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Review article

The white matter architecture underlying semantic processing: A systematic review

E.-M. Cocquyt[a,b,*], E. Lanckmans[a,b], P. van Mierlo[b,c], W. Duyck[d], A. Szmalec[d,e], P. Santens[b,f], M. De Letter[a,b]

[a] Department of Rehabilitation Sciences, Ghent University, Belgium
[b] Research Group BrainComm, Ghent University, Belgium
[c] Department of Electronics and Information Systems, Medical Image and Signal Processing Group, Ghent University, Belgium
[d] Faculty of Psychology and Educational Sciences, Department of Experimental Psychology, Ghent University, Belgium
[e] Psychological Sciences Research Institute, Université catholique de Louvain, Louvain-la-Neuve, Belgium
[f] Department of Neurology, Ghent University Hospital, Belgium

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ABSTRACT

From a holistic point of view, semantic processes are subserved by large-scale subcortico-cortical networks. The dynamic routing of information between grey matter structures depends on the integrity of subcortical white matter pathways. Nonetheless, controversy remains on which of these pathways support semantic processing. Therefore, a systematic review of the literature was performed with a focus on anatomo-functional correlations obtained from direct electrostimulation during awake tumor surgery, and conducted between diffusion tensor imaging metrics and behavioral semantic performance in healthy and aphasic individuals. The 43 included studies suggest that the left inferior fronto-occipital fasciculus contributes to the essential connectivity that allows semantic processing. However, it remains uncertain whether its contributive role is limited to the organization of semantic knowledge or extends to the level of semantic control. Moreover, the functionality of the left uncinate fasciculus, inferior longitudinal fasciculus and the posterior segment of the indirect arcuate fasciculus in semantic processing has to be confirmed by future research.

1. Introduction

Functional imaging studies on the grey matter correlates of language processing have revealed widespread networks of both cortical and subcortical structures (Binder et al., 2009; Cocquyt et al., 2019; Vigneau et al., 2006). The functional interactions between these brain regions, which are highlighted in multiple holistic language models (Berwick et al., 2013; Dominey and Inui, 2009; Friederici, 2002; Hagoort, 2005; Hart et al., 2013; Murdoch, 2009) rely on the efficient transmission of information. This information flow is subserved by structural (sub)cortico-cortical connections through multiple white matter pathways (Dick et al., 2014). Previous postmortem anatomical dissection studies and diffusion tensor imaging (DTI) research (Agrawal et al., 2011; Catani et al., 2002) revealed the fiber bundles that form the anatomical basis of our language connectome (Dick et al., 2014), namely the frontal aslant tract (FAT), the fronto-striatal tract (FST), the arcuate fasciculus (AF), the uncinate fasciculus (UF), the middle longitudinal fasciculus (MdLF), the inferior longitudinal fasciculus (ILF), the inferior fronto-occipital fasciculus (IFOF) (Fig. 1) and the superior longitudinal fasciculi (SLF-II and SLF-III) (Catani and Thiebaut de Schotten, 2012; Catani et al., 2012; Catani, Jones, & ffytche, 2005). For a precise description of their trajectory, we refer to recent tractography and postmortem anatomical dissection studies (Ford et al., 2013; Hau et al., 2017; Martino et al., 2013; Sarubbo et al., 2013) and to anatomical review papers (Bajada et al., 2015; Burks et al., 2017; Burks et al., 2018; Martino and De Lucas, 2014; Thiebaut de Schotten et al., 2011).

In this systematic review, the focus of interest is semantic processing, which refers to the ability to store and regulate the knowledge that we acquired through life experiences. In general, intact semantic processing relies on interactions between a semantic representation/storage system and a semantic control system, as highlighted in the controlled semantic cognition framework (Ralph et al., 2017). Focusing on the representation/storage system, the hub-and-spoke model proposes that semantic knowledge is organized in modality-specific association areas (spokes) and integrated in an amodal convergence area (hub) (Ralph et al., 2017). The modality-specific areas are localized in the

* Corresponding author. Department of Rehabilitation Sciences, Ghent University, Corneel Heymanslaan 10, B-9000, Ghent, Belgium.
E-mail address: elissamarie.cocquyt@ugent.be (E.-M. Cocquyt).

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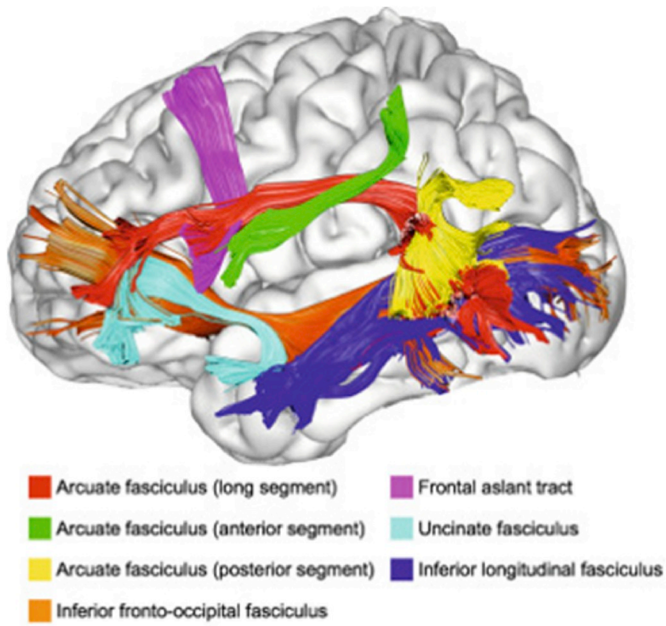

