Structured reporting of clinical fMRI exams - an illustrated neuroradiologist's perspective

Writing a qualified report is crucial to translate clinical fMRI exams into medically relevant conclusions. Given that multiple specialities (referring physicians, clinical neuropsychologists, neuroimagers & -scientists, neuroradiologists, neurosurgeons, neurologists, neuropaediatricians, ENT etc.) are involved, competent reporting constitutes a particular challenge *to adequately communicate the message of clinical fMRI to each party*. As yet, there is no comprehensive template for structured reporting of clinical fMRI exams available. Here, I will outline what I consider the essentials and propose that a "good" clinical fMRI report should contain the following:

1. Indication: First of all, and prior to the mapping, the indication/reason for actual fMRI exam should be verified and stated (*What is your job for the particular patient - what question do you have to answer?*). Two common scenarios are the presurgical workup before:

a) neurosurgical resection of especially intra-axial lesions ("lesion surgery")

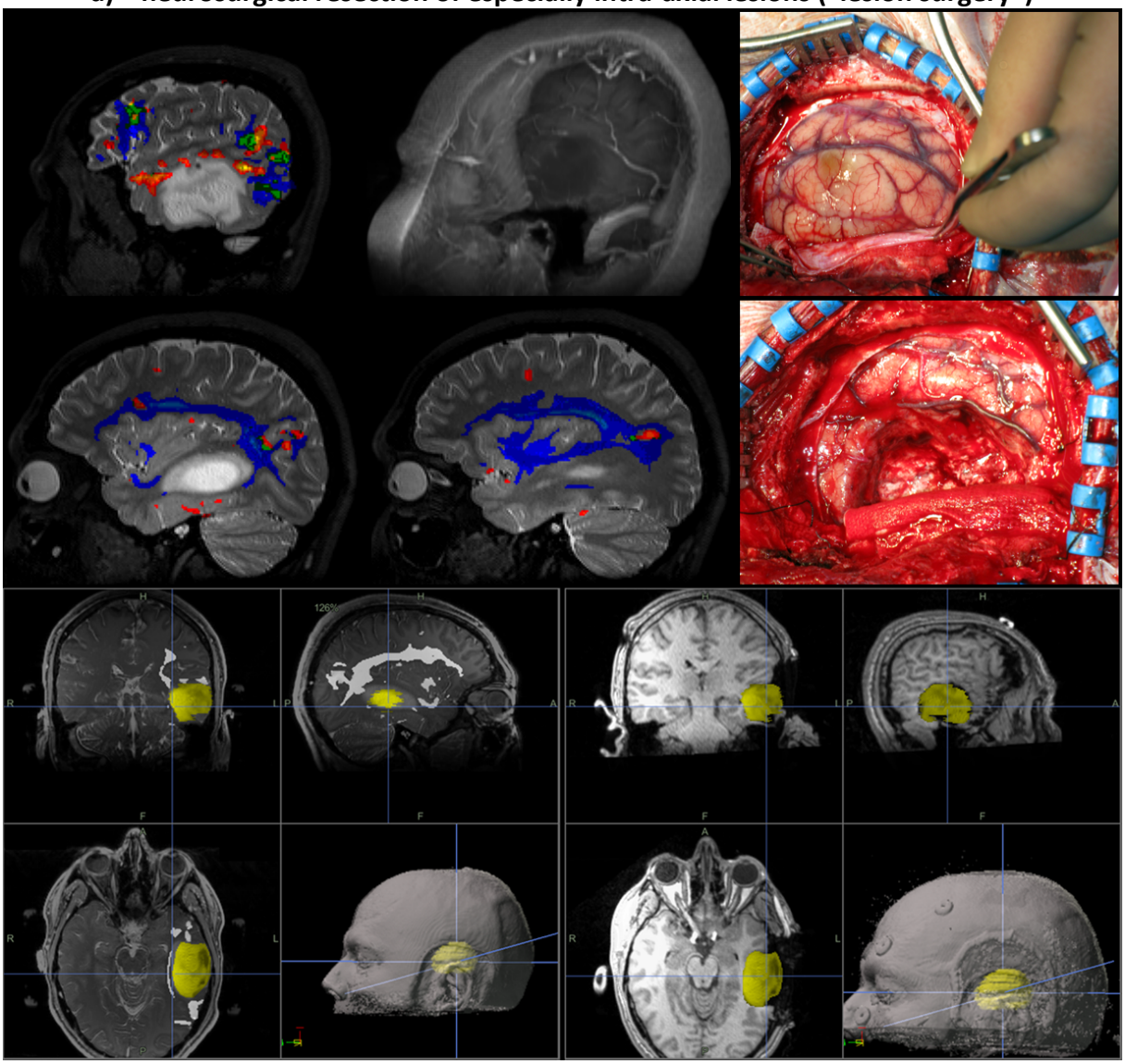

Figure 1: FMRI and tractography prior to lesion (here tumor) surgery (top left) and for intra-operative neuronavigation (bottom) in a patient with a grade III astrocytoma in the lower left temporal lobe centered on the middle to inferior temporal gyrus (T2/3) just below Labbé´s vein (compare with intra-operative surgical situs, top right).

b) neurosurgical treatment of frequent seizures refractory to medication ("epilepsy surgery")

or, in lesional epilepsies (e.g. due to focal cortical dysplasias), a combination of the two.

