Routledge
Taylor & Francis Group

Cognitive Neuropsychology

ISSN: 0264-3294 (Print) 1464-0627 (Online) Journal homepage: https://www.tandfonline.com/loi/pcgn20

Direct electrical stimulation mapping of cognitive functions in the human brain

Bradford Z. Mahon, Michele Miozzo & Webster H. Pilcher

To cite this article: Bradford Z. Mahon, Michele Miozzo & Webster H. Pilcher (2019) Direct electrical stimulation mapping of cognitive functions in the human brain, Cognitive Neuropsychology, 36:3-4, 97-102, DOI: 10.1080/02643294.2019.1630375

To link to this article: https://doi.org/10.1080/02643294.2019.1630375

Published online: 12 Sep 2019.

COGNITIVE NEUROPSYCHOLOGY
2019, VOL. 36, NOS. 3–4, 97–102
https://doi.org/10.1080/02643294.2019.1630375

Routledge
Taylor & Francis Group

INTRODUCTION

OPEN ACCESS Check for updates

Direct electrical stimulation mapping of cognitive functions in the human brain

Bradford Z. Mahon [a,b,c,d,e], Michele Miozzo [f] and Webster H. Pilcher [b]

[a]Department of Psychology, Carnegie Mellon University, Pittsburgh, PA, USA; [b]Department of Neurosurgery, University of Rochester Medical Center, Rochester, NY, USA; [c]Department of Neurology, University of Rochester Medical Center, Rochester, NY, USA; [d]Carnegie Mellon Neuroscience Institute, Carnegie Mellon University, Pittsburgh, PA, USA; [e]Department of Neurological Surgery, University of Pittsburgh Medical Center, Pittsburgh, PA, USA; [f]Department of Psychology, The New School, New York, NY, USA

ABSTRACT
Direct electrical stimulation (DES) is a well-established clinical tool for mapping cognitive functions while patients are undergoing awake neurosurgery or invasive long-term monitoring to identify epileptogenic tissue. Despite the proliferation of a range of invasive and noninvasive methods for mapping sensory, motor and cognitive processes in the human brain, DES remains the clinical gold standard for establishing the margins of brain tissue that can be safely removed while avoiding long-term neurological deficits. In parallel, and principally over the last two decades, DES has emerged as a powerful scientific tool for testing hypotheses of brain organization and mechanistic hypotheses of cognitive function. DES can cause transient "lesions" and thus can support causal inferences about the necessity of stimulated brain regions for specific functions, as well as the separability of sensory, motor and cognitive processes. This Special Issue of *Cognitive Neuropsychology* emphasizes the use of DES as a research tool to advance understanding of normal brain organization and function.

ARTICLE HISTORY
Received 12 May 2019
Revised 30 May 2019
Accepted 5 June 2019

KEYWORDS
Direct electrical stimulation; brain surgery; brain tumour; neural plasticity; cognitive models; causal evidence

Direct electrical stimulation (DES) is a technique that has been in widespread clinical use for over half of a century. Clinical applications of DES include real-time mapping of sensory, motor and cognitive functions during awake surgery, identifying functional pathways, quelling epileptiform activity through chronically implanted closed loop devices, and reducing tremor in motor disorders. There is a longstanding and rich literature using DES in animal models, starting in the nineteenth century, and running through modern studies that pair DES with neurophysiological recordings and in vivo and histological measures of the effect of electrical current on brain tissues (see review in Mazurek and Schieber, 2019). The particular focus of the articles collected together in this Special Issue of *Cognitive Neuropsychology* is on the use of DES during awake neurosurgery, or through chronic implantation of electrodes, to map sensory, motor and cognitive function in the human brain. The proximate goal of the use of DES in those procedures is to inform neurosurgical decisions about what tissue is safe to resect from the standpoint of minimizing post-operative neurologic impairment. In this regard, DES has proven to be an indispensible tool for informing the maximal safe resection for tumour or epilepsy surgery—it allows for a tailored resection of pathological tissue while minimizing the likelihood of post-operative cognitive impairments (Bloch et al., 2012; Brown et al., 2016; Rech, Herbet, Moritz-Gasser, & Duffau, 2014; Sanai, Mirzadeh, & Berger, 2008; Santini et al., 2012; Satoer et al., 2014; Schucht, Moritz-Gasser, Herbet, Raabe, & Duffau, 2013). A testament to the importance of DES as a clinical tool is the fact that it has remained the gold standard for mapping functions in the human brain in a neurosurgical context for over half a century despite the facts that (i) a range of other invasive and non-invasive neuroimaging techniques are now available, and (ii) important challenges have been recognized that attend the use of the technique (Borchers, Himmelbach, Logothetis, & Karnath, 2011).