Fig. 1. Anatomical overview of the arcuate fasciculus (direct segment, and anterior and posterior indirect segment), inferior fronto-occipital fasciculus, uncinate fasciculus, inferior longitudinal fasciculus and frontal aslant tract. Reprinted from Maffei et al. (2015), Imaging white-matter pathways of the auditory system with diffusion imaging tractography. In Handbook of clinical neurology (Vol. 129, pp. 277–288), with permission from Elsevier.

frontal, temporal, parietal and occipital lobes (Patterson et al., 2007; Pulvermuller and Fadiga, 2010), while both a single hub in the anterior temporal lobe (ATL) (Patterson et al., 2007) and multiple hubs in posterior temporo-parietal areas (Binder and Desai, 2011) have been suggested. Moreover, semantic control, which can be defined as the retrieval and selection of appropriate semantic representations in a certain context, has been linked to the anterior and posterior parts of the inferior frontal gyrus (Badre et al., 2005; Badre and Wagner, 2007; Devlin et al., 2003; Gold et al., 2005; Thompson-Schill et al., 2005) and to the posterior part of the middle temporal cortex (Davey et al., 2016; Noonan et al., 2013; Whitney, Kirk, O'Sullivan, Lambon Ralph and Jefferies, 2011). The functional interactions between these cortical areas correspond to the ventral stream in the dual-stream model for language (Hickok and Poeppel, 2007). In line with the bilateral organization of semantic knowledge (Binder and Desai, 2011), the ventral stream is proposed to be bilaterally represented in the brain (Hickok and Poeppel, 2007).

Valuable insights into which white matter pathways subserve the ventral semantic stream are provided by brain-damaged patients with language deficits. Griffis, Nenert, Allendorfer, and Szaflarski (2017) described the effect of stroke-related damage to white matter “bottlenecks”, localized in the depth of the left superior/middle temporal and prefrontal cortices. These areas can be seen as crossroads, where multiple pathways can be disrupted due to one focal lesion (Turken and Dronkers, 2011). Damage to the temporal bottleneck predicted both semantic production (picture naming and semantic fluency) and comprehension deficits (auditory semantic decision-making), whereas damage to the prefrontal bottleneck only predicted deficits in semantic fluency. Both the frontal and temporal bottleneck contain projections associated with the IFOF, UF and ILF, suggesting a semantic contribution of these three pathways. This hypothesis is supported by multiple lesion-symptom mapping results in which stroke lesion volume of the left IFOF and UF are strongly associated with deficits in semantic comprehension and production tasks (Han et al., 2013; Mirman et al., 2015). Moreover, therapy-related semantic improvement has been linked to structural plasticity of the ILF (McKinnon et al., 2017). Additional insights are provided by patients with the semantic variant of primary progressive aphasia (svPPA),[1] a clinical PPA-variant characterized by the gradual deterioration of semantic knowledge due to atrophy of the anterior temporal lobe (ATL) (Gorno-Tempini et al., 2004). In the svPPA, white matter changes are predominantly found in the left ILF and UF (Acosta-Cabronero et al., 2011; Tu et al., 2016) and also emerge in the right UF when the disease duration increases (Tu et al., 2016). However, the aforementioned findings have been attenuated in the dynamic hodotopical model as proposed by Duffau and colleagues. Focusing on picture naming, the authors suggested a direct ventral route, constituted by the IFOF, and an indirect ventral route, consisting of the UF and the anterior part of the ILF. The direct route is postulated as being essential in semantic processing, whereas lesions of the indirect route are proposed to be functionally compensable (Duffau et al., 2014).

Hence, the identification of tracts specifically contributing to semantic processing remains a matter of debate, despite the growing number of studies on the functional role of white matter pathways. Thus, an integration of results from different methodological approaches might shed light on this topic. One potential approach to identify an association between white matter pathways and semantic functions is the investigation of anatomo-functional correlations between DTI-parameters and behavioral performance on a wide range of semantic tasks. DTI is a magnetic resonance imaging technique used to visualize white matter fibers and to measure multiple parameters regarding the diffusion of water molecules in the brain. The most common parameter is fractional anisotropy (FA), which is a normalized measure of diffusion directionality, ranging from zero to one. FA depends on diffusion restrictions caused by local barriers such as cell membranes and myelin sheaths. High values of FA indicate microstructural coherence and better structural integrity (Johansen-Berg and Behrens, 2013). Two other directionality-parameters are the axial diffusivity (AD) and the radial diffusivity (RD), which reflect the diffusion parallel to and perpendicular to the axis of principal diffusion. Contrastingly, mean diffusivity (MD) is direction-independent and reflects the magnitude of diffusion. This parameter often co-varies with FA, since it is also affected by membrane density and myelination (Johansen-Berg and Behrens, 2013). Interestingly, the anatomo-functional correlation approach can be addressed in both healthy and aphasic individuals gaining insights into the relationship between intact or disturbed semantic processing and the integrity of the underlying white matter tracts.

