicate whether differences between reading and writing may occur at the sentence level too. In this particular case, a question that arises is whether the processes used for sentence formation at the functional and positional level are the same, regardless of whether the information is used for oral production (reading) or written production (writing). Lesser et al. (1984) implanted subdural grids in people with epilepsy. In two patients, the authors used one task to assess reading sentences aloud (reading passages from a paperback novel or magazine) and one task to assess writing sentences (writing sentences describing familiar events in and out of the hospital). In one patient, DES induced errors during reading in the MTG and IFG and during both reading and writing in specific areas of the MTG and IFG. In another patient, DES induced errors during reading only in the precentral, postcentral and SMG, during reading and writing in different sites of the precentral and postcentral gyri, and during writing only in the in posterior areas of the SMG.

The second participant presented a within-subject double dissociation, as DES to specific areas induced errors only in reading and, in other areas, DES induced errors only in writing. These differences between the oral reading and the writing tasks can be explained by a dissociation between written production processes (orthographic output lexicon, graphemic buffer, and graphic motor programming) and spoken production processes (visual orthographic analysis, orthographic input lexicon, access to semantics or use of a direct lexical route to the phonological output lexicon, phonological output lexicon, phonological assembly, and articulatory programming). However, the results do not necessarily address the question of whether grammatical processes at the positional and functional level are the same for reading and writing (Figure 2). This is because the writing task required participants to generate and write their own grammatically well-formed sentences. Differently, in the reading task, participants may have read the sentences as sequences of words without necessarily understanding their meaning or activating grammatical processes. In this particular study, an analysis of grammatical error types in reading could have helped make this determination (e.g., use of the infinitive instead of the verb in the correct inflected form, use of a different word order, errors with tense), underscoring the importance of reporting errors as well as accuracy in these studies.

Roux et al. (2014) assessed 30 people with a brain tumor. The authors asked 10 of these patients to perform writing to dictation, single-word oral reading, and spoken object naming. In the writing to dictation task patients listened to sentences of 4 to 8 words and wrote them down (e.g., the chair is beautiful, I like chocolate ice cream, my mother is from Italy, the African elephant has large ears). They reported specific sites in the postcentral gyrus, SMG, STG, and MTG where DES induced errors during writing to dictation in the absence of errors in the other tasks. The occurrence of these sites indicates a dissociation between writing functions and functions used in reading and naming. However, from a functional point of view and due to a lack of systematicity in the error types, it is hard to indicate the origin of the dissociation. DES affected functions that are not used in oral reading of single words or naming and are used by writing to dictation. However, there are many such functions: auditory comprehension (auditory phonological analysis, phonological input lexicon) or for written production (orthographic output lexicon, graphemic buffer) and/or processes for sentence comprehension at the functional and positional level. Additional tasks would be required to isolate the affected function/s.

Discussion

In this article, we reviewed 25 studies that used electrical stimulation (ES) for language testing. The array of tasks and cognitive associations and dissociations that were reported in these studies shows an interest in cognitive neuroscience and neuropsychology that goes beyond the seminal work by Ojemann (1983) and other pioneers of this discipline. We reported associations and dissociations between language functions and we discussed them within cognitive models of language processing at the word and sentence level (i.e., Garrett, 1980; Whitworth et al., 2014) – for discussions using neuro-anatomically based models see Chang et al. (2015), Duffau (2015), Mandonnet and Duffau (2016), Fernández-Coello et al. (2013), Mandonnet (2017). An in-depth comparison between the current surgical studies and other cognitive work is outside the scope of this article. However, the dissociations we reported within auditory phonological analysis, categorical dissociations within lexical-semantic processing, and the existence of semantic and non-semantic/sublexical routes for reading can be accommodated by the models we discussed. This is noteworthy because these models are largely based on the responses of cognitively unimpaired individuals and of individuals with acquired deficits (mostly post-stroke). Therefore, finding parallel results in classic neuropsychological studies and ES studies strengthens the argument that ES is a valid tool for investigating language processing and representation.