DES is powerful because stimulation of a brain region that supports a given cognitive, sensory, motor ability can render a patient transiently unable to perform that ability, evoke a transient sensory percept in the absence of a sensory stimulus, a

CONTACT Bradford Z. Mahon bmahon@andrew.cmu.edu

movement in the absence of an intention to move, or the experience of an intention to move in the absence of an overt movement (Desmurget et al., 2009); for review and discussion see (Borchers et al., 2011; Desmurget, Song, Mottolese, & Sirigu, 2013). Broadly speaking, there are two types of causal inferences that are derived from observations of how DES disrupts or does not disrupt performance in a given task. First, DES supports real time inferences about the necessity of a given brain region or pathway for a given cognitive function. Second, DES supports causal inferences about the separability of sensory, motor and cognitive abilities, and by inference, the separability of representations and computations integral to those abilities. Four of the contributions in this issue emphasize both types of causal inferences through new empirical findings with DES (Chernoff, Sims, Smith, Pilcher, & Mahon, 2019; Herbet, Moritz-Gasser, Lemaitre, Almairac, and Duffau (2018); Leonard et al., 2019; Orena, Caldiroli, Acerbi, Barazzetta, & Papagno, 2019).

The modern application of DES for mapping brain function involves local stimulation of brain tissue with direct current in the range of .5–15 milliamps (mA) (Kayama, 2012; Sanai et al., 2008; Szelényi et al., 2010). DES can be applied via a hand held bipolar or monopolar stimulator, or through implanted grids or strips; the former technique is more frequently used during awake craniotomies, while the latter technique is used in the setting of long-term monitoring and extra-operative mapping of the margins separating epileptogenic from eloquent tissue. The awake craniotomy was the clinical preparation in which DES was developed for use in humans, by pioneers such as Wilder Penfield and George Ojemann (Ojemann, 1979, 1981, 1983a, 1983b, 1983c, 1986, 1987, 1988; Penfield, 1954, 1956, 1961; Penfield & Boldrey, 1937; for reviews, see Mazurek & Schieber, 2019; Rofes et al., 2018). During awake craniotomies, patients are titrated off of general anesthesia during their surgery (if general anesthesia was used), with local anesthetic applied at the site of incision, and are thus comfortable and able to carry out cognitive testing (for a video overview of the procedures involved in an awake craniotomy, see Mahon et al., 2019).

It is important to recognize that research studies using DES are always set against the backdrop of informing a clinical procedure and thus subject to a special set of ethical and practical constraints—that is, providing surgeons with real-time feedback in the service of intra-operative decisions about the margins of tissue that can be safely removed. The use of DES to advance basic scientific understanding of cognitive brain function and organization will always be constrained by the clinical realities that motivate the use of the technique in any given patient (Chiong, Leonard, & Chang, 2017). However, within that framework, and as demonstrated by some of the contributions herein (Chernoff et al., 2018; Herbet, Moritz Gasser, Lemaitre, Almairac, and Duffau (2018); Leonard et al., 2019; Orena et al., 2019), with appropriate planning and preparation, it is possible to interleave into the clinical procedure causal tests of theories of brain organization and function (see also, e.g., Chernoff et al., 2018; Duffau & Capelle, 2001; Duffau, Gatignol, Denvil, Lopes, & Capelle, 2003; Duffau et al., 2002; Garcea et al., 2017).