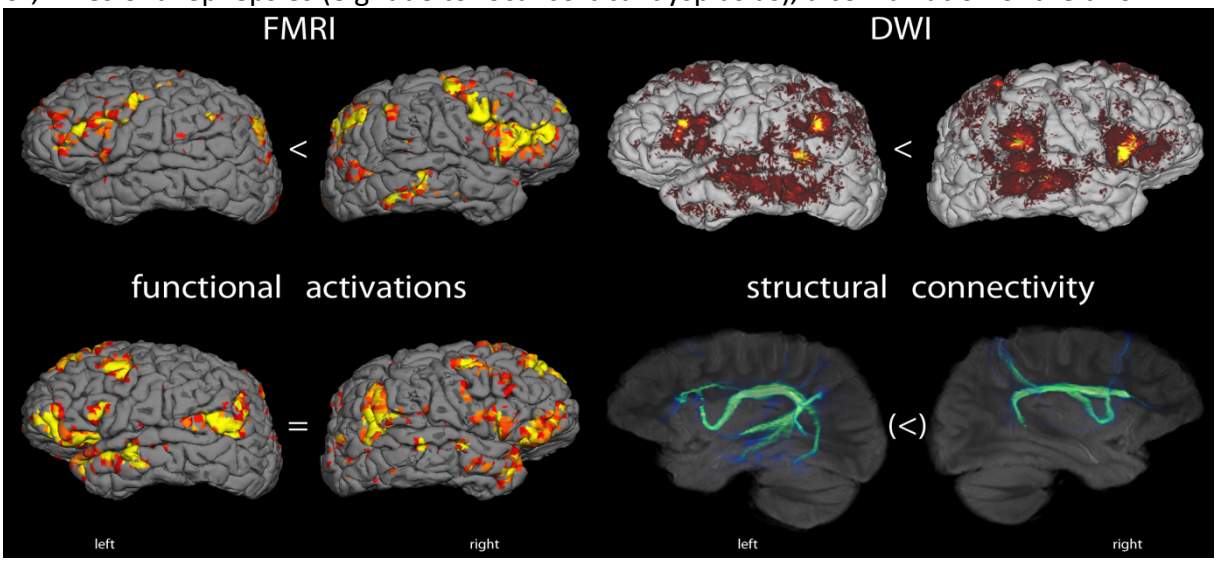

Figure 2: FMRI and tractography prior to nonlesional epilepsy surgery in a 13 year-old left-hander with left frontotemporal seizures to establish language lateralization.

Lesion surgery and "nonlesional" (as jugded by MRI) epilepsy surgery differ in that patients with intra-axial lesions and neurological/neuropsychological deficits prior to the surgery are at high risk that the latter will (at least temporarily) worsen after surgery (the lesion indicates its "eloquent" location in brain parenchyma by the deficits) while in epilepsy surgery it is the patients with no detectable lesions and no interictal neurological/neuropsychological deficits prior to surgery which are at particular risk to develop some postsurgical deficits (since the surgery is likely to entail some largely "healthy" brain tissue).
In this context, language is the most important to map by clinical fMRI, followed by vision and memory. Mapping the latter poses particular challenges (cf. Susan Bookheimer's talk).
Less common scenarios in which clinical fMRI exams may be conducted are the following:

c) fMRI prior to cochlear (CI), brainstem (ABI) or midbrain implantation (MI) to establish residual functional integrity of the auditory system as a prerequisite for successful CI/ABI/MI, to choose the optimal level of implantation and side for CI (or possibly an ABI), using fMRI audiometry and extra- or transtympanic promontory testing, and

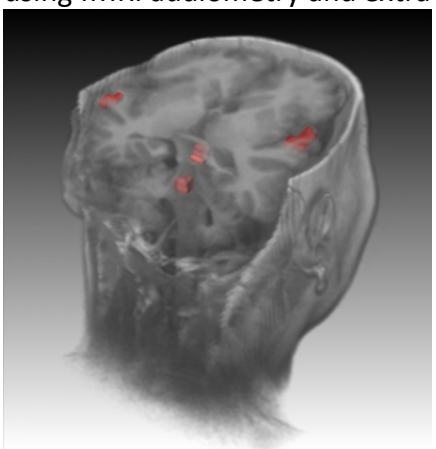

Figure 3: Left extratympanic fMRI promontory testing in a binaurally deaf NF type II patient confirming residual functional integrity of the auditory system and eligibility for left-ear CI.

d) cerebrovascular reactivity mapping (CVRM) to substantiate the indication for

i) surgical or interventional revascularization in steno-occlusive arteriopathies (such as carotid artery stenosis or Moya-Moya disease) or