A second approach that gains fundamental insights on this topic is the direct electrical stimulation (DES) technique during awake surgery. This technique is the sole available method in order to directly investigate the function of white matter fibers (Duffau, 2015). In awake tumor surgeries, DES has become the gold standard to identify (sub)cortical language eloquent structures. DES mimics the effect of a brain lesion by eliciting a transitory interruption within a (sub)cortico-cortical language network. Based upon the structural-functional correlations, the neurosurgeon can maximize the tumor resection in language eloquent areas according to individually defined functional boundaries (Duffau, 2005). Concerning these functional boundaries, preservation of white matter connectivity is crucial. Trinh et al. (2013) reported that subcortical injuries are a predictor of functional deterioration after surgery when only cortical language mapping is used. Therefore, subcortico-cortical stimulation mapping is applied in the patients' best interest, but also provides an unique opportunity to investigate the

[1] PPA is a clinical syndrome characterized by progressive isolated speech and language deficits. PPA encompasses three main phenotypes, namely the non-fluent variant, the logopenic variant and the semantic variant, each of them linked to different clinical symptoms, distributions of brain atrophy and underlying pathophysiological mechanisms (Gorno-Tempini et al., 2004; Gorno-Tempini et al., 2011; Knibb et al., 2006; Mesulam et al., 2008).

white matter network underlying semantic processing.

In this systematic review, we present an integrative overview of the semantic deficits occurring due to DES during awake tumor surgeries and of anatomo-functional correlations performed between DTI-parameters and behavioral semantic performance in both healthy subjects and in patients with aphasia. By comparing and integrating the results from these three populations, we aim to clarify which white matter pathway(s) contribute(s) to semantic processing.

2. Method

A systematic review on the contribution of white matter tracts in semantic processing was conducted. The general approach to identify, select and summarize the evidence in order to answer the research question is consistent with the methodology described in the Cochrane Handbook for Systematic Reviews of Interventions Version 5.1.0 (Cochrane Collaboration, 2011).

The following electronic databases were systematically searched to identify studies relevant for this review: Web of Science, Medline (using the PubMed interface) and Embase (using the Embase.com interface). The strategies used to search in the aforementioned databases are available in Appendix 1. The searches in each database were performed on October 16, 2017 and all references were exported into a reference manager software tool (Endnote) in order to remove the duplicates. Subsequently, titles and abstracts identified by the search were screened for relevance to the research question by two independent reviewers (E.-M.C. and E.L.). During this screening, specific eligibility criteria were taken into account (Table 1). After the exclusion of records according to title and abstract, the full-texts of the remaining references were searched for through SFX (UGent-collection). When no full-text was available, attempts were made to contact the authors. Next, the full-texts were screened against the eligibility criteria. Disagreements on the inclusion of articles were resolved by discussion or by involving a third reviewer (M.D.L), until a consensus was reached. All of the information was processed in a summary table (available from the first author upon request). In order to identify a significant contribution of a white matter tract to semantic processing its role should be 1) confirmed in the majority of studies that investigated a specific tract, 2) determined by the two methods of interest (DES and DTI) and 3) established at group level.

In addition, the quality of the selected articles was evaluated with a scoring system including multiple aspects of the method and results section, in order to secure the validity of the studies. The aspects could achieve a maximum score of 1 or 2, depending on their relative value. The scoring system was based on the "Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies" of the National Institutes of Health (https://www.nih.gov/). The detailed terms and weighted distribution of points for each aspect can be found in Appendices 2, 3 and 4.

Table 1
Overview of the eligibility criteria used for the selection of articles in the systematic review.

Eligibility criteria	Inclusion criteria
Population	General - Adults (male or female) - Right-handed - No developmental or genetic disorders - Native speaker of an Indo-European language Awake surgery - Individuals diagnosed with a tumor, eligible for their first awake surgery DTI - Healthy individuals - Patients with aphasia due to stroke (ischemic or hemorrhagic) - Patients with primary progressive aphasia
Intervention	- Awake surgery: a semantic task in the participants' native language during direct electrical stimulation of a specific white matter tract - DTI: a semantic task combined with diffusion tensor imaging
Outcome	- Awake surgery: a semantic* error due to intra-operative stimulation of a specific white matter tract - DTI: correlations between the performance on semantic tasks and DTI-scalars
Publication type	General - A1-publication - Written in English - Prospective study - Group or single-case study - All publication years until October 16, 2017

Note: DTI = diffusion tensor imaging; *Anomia was not considered as a semantic error since it cannot be ruled out that the underlying deficit is phonological in nature (Mandonnet, 2017).

3. Results

3.1. Study identification and selection process

A flowchart of the identification and selection of the included studies is provided in Fig. 2 (Moher et al., 2009). The literature search in the electronic databases yielded 3705 articles. After removing duplicates and triplicates, 1921 records remained. Screening of titles and abstracts resulted in 192 references. After full-text screening, 149 studies were excluded because our selection criteria were not met. Forty-three studies met the inclusion criteria (24 awake surgery studies, 10 DTI-studies in patients with aphasia and 9 DTI-studies in healthy subjects) and were included for further analysis.