An important generalization, reviewed in Mazurek and Schieber (2019), is that using DES to map function in the brain critically depends on the patient being able to focus on and be engaged by an appropriate task. The type of task that is selected to map a given brain region is influenced by a number of factors, including the purported function of that region, results of pre-operative non-invasive mapping (e.g., fMRI, MEG), and patient-specific factors (e.g., if the patient is bilingual or monolingual, Benjamin et al., 2017; Fernández-Coello et al., 2013a; Połczyńska, Benjamin, Japardi, Frew, & Bookheimer, 2016; Połczyńska, Japardi, & Bookheimer, 2017). Regardless of the task or region, however, both patient participation and the clinical team's ability to "read" the patient's behaviour in real time are critical. For instance, for motor mapping, disruptions in voluntary movement are outwardly observable by the clinical team, and thus the patient "merely" needs to stay on task (e.g., tapping fingers). Similarly, in the setting of mapping of speech production, patients are engaged in a task, such as picture naming, word reading, counting, or sentence production (*inter alia*—see Rofes, de Aguiar, & Miceli, 2015; Rofes, Spena, Miozzo, Fontanella, & Miceli, 2015; Rofes et al., 2018). When patients make errors (i.e., errors of commission, failure to respond) due to DES, the effect of DES is observed directly by the clinical team. However, in the setting of sensory mapping or a comprehension task, there is no overt response that can be "read" in the operating room and thus the effect of the mapping can be directly contingent on patient report (Rofes, Spena, et al., 2015). As such, there are a number of considerations that must be taken into account, having to do with response criteria, reliability of patient report, and a patient's ability to maintain focus on the phenomenological effects of stimulation in what otherwise can be a complex environment. Another critical issue is selection of the appropriate task to effectively map functions in a given region (Chang, Raygor, & Berger, 2015; Duffau, 2015; Duffau, Moritz-Gasser, & Mandonnet, 2014; Fernández-Coello et al., 2013b; Mandonnet, 2017). In the current issue, Rofes and colleagues (2018) address this critical issue, with a particular focus on language mapping.

While simple in its application, DES is a complex technique, and in many ways, the basic science of how DES can be most efficiently used to map function in the human brain is still catching up to its widespread clinical use. For instance, stimulation can sometimes facilitate processing and sometimes interfere with processing, with the polarity of the modulation likely affected by a range of factors that include stimulation location, the task in which subjects are engaged, the timing of stimulation relative to task engagement, and the amount of current being delivered (Borchers et al., 2011; Desmurget et al., 2013; Mazurek & Schieber, 2019). Furthermore, the effect of stimulation on patient behaviour is a result of not only the computations affected local to the site of stimulation, but how the electrical stimulus is propagated through a broader network (Alhourani et al., 2015; Ellmore, Beauchamp, O'Neill, Dreyer, & Tandon, 2009; Garcea et al., 2017; Thiebaut de Schotten et al., 2005).

Another important issue has to do with whether the presence of (potentially longstanding) pathology in a patient's brain may have spurred reorganization, for instance in the form of redundancy in functional pathways not observed in healthy brains (Friston & Price, 2003; Price & Friston, 2002). Herbet Moritz-Gasser, Lemaitre, Almairac, and Duffau (2018) report a case series of patients in which some of the patients had longstanding pathology of the left anterior temporal lobe while others did not. All of the patients underwent an awake craniotomy with language mapping, and specifically, DES of the inferior longitudinal fasciculus (ILF) in the dominant hemisphere. The authors found that stimulation of the ILF caused anomic errors, but only in patients who did not have longstanding pathology that involved the anterior temporal lobe. The implications of these findings are that i) the ILF does play a critical role in language processing, and specifically naming; and ii) if tumors have infiltrated the left anterior temporal lobe, there is reorganization of the language network (such that stimulation of the ILF no longer disrupts naming). Future systematic investigations such as reported by Herbet and colleagues will be critical for understanding plasticity, reorganization of function, and redundancy of functional pathways.

It is important to recognize that the open issues that attend the use of DES are not unique to the method—analogues to those questions are present for other methods for evoking or measuring responses from the human brain, for interpreting relations of neural measures to patient behaviour (Miozzo, Williams, Mckhann, & Hamberger, 2017), and for deriving inferences about normal cognitive organization through studies of individuals with acquired or developmental impairments (Behrmann & Geskin, 2018; Caramazza, 1984; Fischer-Baum & Campana, 2017; Geskin & Behrmann, 2018). This is not to say that these issues are not important or that they do not need to be carefully unpacked and addressed; rather, the take away message should be that resolution of those challenges, to be achieved through future research, promises to have broad implications for understanding normal and pathological brain function.