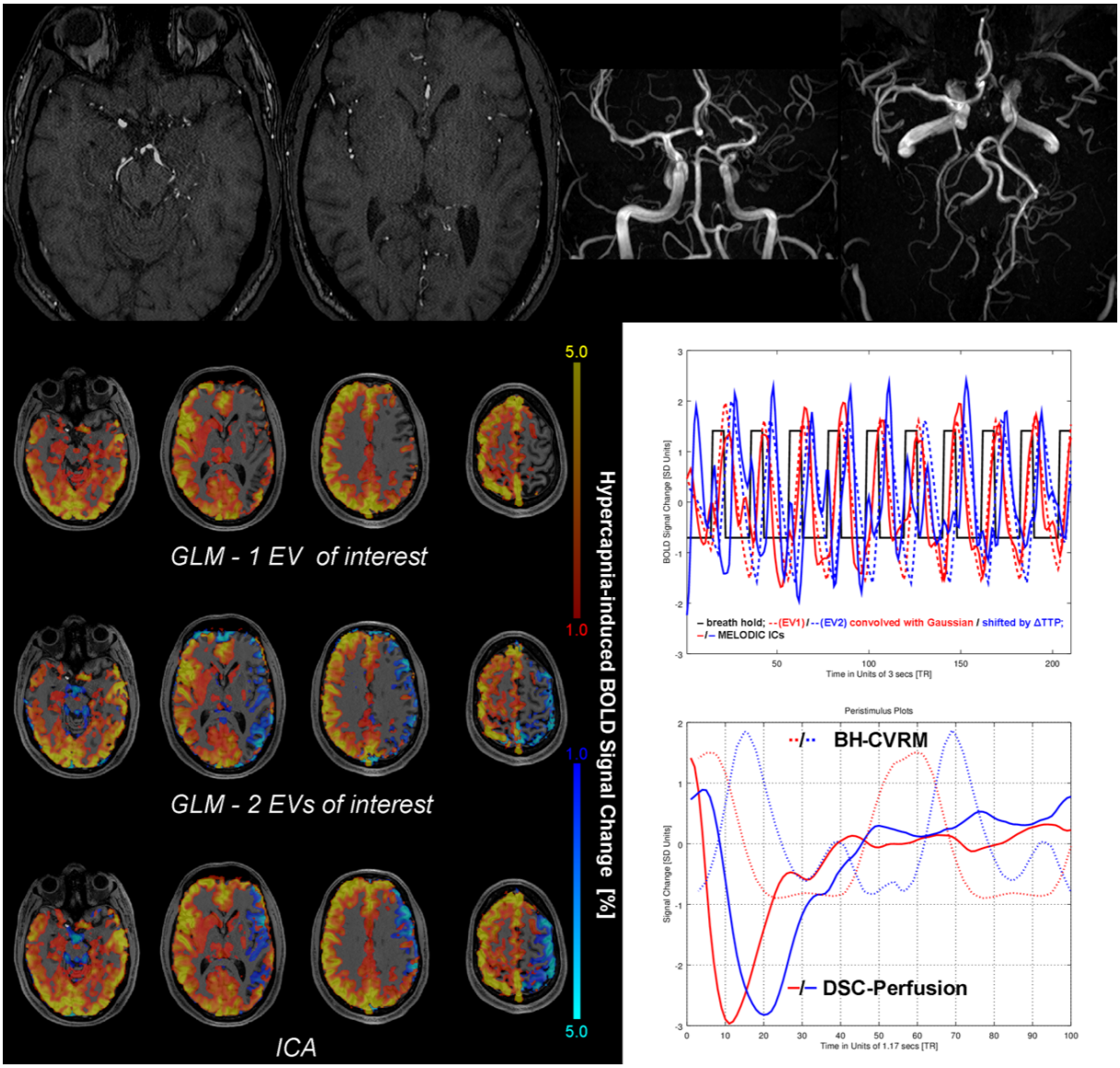

Figure 4: Breath-Hold (BH) CVRM in a NF type I patient with left terminal ACI-, M1- and A1-stenosis due to intimal hyperplasia (Pseudo-"Moya-Moya") confirming a delayed but preserved cerebrovascular reserve so that extra-to-intracranial bypass surgery was not indicated. Note that general linear modelling (GLM) by a single explanatory variable (EV) of interest delivered false-negative results for the left ACM territory which would have prompted unnecessary and risky bypass surgery.

ii) awake surgery with intra-operative cortical electrical stimulation mapping (ESM) when peri- or intralesional areas at high risk for false-negative detections by conventional fMRI are identified (cf. my other talk on CVRM).