3.2. Direct electrical stimulation (DES) of white matter tracts during awake surgery

Quality of evidence – Fig. 3 shows the quality parameters of the twenty-four studies on awake tumor surgeries. Concerning patient demographics, the age (mean and standard deviation) of the patients was clearly reported in most of the studies (18/24–75%). Conversely, the lack of information on their education level is the most notable shortcoming. Years of education were reported in only 16.7% of the studies (4/24). Moreover, the localization of the tumor was often vaguely described in terms of cortically involved grey matter (e.g. "a low-grade glioma in the temporal lobe") and white matter tract(s) displacement or interruption, resulting in a rather low quality score (20/48). Furthermore, pre-operative language dominance and language deficits were described in the majority of studies, in 58.3% (14/24) and 66.7% (16/24) respectively. Regarding the intra-operative logopedic procedure, the used language tasks, materials and methods were accurately described in almost every study (68/72–94.4%). In addition, a precise description of the white matter stimulation site (the name of the stimulated tract and an anatomical description of the stimulation areas) was provided in most of the studies. Therefore, a general quality score of 34/48 was achieved. Finally, the outcome measures, namely the language deficits occurring due to DES, were mainly described in a detailed way (30/48–62.5%).

In the paragraphs below, results on the semantic deficits that occurred due to the stimulation of specific white matter tracts are summarized. An overview of the results (i.e. patient demographics, specific stimulation areas and intra-operative language deficits) can be found in Table 2 for the fronto-striatal tract as well as the uncinate, inferior longitudinal and arcuate fasciculus, and in Table 3 for the inferior fronto-occipital fasciculus.

Uncinate fasciculus (UF) – During picture naming, the left UF was intra-operatively stimulated in 12.5% of the studies (3/24). No language disorders were observed in two studies (Duffau et al., 2009; Vassal et al., 2013), whereas Bello et al. (2008) reported semantic

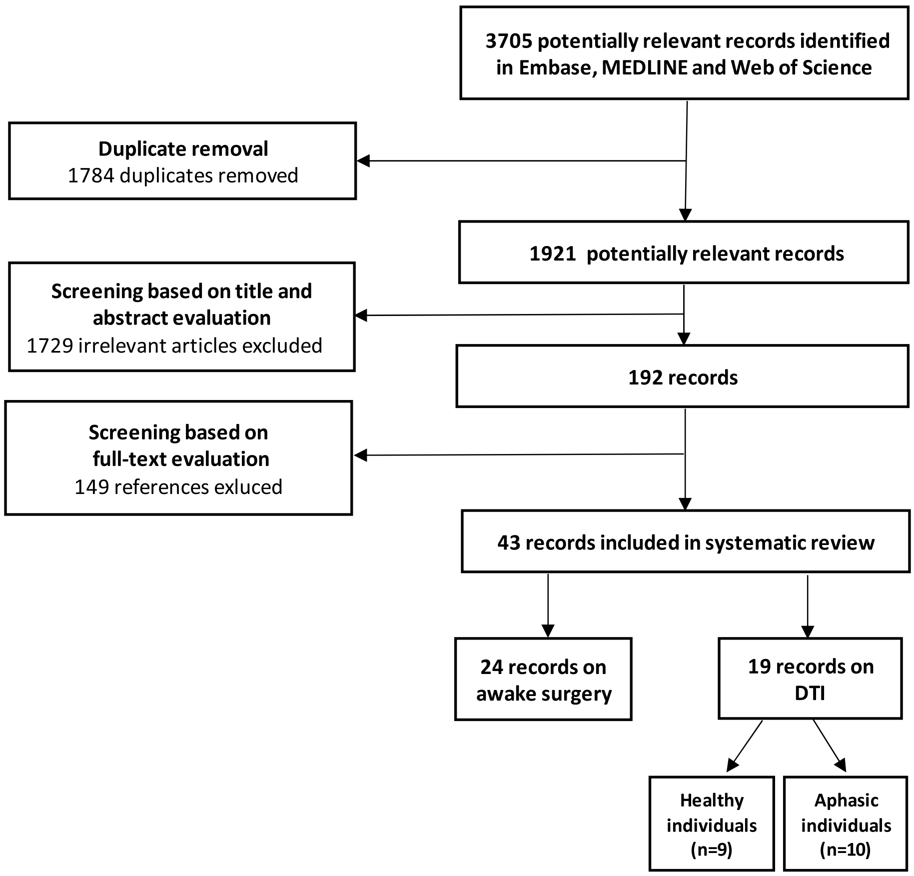

Fig. 2. A flowchart of the identification and selection of studies, based on the PRISMA flowchart - Moher et al. (2009).