The journal *Cognitive Neuropsychology* has historically supported research directed at drawing inferences about normal cognition through careful studies of patients who exhibit dissociations among separable cognitive abilities. The scope of the journal was expanded in recent years to mirror the expanding footprint of methods that can be used to inform models of normal cognitive function. Direct electrical stimulation mapping is one such method. As noted above, and as is the case for "classic" cognitive neuropsychological research, DES supports causal inferences about the separability of cognitive processes, and the neural substrates of those processes. However, unlike classic cognitive neuropsychological approaches, DES supports causal inferences through "transient" or "temporary" lesions. Combined with the high spatial resolution afforded by the fact that DES is applied to the brain directly (for instance in comparison to Transcranial Magnetic Stimulation, TMS, or Transcranial Direct Current Stimulation, TDCS), DES is a technique that should enjoy a special place in cognitive neuropsychological research. As such, the goal of this special issue is to draw a connection between the logic of cognitive neuropschology and the use of DES to infer the underlying computations of brain regions and the separability of cognitive processes.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

Preparation of this article was supported by National Eye Institute [Grant Number R01EY028535] and National Institute of Neurological Disorders and Stroke [Grant Number R01NS089609].

ORCID

Bradford Z. Mahon http://orcid.org/0000-0002-2018-4797

References

Alhourani, A., McDowell, M. M., Randazzo, M. J., Wozny, T. A., Kondylis, E. D., Lipski, W. J., … Richardson, R. M. (2015). Network effects of deep brain stimulation. *Journal of Neurophysiology*, *114*(4), 2105–2117. doi:10.1152/jn.00275.2015

Behrmann, M., & Geskin, J. (2018). Over time, the right results will emerge. *Cognitive Neuropsychology*, *35*(1–2), 102–111. doi:10.1080/02643294.2018.1447917

Benjamin, C., Walshaw, P., Hale, K., Gaillard, W., Baxter, L., Berl, M., … Bookheimer, S. (2017). Presurgical language fMRI: Mapping of six critical regions. *Human Brain Mapping*, *38*, 4239–4255. doi:10.1002/hbm.23661

Bloch, O., Han, S. J., Cha, S., Sun, M. Z., Aghi, M. K., McDermott, M. W., … Parsa, A. T. (2012). Impact of extent of resection for recurrent glioblastoma on overall survival. *117*(6), 1032. doi:10.3171/2012.9.Jns12504

Borchers, S., Himmelbach, M., Logothetis, N., & Karnath, H. O. (2011). Direct electrical stimulation of human cortex - the gold standard for mapping brain functions? *Nature Reviews Neuroscience*, *13*(1), 63–70. doi:10.1038/nrn3140

Brown, T. J., Brennan, M. C., Li, M., Church, E. W., Brandmeir, N. J., Rakszawski, K. L., … Glantz, M. (2016). Association of the extent of resection with survival in glioblastoma: A systematic review and meta-analysis. *JAMA Oncology*, *2*(11), 1460–1469. doi:10.1001/jamaoncol.2016.1373

Caramazza, A. (1984). The logic of neuropsychological research and the problem of patient classification in aphasia. *Brain and Language*, *21*(1), 9–20. doi:10.1016/0093-934X(84)90032-4

Chang, E., Raygor, K., & Berger, M. (2015). Contemporary model of language organization: An overview for neurosurgeons. *Journal of Neurosurgery*, *122*, 250–261. doi:10.3171/2014.10.JNS132647

Chernoff, B. L., Sims, M. H., Smith, S. O., Pilcher, W. H., & Mahon, B. Z. (2019). Direct electrical stimulation of the left Frontal Aslant Tract disrupts sentence planning without affecting articulation. *Cognitive Neuropsychology*. doi:10.1080/02643294.2019.1619544