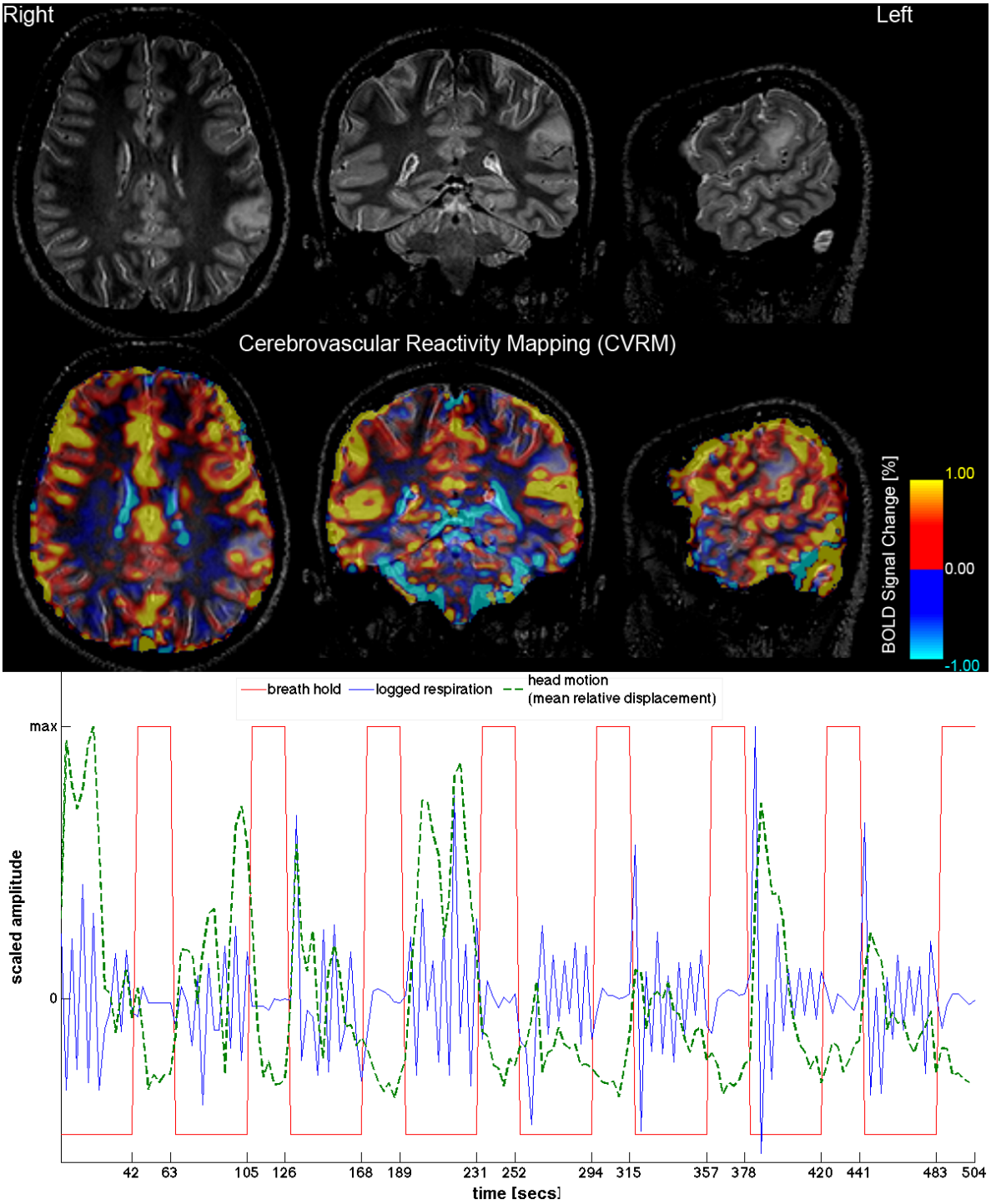

Figure 5: Attenuated intralesional cerebrovascular reactivity in a patient with a left inferior parietal, supramarginal space-occupying lesion prior to language fMRI and resective surgery emphasizing the need for ESM to guide a safe resection attempt.

2. Patient history and condition: *Radiology is chronology* – so review previous records and exams of the patient available for comparison. Also remember that *we treat patients not images*: Neurological/neuropsychological impairments and handedness (or, more broadly, behavioral hand, leg, eye and ear dominance; cf. Figure 2) of the patient should be stated, preferably with reference to the results of a separate, comprehensive neuropsychological evaluation. This, in turn, will justify the selection of the paradigms employed. Record the medications the patient has recently been and is currently on (as these may influence your fMRI results).

3. Lesion description: Intra-axial target lesions should be precisely characterized in terms of their location in the brain and their signal behavior, i.e. their spatial relation/distance to "known"/presumed eloquent areas and intra-/perilesional T2*-signal losses/black-outs which exponentially increase the risk for false-negative detections in clinical fMRI and may, to start with, be excluded from default analysis inclusion masks. Attention must be paid to other structures which will impact the surgical procedure (such as vessels encased by tumor but supplying/draining more distant areas, presence of en-passant feeders in AVMs, superficial veins that facilitate orientation when brain shift sets in, deep veins to be spared from surgical damage, distance to ventricle border and risk for subependymal spread etc.). Don't miss other lesions by focusing on the obvious primary target.

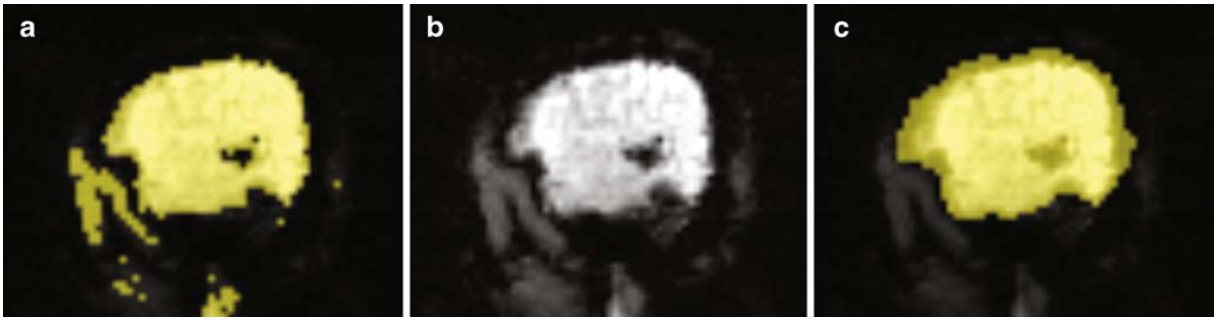

Figure 6: Left temporal AVM with EPI signal loss (b), being excluded from an intensity-based fMRI inclusion mask (a) but included by more liberal masking (c). Always make sure that the lesion is covered by the analysis mask. Even when included, intra- and perilesional signal loss ("blooming" in cavernomas or intratumoral hemorrhages, for example) can dramatically reduce the sensitivity of clinical fMRI to detect activations.

4. Paradigm selection (primarily in task- but also for task-free fMRI): Briefly describe the paradigm(s)/stimulation used for the mapping. Has a set of standard paradigms been used and/or was it specifically chosen based on patient performance, lesion location, and/or proven/postsurgically anticipated deficits? Were adjustments to stimulation mode (auditory vs. visual) and speed made to challenge the patient at but not beyond his upper performance level? Mention if training sessions were performed. Also mention if and how the scanner (EPI) noise has been attenuated / cancelled.