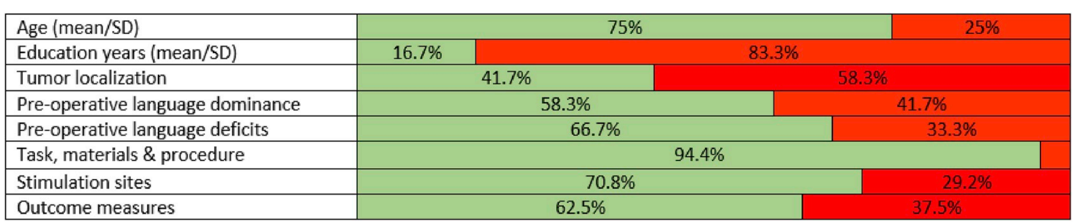

Fig. 3. Overview of the quality parameters of the 24 included studies on awake surgery. We refer to Appendix 2 for the detailed terms and weighted distribution of points for each row header. Green = high quality, red = low quality (SD = standard deviation). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

paraphasias (SPs). However, the latter result is not very reliable since it is unclear in how many patients this symptom occurred.

Inferior fronto-occipital fasciculus (IFOF) – The left (or right[2]) IFOF was stimulated during picture naming in 66.7% of the awake surgery studies (16/24). In all sixteen studies, semantic paraphasias (SPs) were reproducibly induced, either due to stimulation of the frontal, insular, parietal or occipito-temporal portion of the IFOF (Almairac et al., 2015; Bello et al., 2007, 2008; Chan-Seng et al., 2014; Hamer et al., 2011; De Witte et al., 2015; Duffau et al., 2005, 2008, 2009; Gil-Robles et al., 2013; Leclercq et al., 2010; Mandonnet et al., 2007; Moritz-Gasser et al., 2013; Sarubbo et al., 2015; Vassal et al., 2013; van Geemen et al., 2014). Specific information on the type of semantic paraphasias was provided in only two studies. Moritz-Gasser et al. (2013) reported associative (e.g. “key” for “padlock”) or coordinate SPs (e.g. “tiger” for “lion”) due to stimulation of the temporal part of the left IFOF. In Duffau et al. (2005), stimulation of the frontal, insular or temporal portion of the language dominant IFOF most frequently elicited coordinate SPs or the use of a hyperonym (e.g. “bird” for “eagle”). Interestingly, the difficulty to distinguish the posterior part of the IFOF and the middle longitudinal fasciculus (MdLF) under the superior temporal sulcus was mentioned in two studies. The authors remained inconclusive on which fasciculus was stimulated (Maldonado et al., 2011a, 2011b). However, stimulation and resection of at least one part of the MdLF did not induce SPs or other naming deficits in Hamer et al. (2011).

In 8.3% of the studies (2/24), direct electrical stimulation of either the left IFOF (Moritz-Gasser et al., 2018) or the right IFOF (Herbet et al., 2017) induced semantic association impairments during a visual non-verbal association task, which requires subjects to identify associative relationships among pictures i.e. the Pyramids and Palm Trees Test (PPTT; Howard and Patterson, 1992).

Inferior longitudinal fasciculus (ILF) – Intra-operative stimulation of the left ILF was described in 25% of the studies (6/24). Linguistic deficits due to DES of the left ILF presented either as alexia during reading tasks (Chan-Seng et al., 2014; Gil-Robles et al., 2013; Sarubbo

[2] Duffau et al. (2005) included three patients with a tumor in the language dominant right hemisphere, DES was administered at the right IFOF.

Table 2
Overview of the studies in which the left uncinate fasciculus (UF) (1–3), the left inferior longitudinal fasciculus (ILF) (4–6), the left or right arcuate fasciculus (AF) (7–8) and the left fronto-striatal tract (FST) (9–10) were intra-operatively stimulated during picture naming, resulting in semantic paraphasias or no naming deficits. The following information is presented: characteristics of the patients, the localization of direct electrical stimulation area(s) and the resulting language disturbances.

No	References	N	Age range (mean, SD)	Tumor localization in the left hemisphere	Specific area of white matter stimulation	Language disturbances
1.	Bello et al. (2008)	ns	ns	ns	ns	SPs
2.	Duffau et al. (2009)	12/12	26-60 (38, 11)	Anterior temporal, orbitofrontal	ns	None
3.	Vassal et al. (2013)	ns	ns	ns	ns	None
4.	Bello et al. (2007)	ns	ns	Temporal	Superior temporal gyrus (posterior part superior wall temporal horn of the lateral ventricle)	SPs
5.	Mandonnet et al. (2007)	ns	ns	ns	Laterally and inferiorly to the wall of temporal horn of lateral ventricle	None
6.	Vassal et al. (2013)	ns	ns	ns	ns	None
7.	Leclercq et al. (2010)	2/3	33-39 (36, 3)	Infero-lateral frontal, medial frontal (RH)	ns	SPs
8.	Rofes et al. (2017)	1/ns	39	Inferior parietal	ns	SPs
9.	Bello et al. (2006)	2/3	ns	Precentral	Antero-lateral border of the frontal horn of the lateral ventricle	SPs
10.	Bello et al. (2007)	ns	ns	Frontal	Inferior antero-lateral border of the frontal horn of the lateral ventricle	SPs

Note: N = The amount of patients in which (no) language errors occurred during stimulation of a specific fiber bundle, related to the total number of patients in which this fiber bundle was identified and stimulated, SD = standard deviation, ns = not specified, SPs = semantic paraphasias, RH = right hemisphere.

et al., 2015) or as semantic paraphasias during picture naming (Bello et al., 2007). Concerning the latter finding, the amount of patients in whom this occurred remains indistinct. Moreover, contrasting findings were reported by Mandonnet et al. (2007) and Vassal et al. (2013), who did not observe naming errors.