Chernoff, B. L., Teghipco, A., Garcea, F. E., Sims, M. H., Paul, D. A., Tivarus, M. E., … Mahon, B. Z. (2018). A role for the frontal aslant tract in speech planning: A neurosurgical case study. *Journal of Cognitive Neuroscience*, *30*(5), 752–769. doi:10.1162/jocn_a_01244

Chiong, W., Leonard, M., & Chang, E. (2017). Neurosurgical patients as human research subjects: Ethical considerations in intracranial electrophysiology research. *Neurosurgery*, *83*, 29–37. doi:10.1093/neuros/nyx361

Desmurget, M., Reilly, K., Richard, N., Szathmari, A., Mottolese, C., & Sirigu, A. (2009). Movement intention after parietal cortex stimulation in humans. *Science*, *324*, 811–813. doi:10.1126/science.1169896

Desmurget, M., Song, Z., Mottolese, C., & Sirigu, A. (2013). Re-establishing the merits of electrical brain stimulation. *Trends in Cognitive Neuroscience*, *17*, 442–449. doi:10.1016/j.tics.2013.07.002

Duffau, H. (2015). Stimulation mapping of white matter tracts to study brain functional connectivity. *Nature Reviews Neurology*, *11*(5), 255–265. doi:10.1038/nrneurol.2015.51

Duffau, H., & Capelle, L. (2001). Intraoperative electrical stimulation mapping of the subcortical language pathways during surgery of low-grade glioma: An anatomo-functional study. *Neuroimage*, *13*(6), 525–S525. doi:10.1016/S1053-8119(01)91868-3

Duffau, H., Capelle, L., Sichez, N., Denvil, D., Lopes, M., Sichez, J., … Fohanno, D. (2002). Intraoperative mapping of the subcortical language pathways using direct stimulations - an anatomo-functional study. *Brain*, *125*, 199–214. doi:10.1093/brain/awf016

Duffau, H., Gatignol, P., Denvil, D., Lopes, M., & Capelle, L. (2003). The articulatory loop: Study of the subcortical connectivity by electrostimulation. *Neuroreport*, *14*(15), 2005–2008. doi:10.1097/01.wnr.0000094103.16607.9f

Duffau, H., Moritz-Gasser, S., & Mandonnet, E. (2014). Are-examination of neural basis of language processing: Proposal of a dynamic hodotopical model from data provided by brain stimulation mapping during picture naming. *Brain and Language*, *131*, 1–10. doi:10.1016/j.bandl.2013.05.011

Ellmore, T. M., Beauchamp, M. S., O'Neill, T. J., Dreyer, S., & Tandon, N. (2009). Relationships between essential cortical language sites and subcortical pathways clinical article. *Journal of Neurosurgery*, *111*(4), 755–766. doi:10.3171/2009.3.jns081427

Fernández-Coello, A., Moritz-Gasser, S., Martino, J., Martinoni, M., Matsuda, R., & Duffau, H. (2013a). Selection of intraoperative tasks for awake mapping based on relationships between tumor location and functional networks: A review. *Journal of Neurosurgery*, *119*, 1380–1394. doi:10.3171/2013.6.JNS122470

Fernández-Coello, A., Moritz-Gasser, S., Martino, J., Martinoni, M., Matsuda, R., & Duffau, H. (2013b). Selection of intraoperative tasks for awake mapping based on relationships between tumor location and functional networks: A review. *Journal of Neurosurgery*, *119*, 1380–1394. doi:10.3171/2013.6.JNS122470

Fischer-Baum, S., & Campana, G. (2017). Neuroplasticity and the logic of cognitive neuropsychology. *Cognitive Neuropsychology*, *34*(7–8), 403–411. doi:10.1080/02643294.2017.1389707

Friston, K. J., & Price, C. J. (2003). Degeneracy and redundancy in cognitive anatomy. *Trends in Cognitive Sciences*, *7*(4), 151–152. doi:10.1016/S1364-6613(03)00054-8

Garcea, F. E., Chernoff, B. L., Diamond, B., Lewis, W., Sims, M. H., Tomlinson, S. B., … Mahon, B. Z. (2017). Direct electrical stimulation in the human brain disrupts Melody processing. *Current Biology*, *27*(17), 2684–2691.e7. doi:10.1016/j.cub.2017.07.051