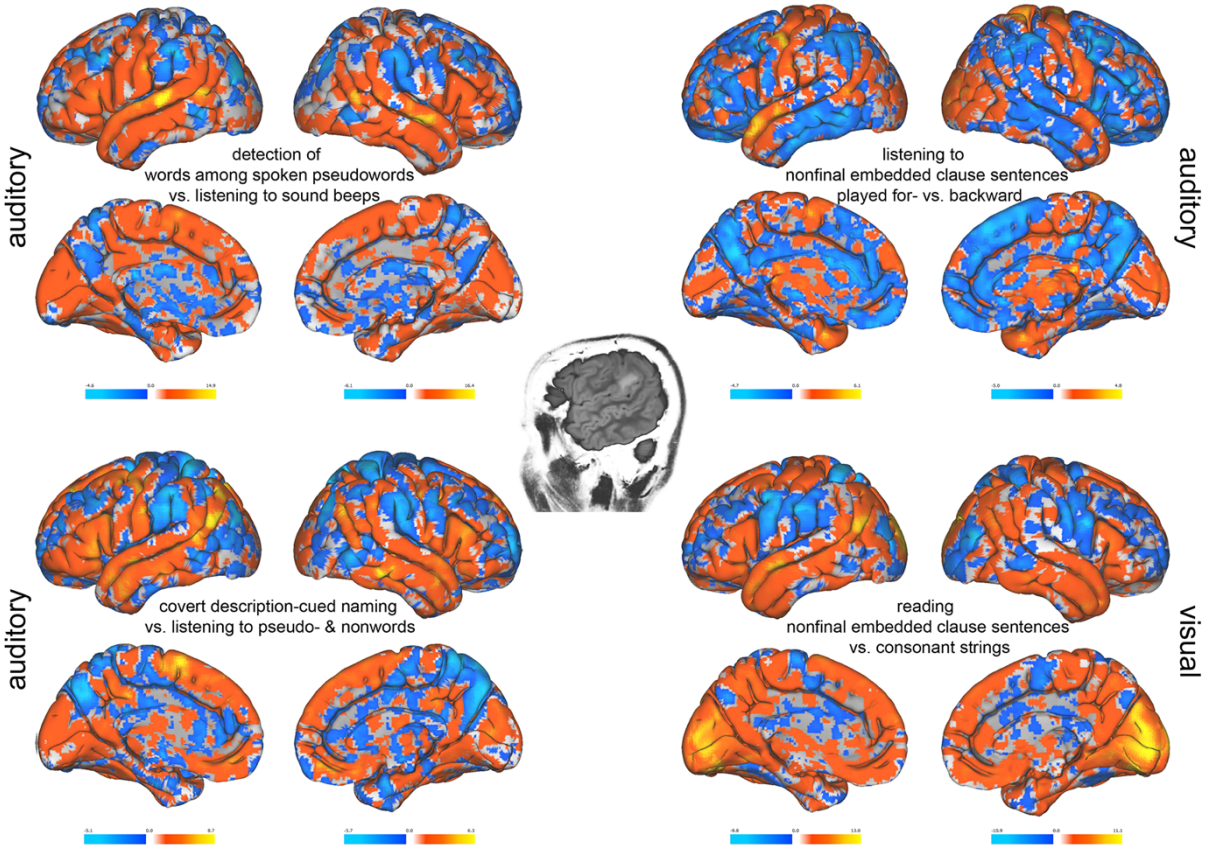

Figure 7: FMRI results depend on stimulation mode and paradigm, i.e. there is no single "speech and language map". Same patient as in Fig. 5, with different language tasks evoking different activations. The phonological challenge to discriminate spoken words from pseudowords (top left) reveals activations closest to the left anterior supramarginal lesion. Active-noise-cancellation (ANC) and left monaural auditory stimulus presentation was used to minimize language-unspecific, auditory stimulation-mode dependent activations.

5. Technique: Describe the basic MR acquisition parameters (static field strength, GE-EPI, TR/TE/FA/ESP, MB/SMS, spatial resolution/interslice gap, number of volumes recorded, prospective motion correction), the data pre- (retrospective motion- and distortion correction, smoothing) and postprocessing, analysis (GLM vs. ICA, type/threshold of statistical inference) and QA-measures (e.g., amount of motion detected, quality of registration of functionals to structural scan; cf. Mark Jenkinson's & Cyril Pernet's talks). All of these can seriously impact fMRI results, their spatial accuracy and statistical confidence (cf. Figs. 8-12). *Minimizing false-negative detections is crucial for a) and b) to avoid postsurgical deficits, while for c) controlling false-positive rates is at least equally important to assure eligibility for CI.*