Examples of the parallels between ES and cognitive neuropsychological findings include the following. First, a dissociation within auditory phonological analysis between consonant and vowel perception reported by Boatman et al. (1997) finds its parallel in a double dissociation reported in people with aphasia with the same tasks by Denes and Semenza (1975) and Auerbach et al. (1982). Second, the distinction between lexical and nonlexical routes for repetition of pseudowords and words, respectively, reported by Sierpowska et al. (2017) finds a parallel in McCarthy and Warrington (1984), who reported a double dissociation for word and pseudoword repetition. Third, dissociations between word categories are found in both literatures. The dissociation between verbs and nouns in lexical-semantic processing to which ES has provided a large amount of evidence (e.g., Corina et al., 2005; Havas et al., 2015; Lubrano et al., 2014; Rofes, Spena, et al., 2017) has also been extensively reported in the aphasia literature (e.g., Mätzig et al., 2009; Miceli et al., 1988). The same holds for the categorical dissociation of nouns and proper nouns reported by Giussani et al. (2009), which finds convergent results in a double dissociation in the aphasia literature (Semenza & Zettin, 1989; Warrington & McCarthy, 1987) and also in more recent perioperative work in people with brain tumors (Papagno et al., 2011, 2016). Also, the difference between naming living and non-living things reported by Ilmberger et al. (2002) has been reported in double dissociations in individuals with aphasia due to stroke and traumatic injury (Hillis & Caramazza, 1991) as well as in neuroimaging studies (e.g., Chao, Haxby, & Martin, 1999; Perani et al., 1995). Additionally, the existence of semantic and non-semantic/sublexical routes for reading reported in Zemmoura et al. (2015) is supported by a similar double dissociation in the aphasia literature (Funnel, 1983; McCarthy & Warrington, 1986). Finally, the dissociation between single-word and sentence comprehension reported in Malow et al. (1996) has a parallel in people after stroke and people with dementia (Goodglass & Stuss, 1979; Miller, Finney, Meador, & Loring, 2010).

In addition to confirming findings from other literatures, task associations and dissociations identified using ES and described in this article also allow us to generate novel hypotheses about language processing. The double dissociation between object concepts and lexical-semantic concepts reported by Gatignol et al. (2004) serve as an example. The ES results are relevant to Kremin (1986), who reported data from a person with traumatic brain injury and another person with a stroke whose performance on an object-naming task was within normal range but below normal in picture comprehension. According to Whitworth et al. (2014), object recognition precedes semantic and lexical processing, and therefore those individuals who are impaired in picture comprehension would be expected to perform below normal in naming. The work by Kremin (1986), in agreement with the ES findings by Gatignol et al. (2004), suggests that it may be possible to say the name of an object even though we may not fully understand or access its meaning. One interpretation is that there are direct connections between object recognition and the phonological output lexicon bypassing object concepts or object concepts and the lexical semantic system (e.g., Ferrand, 1997). While alternative interpretations need to be ruled out (e.g., Silveri & Colosimo, 1995), this serves to illustrate that ES findings do not only provide converging evidence with relatively well-established findings from other literatures, but they can also motivate novel hypotheses and issues for further research.