Arcuate fasciculus (AF) – The left AF was the target of stimulation during picture naming in 62.5% of the awake surgery studies (15/24). In 13.3% of these studies (2/15), semantic paraphasias occurred due to the temporary disruption of the left or the right AF (Leclercq et al., 2010; Rofes et al., 2017). However, these symptoms were only present in single subjects and are rather unexpected since the majority of studies indicated phonological paraphasias (Almairac et al., 2015; Bello et al., 2006, 2007; Chan-Seng et al., 2014; Hamer et al., 2011; Duffau et al., 2008, 2009; Maldonado et al., 2011a, 2011b; Mandonnet et al., 2007; Sarubbo et al., 2015; Vassal et al., 2013; van Geemen et al., 2014).

Remaining pathways – The superior longitudinal fasciculus (SLF), frontal aslant tract (FAT) and fronto-striatal tract (FST) were intra-operatively stimulated in 8.3%, 20.8% and 20.8% of the studies respectively (2/24, 5/24 and 5/24). Stimulation along the left SLF(/AF) induced articulatory disorders (Maldonado et al., 2011a, 2011b; van Geemen et al., 2014), phonological paraphasias (Bello et al., 2008) or syntactic gender disorders (Vidorreta et al., 2011), whereas stimulation of the left FAT resulted in speech initiation disorders (Kinoshita et al., 2015) or morphological overregularization (Sierpowska et al., 2015). Importantly, stimulation of the SLF/(AF) or FAT never resulted in semantic errors during picture naming. Focusing on the left FST, Bello et al. (2006) and Bello et al. (2007) reported semantic paraphasias, although in a very limited amount of patients. Their findings are generally not supported within the literature since a speech initiation disorder seems to be the main deficit due to electrostimulation of the left FST (Vassal et al., 2013; Duffau et al., 2008; Kinoshita et al., 2015).

Summary – Semantic paraphasias were the most common observed deficits during intra-operative stimulation of the language dominant (left) IFOF. Moreover, a contributive role of both the left and right IFOF during non-verbal association was preliminarily suggested. Regarding the left UF, ILF, AF, SLF, FAT and FST, awake surgery results did not support an essential function in picture naming.

3.3. Diffusion tensor imaging (DTI) in patients with aphasia: anatomo-functional correlations

Quality of evidence – Fig. 4 shows the quality parameters of the ten DTI-studies in patients with aphasia. In general, patient demographics were properly reported (age: 10/10–100%; education level: 6/10–60%; type of aphasia: 7/10–70%; disease duration: 9/10–90%). However, a precise description of the localization of the ischemic/hemorrhagic lesion in stroke-patients or the atrophy in patients with PPA was lacking in 60% of the studies (6/10). Associated with the latter aspect, controlling for overall cortical lesion volume in statistical analyses was applied in only 30% of the studies (3/10). Finally, the used language tasks, materials and procedures, DTI-parameters and analysis methods, fasciculi of interest and outcome measures were accurately described in all of the studies.

In the following paragraphs, results on the anatomo-functional correlations between DTI-metrics of white matter tracts and aphasic patients' behavioral scores on tasks that require semantic processing are reported. An overview of the patient demographics can be found in Table 4, whereas the results are presented in Table 5.

Uncinate fasciculus (UF) – Correlations between DTI-parameters of the left UF and behavioral performance on tasks that target semantic processing were described in 60% of the studies (6/10). In 83.3% of these studies (5/6) a contribution of the left UF in word comprehension or production was suggested. Regarding comprehension, significant correlations between FA values (+), the number of streamlines (+) and radial diffusivity (−) of the left UF and auditory word-picture matching

Table 3
Overview of 1) the studies in which the inferior fronto-occipital fasciculus (IFOF) (1–16) or the IFOF/middle longitudinal fasciculus (MdLF) (17–18) were intra-operatively stimulated during picture naming, resulting in reproducible semantic paraphasias and 2) the studies in which the IFOF was intra-operatively stimulated during a non-verbal association task (19–20), resulting in semantic association impairments.