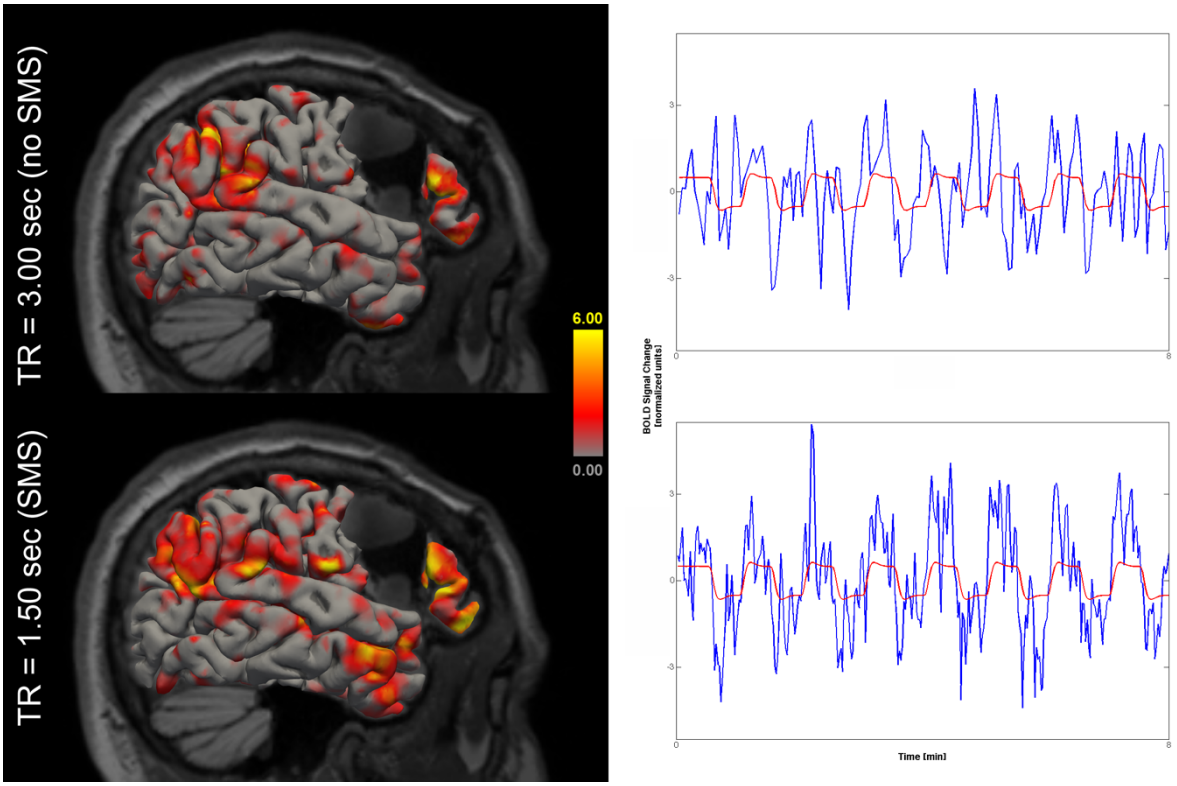

Figure 8: FMRI results depend on data acquisition. Accelerated fMRI by simultaneous multi-slice (SMS) sampling that doubles the temporal resolution improves the statistical confidence of frontal language fMRI activations and temporal correlation of the time-courses with the model (r = 0.2 vs. 0.7).

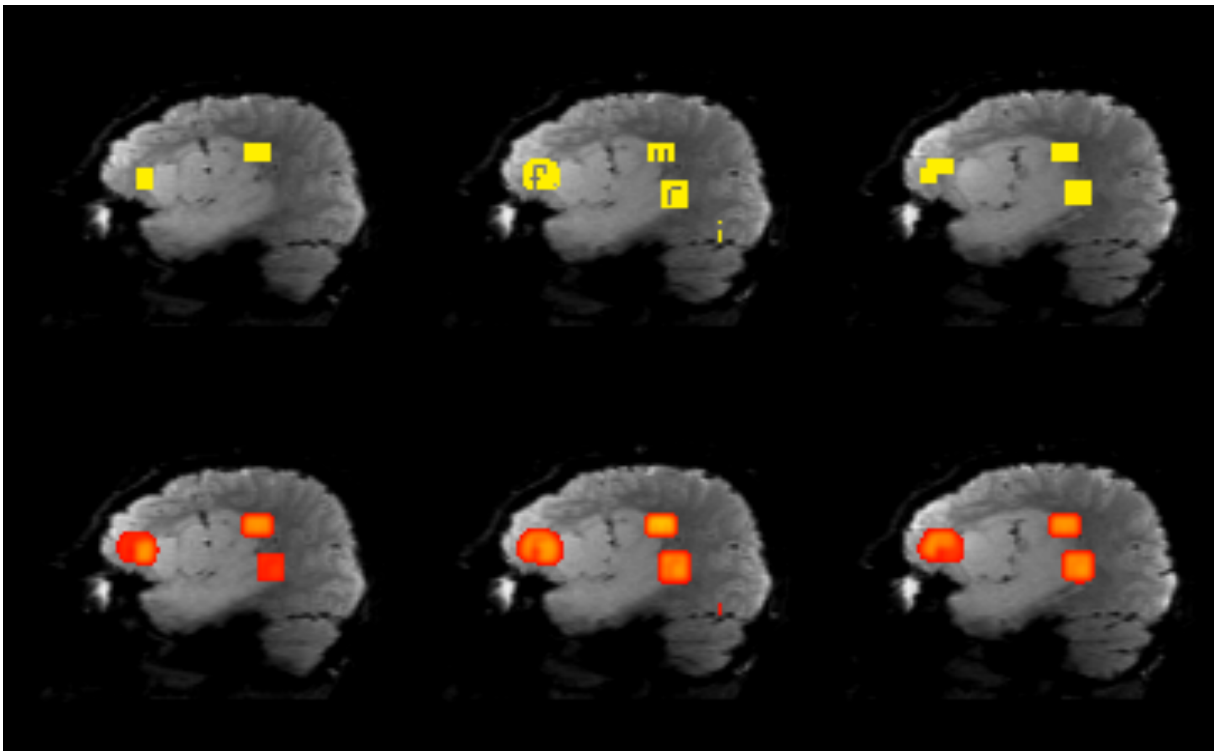

Figure 9: FMRI results depend on data preprocessing. Smoothing 1.8x1.8x2.1mm voxels by Gaussian 4.5mm FWHM quenches small (dot on "i") and spreads out other activations, causing both false-negative (FN) and false-positive (FP) detections.