Geskin, J., & Behrmann, M. (2018). Congenital prosopagnosia without object agnosia? A literature review. *Cognitive Neuropsychology*, *35*(1–2), 4–54. doi:10.1080/02643294.2017.1392295

Herbet, G., Moritz-Gasser, S., Lemaitre, A. L., Almairac, F., & Duffau, H. (2018). Functional compensation of the left inferior longitudinal fasciculus for picture naming. *Cognitive Neuropsychology*. doi:10.1080/02643294.2018.1477749

Kayama, T. (2012). The guidelines for awake craniotomy guidelines committee of the Japan awake surgery conference. *Neurologia Medico-Chirurgica*, *52*, 119–141. doi:10.2176/nmc.52.119

Leonard, M. K., Desai, M., Hungate, D., Cai, R., Singhal, N. S., Knowlton, R. C., & Chang, E. F. (2019). Direct cortical stimulation of inferior frontal cortex disrupts both speech and music production in highly trained musicians. *Cognitive Neuropsychology*. doi:10.1080/02643294.2018.1472559

Mahon, B., Mead, J., Chernoff, B., Sims, M., Garcea, F., Prentiss, E., … Pilcher, W. (2019). Translational brain mapping at the University of Rochester Medical Center: Preserving the mind through personalized brain mapping. *Journal of Visualized Experiments*.

Mandonnet, E. (2017). A surgical approach to the anatomo functional structure of language. *Neuro-Chirurgie*, *63*, 122–128. doi:10.1016/j.neuchi.2016.10.004

Mazurek, K. A., & Schieber, M. H. (2019). How is electrical stimulation of the brain experienced, and how can we tell? Selected considerations on sensorimotor function and speech. *Cognitive Neuropsychology*. doi:10.1080/02643294.2019.1609918

Miozzo, M., Williams, A. C., McKhann, G. M., & Hamberger, M. J. (2017). Topographical gradients of semantics and phonology revealed by temporal lobe stimulation. *Human Brain Mapping*, *38*(2), 688–703. doi:10.1002/hbm.23409

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

Ojemann, G. (1981). Methods of intra-operative localization in the human cortex. *International Journal of Neuroscience*, *12*(3–4), 174–174.

Ojemann, G. (1983a). Brain organization for language from the perspective of electrical-stimulation mapping. *Behavioral and Brain Sciences*, *6*(2), 189–206. doi:10.1017/S0140525X00015491

Ojemann, G. (1983b). Electrical-stimulation and the neurobiology of language. *Behavioral and Brain Sciences*, *6*(2), 221–230. doi:10.1017/S0140525X0001565X

Ojemann, G. (1983c). The intrahemispheric organization of human language, derived with electrical-stimulation techniques. *Trends in Neurosciences*, *6*(5), 184–189. doi:10.1016/0166-2236(83)90083-8

Ojemann, G. (1986). Mapping of neuropsychological language parameters at surgery. *International Anesthesiology Clinics*, *24*(3), 115–131. doi:10.1097/00004311-198602430-00011

Ojemann, G. (1987). Surgical therapy for medically intractable epilepsy. *Journal of Neurosurgery*, *66*, 489–499. doi:10.3171/jns.1987.66.4.0489

Ojemann, G. (1988). Stimulation mapping of frontal-lobe during language tasks. *Epilepsia*, *29*(2), 210–210.

Orena, E. F., Caldiroli, D., Acerbi, F., Barazzetta, I., & Papagno, C. (2019). Investigating the functional neuroanatomy of concrete and abstract word processing through direct electric stimulation (DES) during awake surgery. *Cognitive Neuropsychology*. doi:10.1080/02643294.2018.1477748

Penfield, W. (1954). Mechanisms of voluntary movement. *Brain*, *77*(1), 1–17. doi:10.1093/brain/77.1.1

Penfield, W. (1956). Thoughts on the function of the temporal cortex. *Neurosurgery*, *4*, 21–33. discussion 31–23. doi:10.1093/neurosurgery/4.CN_suppl_1.21