N°	References	N	Age range (mean, SD)	Tumor localization in the left hemisphere	Localization of white matter stimulation	
					Hemisphere	Specific stimulation area
1.	Almairac et al. (2015)	31/31	21-54 (35.7, 9.8)	● Supra-tentorial	Left	● Posterior orbito-frontal area (10/10) ● Limen insulae (posterior part temporal stem) (14/14) ● Floor of the external capsule (7/7)
2.	Bello et al. (2007)	ns/10 ns/2	ns ns	● Paralimbic ● Parietal	Left Left	● Anterior floor of the external capsule ● Inferior border of the parietal lobe
3.	Chang-Seng et al. (2014)	8/8	32-61 (41.7, 9.6)	● Temporo-occipital junction (sagittal stratum)	Left	● Superior part temporal-occipital junction
4.	Duffau et al. (2005)	9/9 2/2 6/6	25-52 (37, ns) 32-33 (32,5) 17-43 (26, ns)	● SFG/MFG ● Insular lobe ● MTG/ITG, fusiform gyrus*	Left (7/9) Right (2/9)* Left Left (5/6) Right (1/6)*	● Under the IFS (MFG-glioma) + laterally/above the anterior part of the head of the caudate nucleus (SFG-glioma) ● Anterior part external capsule ● Under the STS, above the temporal horn of the lateral ventricle
5.	Duffau et al. (2009)	7/8 5/5	26-54 (36, 10.5) 27-60 (41, 12.5)	● Antero-temporal ● Orbitofrontal	Left Left	● Under the STS, above the temporal horn of the lateral ventricle ● Under the IFS/MFG
6.	Duffau et al. (2008)	20/20 14/14 29/29	ns ns ns	● Temporal (not specified) ● Insular ● MFG/IFG	Left Left Left	● ns ● Antero-inferior ● (Antero)lateral
7.	Hamer et al. (2011)	8/8	27-61 (41, 14)	● Temporo-insular	Left	● STG
8.	Leclercq et al. (2010)	4/4	23-37 (30.1, 5.7)	● Infero-lateral frontal, SMA, lateral temporal, insular (DTI: AF and IFOF)	Left	● ns
9.	Mandonnet et al. (2007)	7/7	26-50 (34.9, 8)	● MTG/ITG/fusiform and parahippocampal gyrus, hippocampus, amygdala and STG	Left	● Under STS, just above the roof of the temporal horn of the lateral ventricle
10.	Moritz-Gasser et al. (2013)	7/8	21-52 (41.6, 11.2)	● Temporal, fusiform, fronto-temporo-insular	Left	● Temporal part (not further specified)
11.	Vassal et al. (2013)	2/ns	ns	● ns	Left	● ns
12.	van Geemen et al. (2014)	2/2	20-36 (28; 8)	● Ventral premotor cortex, insula and Broca's area	Left	● Anterior part (ns)
13.	De Witte et al. (2015)	1/1	46	● Fronto-temporal (DTI: IFOF)	Left	● ns
14.	Bello et al. (2008)	ns	ns	● Prerolandic, parietal and temporal	Left	● ns
15.	Gil-Robles et al. (2013)	2/2	60-64 (62; 2)	● Fusiform gyrus	Left	● Superior wall of the lateral ventricle
16.	Sarubbo et al. (2015)	ns	ns	● ns	Left/Right	● Ventro-medial fusiform gyrus, above the roof of the temporal horn of the lateral ventricle, middle/posterior MFG, SFG and IFG
17.	Maldonado et al. (2011a)	4/4	27-52 (39.5, 10.4)	● SMG, AG and STG	Left	● Posterior part of the STG (2/4) and STS (2/4)
18.	Maldonado et al. (2011b)	4/4	27-52 (39.5, 10.4)	● SMG, AG and pSTG	Left	● Deepest portion of STS and under STG
19.	Herbet et al. (2017)	2/2 2/3 8/8	24-67 (44.7–12.8)	● Prefrontal (RH) ● Parietal/angular gyrus (RH) ● Fronto-temporo-insular (RH)	Right Right Right	● In the depth of the DLPFC ● Posterior parietal ● ns
20.	Moritz-Gasser et al. (2013)	ns/8	21-52 (41.6–11.2)	● Temporal, temporo-occipital junction, fronto-temporo-insular	Left	● Temporal part (not further specified)

Note: N = The amount of patients in which language errors occurred during stimulation of a specific fiber bundle, related to the total number of patients in which this fiber bundle was identified and stimulated; SD = standard deviation; ns = not specified; SFG = superior frontal gyrus; MFG = medial frontal gyrus; IFS = inferior frontal sulcus; MTG = medial temporal gyrus; ITG = inferior temporal gyrus; STS = superior temporal sulcus; IFG = inferior frontal gyrus; (p)STG = (posterior) superior temporal gyrus; MdLF = medial longitudinal fasciculus; SMA = supplementary motor area; DTI = diffusion tensor imaging; AF = arcuate fasciculus; IFOF = inferior fronto-occipital fasciculus; SMG = supramarginal gyrus; AG = angular gyrus; * Duffau et al. (2005) included three patients with a tumor located in the right hemisphere (frontal lobe: n = 2, temporal lobe: n = 1), right-hemisphere language dominance was reported.

Fig. 4. Overview of the quality parameters of the 10 included studies on diffusion tensor imaging in patients with aphasia. We refer to Appendix 3 for the detailed terms and weighted distribution of points for each row header. Green = high quality, red = low quality (SD: standard deviation; DTI = diffusion tensor imaging). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

was reported in patients with aphasia due to stroke (Harvey et al., 2013; Xing et al., 2017) and in patients with PPA (Catani et al., 2013; Marcotte et al., 2017). Moreover, FA values of the left UF predicted performance on the spoken word PPTT (Howard and Patterson, 1992), which requires subjects to identify associative relationships between words and pictures. Harvey et al. (2013) considered the performance on the spoken word PPTT as well as on their auditory word-picture matching task as a specific behavioral measure of semantic control. Finally, FA values and the number of streamlines of the left UF predicted performance on picture naming and on semantic fluency tasks in patients with PPA (Powers et al., 2013; Catani et al., 2013).