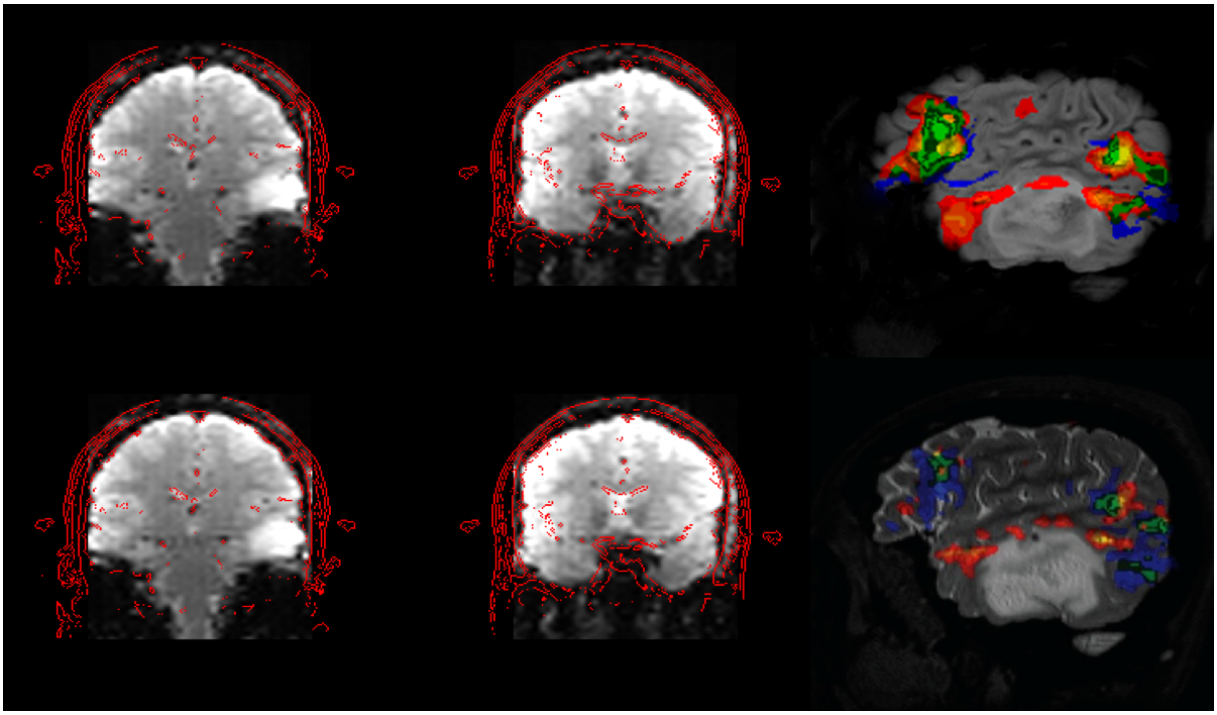

Figure 10: FMRI results depend on image registration. Same patient as in Fig. 1. Top row: Z-shift from EPI signal loss at the skull base simulating intratumoral fMRI activations at the primary exam, suggesting macroscopic tumor resection could not be achieved (rigid-body, correlation ratio registration of undistorted functional to structural). Bottom row: Elimination of z-shift by boundary-based registration at follow-up exam reveals fMRI activations at the border of but not within the tumor. Complete gross tumor resection was achieved.

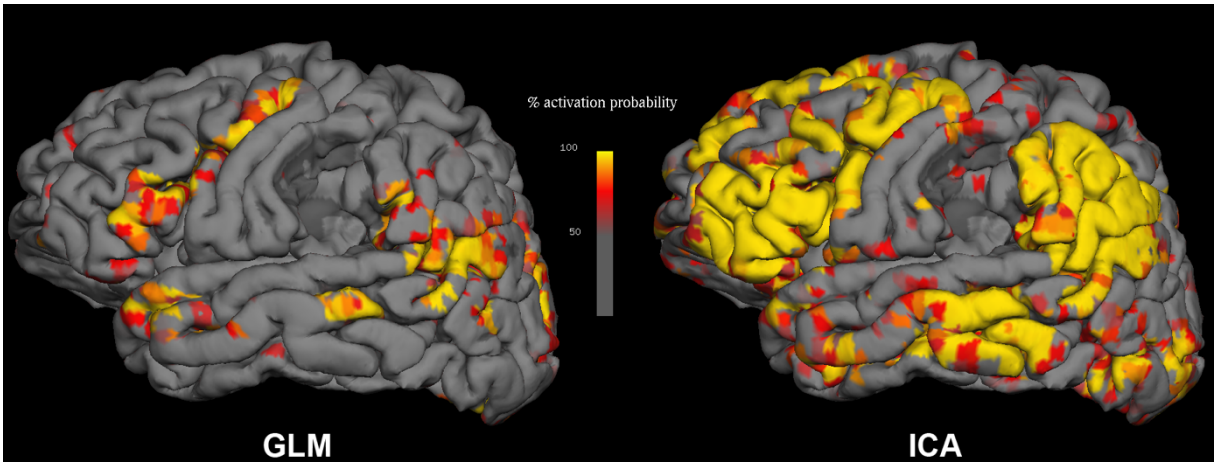

Figure 11: FMRI results depend on data analysis. Virtual neurosurgery of a left parietal glioma. Left – Gaussian-Gamma-Mixture-Modeling (GGMM) of z-statistical maps from the General Linear Model (GLM) which relies on prediction of a specific BOLD response. Right – GGMM of z-statistical maps from Independent Component Analysis (ICA) which extracts spatial maps and time-courses from the fMRI data that can be correlated post-hoc with the paradigm.

6. Findings: Describe the observed activation patterns and extent, and, prior to lesion(al epilepsy) surgery, their spatial relation to the lesion and surrounding intra-/extra-axial structures of interest (see above; incl. skull sutures, veins & dural sinuses relevant for access), with special reference to "function in lesion/tumor", for example, and displacement of perilesional activations. If relevant, assess lateralization of findings, and report how you did it.