Another example is the double dissociation between lexical-phonology and lexical-syntax reported by Vidorreta et al. (2011). These authors reported instances in which patients could access syntactic features (e.g., the correct gender for nouns, auxiliary for verbs) in the absence of phonological information during ES, as well as the reverse pattern (e.g., reported the correct object but used an incorrect article). These observations are relevant to the debate between sequential and parallel accounts of lexical access. In sequential accounts (e.g., Levelt, Roelofs, & Meyer, 1999), activation and selection of words takes place in two distinct stages: first, a semantically and syntactically specified lexical representation (the "lemma") is retrieved, and then its corresponding phonological information (the "lexeme") is accessed. In parallel accounts (e.g., Caramazza & Miozzo, 1997), the two sets of features are accessed independently and in parallel. The two theories make different predictions concerning the availability of lexical-syntactic and lexical-phonological information in the event of word retrieval failure. On the sequential account, failed access to syntactic features should lead to the unavailability of the corresponding phonological features; whereas syntactic features could still be available if phonological information cannot be retrieved. By contrast, the parallel account predicts that both access the syntactic properties of a word but not its phonological features, and the reverse pattern should be observed. Selective unavailability of phonological features has been reported in anomic patients (Badecker, Miozzo, & Zanuttini, 1995; Gonon, Bruckert, & Michel, 1989). The reverse pattern is reported only anecdotally in aphasia. For example, the patient described by Miceli and Caramazza (1988) produced utterances like **vado la*$_{F.SG.}$*mia*$_{F.SG.}$ *studia*$_{F.SG.}$ ["I go [to] my office"], and **molto delicata*$_{F.SG}$, *la*$_{F.SG.}$-*baffa*$_{F.SG.}$ ["very tricky, the moustache"] in which noun phonology is retrieved correctly, but grammatical gender (*lo studio*$_{M.SG.}$) or gender and number (*i baffi*$_{M.PL.}$) are incorrect (personal communication). A study of the Tip-Of-the-Tongue (TOT) phenomenon in healthy volunteers also supported the parallel access view, as no correlation between the retrieval of phonological and syntactic properties was found (Caramazza & Miozzo, 1997). Vidorreta et al.'s observations support this view. However, the debate is still open. For example, Roelofs et al. (1998) argued that results can be accommodated by the sequential hypothesis by refining some of its the postulates and controlling more thoroughly word properties such as frequency in experimental tasks (for an opposite view, see Caramazza & Miozzo, 1998). Studies conducted during ES could help gather further evidence on this issue. For example, when ES disrupts naming, patients may be asked to say the word's grammatical gender (this is possible in languages like Italian, Portuguese, Dutch and German; impossible in Chinese, Japanese, or Korean; and difficult to test in English), the initial and/or final letters.

Challenges of interpreting ES data for understanding language models

The current ES literature is populated more with studies of auditory comprehension and spoken production than of written comprehension and production. This is not strange, provided that spoken tasks, such as object naming, have been traditionally used to map language in the brain, and influential groups use nonverbal semantic association tasks to map functions related to language comprehension (e.g., Herbet et al., 2017; Moritz-Gasser et al., 2013). Of course, this should not undermine the valuable efforts to map functions of written production and comprehension, as reading and writing are language abilities that are heavily used in everyday life, and people with brain tumors have shown persistent postoperative difficulties with reading and writing with relatively spared naming abilities (Tsapkini & Rapp, 2010; Van Ierschot et al., 2017). However, it hampers our ability to discuss important aspects of the language models and of language processing in general.

Some studies compared functions by using tasks that shared too many or too few language functions, which made results difficult to interpret from a cognitive neuropsychological perspective (Roux et al., 2004). For example, comparing object naming and sentence reading could be deemed sufficient to investigate differences between these tasks, in research focusing on the individual's ability to function in everyday life. However, in research aiming to identify the cognitive nature of associations and dissociations between the two tasks, this comparison is difficult to interpret. On the one hand, associations between errors in the two tasks may reflect one of several shared levels of processing (semantics, phonological output lexicon, phonological buffer, motor speech, and connections between these levels). As a result, it is not possible to determine at which of these levels an association originates. On the other hand, identifying a dissociation in task performance across object naming and sentence reading may also reflect the role of one of several cognitive processes, as the tasks differ in terms of multiple cognitive functions: visual vs. written input processes, single-word vs. sentence-level processing. Hence, when trying to make inferences related to language processing using ES, the careful conceptualization of levels of processing engaged by tasks that are to be compared is a crucial experimental consideration.

Mapping language functions while considering models of language processing

There is currently no agreed-upon clear-cut proposal on how to map specific language functions in individuals with tumors—whether the goal is to advance our understanding of how language is processed in the brain or to allow surgical teams to tailor surgeries to patient needs. Options to improve current practice rely on a better understanding of the language functions assessed by each task and, perhaps more importantly, on devising and testing strategic combinations of tasks (two or more) that tap specific functions.