Penfield, W. (1961). Activation of the record of human experience: Summary of the lister oration delivered at the Royal College of surgeons of England on 27th April 1961. *Annals of the Royal College of Surgeons of England*, *29*(2), 77–84. Retrieved from https://europepmc.org/backend/ptpmcrender.fcgi?accid=PMC2414108&blobtype=pdf

Penfield, W., & Boldrey, E. (1937). Somatic motor and sensory representation in the cerebral cortex of man as studied by electrical stimulation. *Brain*, *60*, 389–443. doi:10.1093/brain/60.4.389

Połczyńska, M., Benjamin, C., Japardi, K., Frew, A., & Bookheimer, S. (2016). Language system organization in a quadrilingual with a brain tumor: Implications for understanding of the language network. *Neuropsychologia*, *86*, 167–175. doi:10.1016/j.neuropsychologia.2016.04.030

Połczyńska, M., Japardi, K., & Bookheimer, S. (2017). Lateralizing language function with pre-operative functional magnetic resonance imaging in early proficient bilingual patients. *Brain and Language*, *170*, 1–11. doi:10.1016/j.bandl.2017.03.002

Price, C. J., & Friston, K. J. (2002). Degeneracy and cognitive anatomy. *Trends in Cognitive Sciences*, *6*(10), 416–421. doi:10.1016/S1364-6613(02)01976-9

Rech, F., Herbet, G., Moritz-Gasser, S., & Duffau, H. (2014). Disruption of bimanual movement by unilateral subcortical electrostimulation. *Human Brain Mapping*, *35*, 3439–3445. doi:10.1002/hbm.22413

Rofes, A., de Aguiar, V., & Miceli, G. (2015). A minimal standardization setting for language mapping tests: An Italian example. *Neurological Sciences*, *36*(7), 1113–1119. doi:10.1007/s10072-015-2192-3

Rofes, A., Mandonnet, E., de Aguiar, V., Rapp, B., Tsapkini, K., & Miceli, G. (2018). Language processing from the perspective of electrical stimulation mapping. *Cognitive Neuropsychology*. doi:10.1080/02643294.2018.1485636

Rofes, A., Spena, G., Miozzo, A., Fontanella, M. M., & Miceli, G. (2015). Advantages and disadvantages of intraoperative language tasks in awake surgery: A three-task approach for prefrontal tumors. *Journal of Neurosurgical Sciences*, *59*(4), 337–349.

Sanai, N., Mirzadeh, Z., & Berger, M. (2008). Functional outcome after language mapping for glioma resection. *New England Journal of Medicine*, *358*(1), 18–27. doi:10.1056/NEJMoa067819

Santini, B., Talacchi, A., Squintani, G., Casagrande, F., Capasso, R., & Miceli, G. (2012). Cognitive outcome after awake surgery for tumors in language areas. *Journal of Neuro-Oncology*, *108*, 319–326. doi:10.1007/s11060-012-0817-4

Satoer, D., Visch-Brink, E., Smits, M., Kloet, A., Looman, C., Dirven, C., & Vincent, A. (2014). Long-term evaluation of cognition after glioma surgery in eloquent areas. *Journal of Neuro-Oncology*, *116*, 153–160. doi:10.1007/s11060-013-1275-3

Schucht, P., Moritz-Gasser, S., Herbet, G., Raabe, A., & Duffau, H. (2013). Subcortical electrostimulation to identify network subserving motor control. *Human Brain Mapping*, *34*, 3023–3030. doi:10.1002/hbm.22122

Szelényi, A., Bello, L., Duffau, H., Fava, E., Feigl, G., Galanda, M., … Sala, F. (2010). Intraoperative electrical stimulation in awake craniotomy: Methodological aspects of current practice. *Neurosurgical Focus*, *28*, E7. doi:10.3171/2009.12.FOCUS09237

Thiebaut de Schotten, M., Urbanski, M., Duffau, H., Voue, E., Levy, R., Dubois, B., & Bartolomeo, P. (2005). Direct evidence for a parietal-frontal pathway subserving spatial awareness in humans. *Science*, *309*(5744), 2226–2228. doi:10.1126/science.1116251