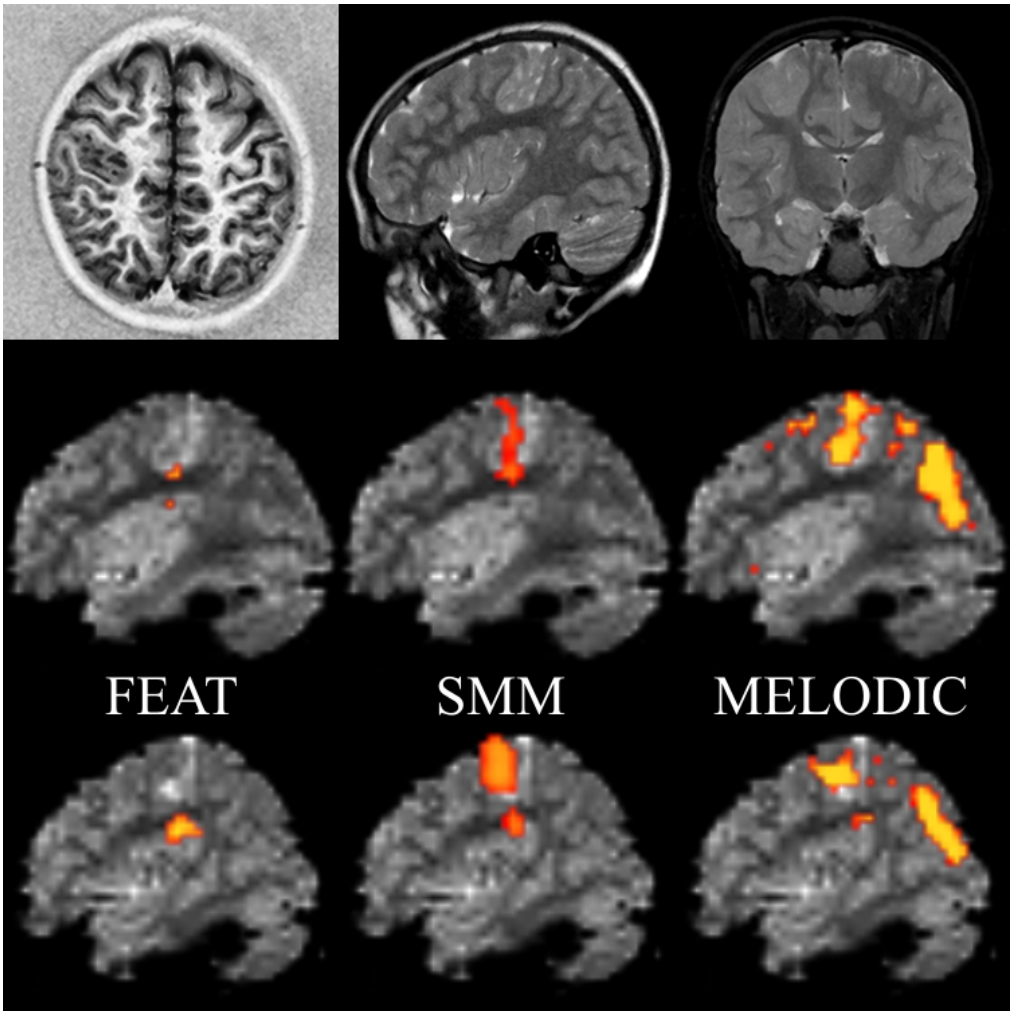

Figure 12: FMRI results depend on data analysis and statistical thresholding. 5 year-old boy with left-sided Jacksonian seizures and a right-precentral focal cortical dysplasia exhibiting a positive transmantle sign but somewhat ambiguous gyration. Conventional cluster-FWER-corrected $p_{(FP)} \leq 0.05$ motor fMRI maps (FEAT) largely suggest resectability while spatial mixture modeling (SMM) of the same z-statistics and ICA (MELODIC) reveal motor "eloquence" at $p_{(TP)} > 0.80$.

7. Conclusions: Provide a concise synthesis of your findings, including the information of further studies like diffusion tractography, perfusion and CVRM. Answer the question that has been asked by the referrers and posed by the indication to conduct the clinical fMRI exam.
In a), for example, discuss the consequences and favoured route of surgical access, the suggested extent of surgery (cave: this will crucially depend on your analysis, type of inference and statistical thresholds chosen), the patient's risk to potentially develop postsurgical deficits, their nature and prognosis, and the implications for presurgical councelling. Mention if/when results of your analysis are ready to be transferred into the neuronavigation system, usually along with tractography (and possibly perfusion, CVRM and spectroscopy) results. Explain how these could guide intra-operative stimulation (cf. Susan Bookheimer's & Natalie Voet's talks). Be to the point, clear and as brief as possible. *Good neuroradiological reporting takes the mindful courage to be potentially wrong.*

8. Disclaimer (for legal reasons): Institutional legal disclaimer

Pearls:

- Structured reporting is not an end in itself. Instead, its purpose is to increase the clinical utility, reliability and reproducibility of fMRI. Hopefully, it will also enhance the attention to, recognition of and reimbursement for the extended efforts that go into clinical fMRI. Structured reporting may also foster meta- and "big data" analyses of clinical fMRI.
- It is crucial to establish and explicitly state the intra- vs. extra-axial location of a lesion. Clinical fMRI is rarely indicated in extra-axial lesions (only if the surgical access route traverses through the brain parenchyma or to predict the consequence of potential complications of extra-axial surgery). However, for some lesions it is difficult to decide upon their intra- vs. extra-axial location, and others are, in fact, mixed.
- Despite still being frequently requested and conducted, motor mapping is hardly ever justified for presurgical localization of the precentral gyrus (only when the sensorimotor strip *cannot* be unequivocally identified by anatomic criteria or when the lesion under consideration could be both functionally active or silent, cf. Fig. 12).
- When the patient cannot perform the task, there is no point in mapping the response to it. Stimulation mode, speed and paradigm should match yet challenge the patient's abilities to obtain optimal results.
- Smoothing can literally quench and artificially spread out fMRI activations, both of which may be harmful for the patient in the clinical setting.
- Contrary to neuroscientific investigations, false-positive control is usually NOT the top concern in clinical fMRI.
- Whenever possible, join the neurosurgeon in the operating room. It will help you to appreciate the surgical perspective, the practical consequences of your exams and to improve your structured reporting abilities.

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