For example, to establish whether or not specific functions for speaking and reading aloud dissociate, we could use an approach with three tasks: spoken object naming, picture association (non-verbal association, such as the PPTT), and written word association (e.g., same as the PPTT, but in written form—patients are to point to which of the two written words below is most associated with the written word above). The rationale for using these three tasks is as follows: the spoken object-naming task and the non-verbal picture association task share object recognition and semantic functions. However, object naming requires spoken production functions that are not required by the picture non-verbal association task. At the same time, the non-verbal picture association task and the written word association task require similar functions to select which of two alternatives is closer in meaning to the stimulus, regardless of the stimulus modality (pictures or written words). Interestingly, the task that uses words requires the patient to read, hence, it engages written comprehension functions that are not engaged by the non-verbal picture association task or picture naming. With this type of setting, then, finding areas where ES induces errors with spoken object naming but not during picture or word association tasks would identify areas involved in speech production (finding words in the phonological output lexicon and/or articulating them). Likewise, finding areas where ES induces errors with the written word association task but not with picture association task would suggest that those areas relate to reading comprehension functions (orthographic analysis of graphemes, recognition of word forms in the orthographic input lexicon).

Of course, this is only one example of an ideal scenario. In a surgical setting, many other combinations of errors may occur, and time constraints may make it difficult to use three tasks. Furthermore, one should always keep in mind that the primary goal of surgical teams is an optimal onco-functional balance—resecting as much tumor as possible while preserving functioning to allow the patient to participate in everyday life activities after surgery (e.g., Mandonnet & Duffau, 2018). For that goal, two key questions are critical: whether there are language functions that are less likely to recover spontaneously and, if so, which combination(s) of tasks should be used to identify and thus avoid/limit permanent damage to those functions. The approach we have described, where combinations of strategically selected tasks allow us to evaluate specific functions, is a first step towards a finer-grained mapping procedure of language functions, and consequently towards a surgical practice more directly tailored to the patient's personal and clinical needs. The approach seems at hand today, at a moment in which surgical teams are actively engaged in the standardization of language tasks for perioperative use (e.g., Połczyńska, 2009; Rofes, Spena, et al., 2015).

Conclusion

ES studies have revealed dissociations and associations between language functions that can be interpreted with models of single-word and sentence processing, and that can contribute to the further development of such models. Embracing cognitive models of language will facilitate the understanding of which language functions are assessed with each task and how to best combine language tasks to tailor surgeries to the personal and clinical needs of each patient. This approach seems feasible, particularly, in this fruitful time during which cognitive neuroscience and surgical practice are interacting more than ever.

Notes

1. Differently from the model by Whitworth et al. (2014), we referred to lexical-semantics (instead of semantic system), included object concepts as a distinct function separate from lexical-semantics, and added a function for the representation and processing of lexical syntax that is shared by the output phonological and orthographic output lexica. The distinction between object concepts and lexical-semantics, as well as a separate level for lexical-syntax, are useful for explaining some of the DES findings.
2. Future work may consider ES studies of bilingual/multilingual questions (e.g., Borius, Giussani, Draper, & Roux, 2012; Fernández-Coello et al., 2017; Giussani et al., 2009; Mesgarani & Chang, 2012; Ojemann & Whitaker, 1978; Penfield & Roberts, 1959; Rodríguez-Fornells, Rotte, Heinze, Nösselt, & Münte, 2002). Here we chose not to include these studies because the questions investigated typically differ from those of monolingual studies. For example, from a cognitive perspective, bilingual studies have traditionally focused on answering whether two or more languages are realized in the same or different neural substrates (Macnamara, Krauthammer, & Bolgar, 1968; Penfield & Roberts, 1959). More recent studies have examined the possibility of inhibitory mechanisms that suppress one language, while allowing the production of a second language (e.g., Colomé, 2001; Dijkstra, Timmermans, & Schriefers, 2000; Green, 1998; Mosca & de Bot, 2017).
3. Here "writing" refers to the processes that involve lexical-semantics, orthographic output lexicon, graphemic buffer, including graphic motor programming. Note that researchers may refer to "writing" as motor aspects (graphic motor programming) and to "spelling" as the cognitive processes needed to write a word (e.g., orthographic output lexicon, graphemic buffer).

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