Concerning the right UF, FA (+) and RD (−) were significantly correlated with naming scores (Powers et al., 2013) and with the amount of semantic features during speech production (Marcotte et al., 2017) in patients with PPA.

Inferior fronto-occipital fasciculus (IFOF) – In 50% of the studies (5/10) correlations between DTI-metrics of the IFOF and performance on auditory word and sentence comprehension, non-verbal association or picture naming were described. Results in patients with stroke-related aphasia and PPA are quite unanimous, 80% of these studies (4/5) support an important contribution of the left IFOF during (lexico) semantic comprehension and production (Ivanova et al., 2016; Xing et al., 2017; Rolheiser et al., 2011; Powers et al., 2013). However, FA of the left IFOF did not predict performance on an auditory word-picture matching task and on the spoken word PPTT (Howard and Patterson, 1992). From these results, the authors concluded that the left IFOF does not subserve an essential semantic control function (Harvey et al., 2013). Finally, correlations between DTI-metrics of the right IFOF and auditory comprehension or picture naming scores were not significant (Ivanova et al., 2016).

Inferior longitudinal fasciculus (ILF) – DTI-scalars of the ILF were correlated with performance on tasks requiring semantic computations in 70% of the studies (7/10). The results of 71.4% of these studies (5/7) support a contributive role of the left ILF in word or sentence comprehension. Significant correlations between test performance and FA (+), MD (−), RD (−) or AD values (−) were reported both in patients with stroke-related aphasia (Ivanova et al., 2016; Mandelli et al., 2014; Marcotte et al., 2017) and in patients with PPA (Agosta et al., 2010; Xing et al., 2017). However, diverging results were found by Harvey et al. (2013). More specifically, no relationship was found between FA of the left ILF and the performance on an auditory word-picture matching task and on the spoken word PPTT (Howard and Patterson,

Table 4
Characteristics of the patients with stroke-related aphasia or primary progressive aphasia in studies focusing on anatomo-functional correlations between DTI-parameters and behavioral semantic measures.

N°	References	Population	N	Age range (mean, SD)	Education years Range (mean, SD)	Handedness	Months post stroke Range (mean, SD)	Years from symptom onset (PPA) Range (mean, SD)	Type of aphasia/PPA subtype
1.	Agosta et al. (2010)	PPA	5	56-67 (62.6, 4.6)	12-16 (14.2, 1.8)	R (4) L (1)	n.a.	3-8 (6.2, 1.9)	sv (5)
2.	Breier et al. (2008)	Stroke	20	38-77 (58, 11)	ns	ns	1-72 (22, 24)	n.a.	ns
3.	Catani et al. (2013)	PPA	35	ns (63.2, 8.3)	ns	R (35)	n.a.	ns (3.9, 1.8)	sv (8), nfv (14), lv (9) mixed (2), unclassified (2)
4.	Harvey et al. (2013)	Stroke	10	41-83 (63, ns)	11-22 (16, ns)	ns	8-127 (70, ns)	n.a.	anomic (6), conduction (1), Broca (2), not available (1)
5.	Ivanova et al. (2016)	Stroke	37	34-78 (54, 10.53)	ns	R (37)	4-100 (26.38, 21.40)	n.a.	fluent (13), nonfluent (20), mixed (4)
6.	Mandelli et al. (2014)	PPA	9 8 8	ns (67.3, 5.7) ns (61.4, 5.6) ns (63.6, 7.1)	ns (15.1, 2.8) ns (16.0, 1.5) ns (16.1, 3.2)	R (9) R (8) R (8)	n.a.	ns (4.2, 1.8) ns (5.4, 3.2) ns (5.1, 4.4)	nfv (9) sv (8) lv (8)
7.	Marcotte et al. (2017)	PPA	13 12	ns (65.2, 10.6) ns (68.7, 7.3)	ns (13.5, 2.6) ns (18.1, 5.4)	R (12) R (11)	n.a.	ns ns	nfv (13) sv (12)
8.	Powers et al. (2013)	PPA	11 13	ns 63.8, 7.4) ns (65.9, 7.5)	ns (17.2, 3.4) ns (14.6, 2.8)	ns ns	n.a.	ns (3.9, 2.6) ns (2.7, 1.8)	sv (11) lv (13)
9.	Rolheiser et al. (2011)	Stroke	24	34-76 (57.5, 12.6)	ns	R (24)	1-21 (ns, ns)	n.a.	ns
10.	Xing et al. (2017)	Stroke	40	ns (59.6, 10.1)	ns (16.3, 2.9)	R (33) L (6) A (1)	ns (45.3, 38.6)	n.a.	ns

Note: n = the amount of patients; SD = standard deviation; PPA = primary progressive aphasia; R = right-handed; L = left-handed; A = ambidextrous; n.a. = not applicable; ns = not specified, sv = semantic variant; nfv = nonfluent variant; lv = logopenic variant.

Table 5
An overview of the anatomo-functional correlations between DTI-parameters and behavioral semantic measures in patients with stroke-related and primary progressive aphasia.

VAFasciculus	Population	Semantic measures	Semantic assessment tool	Significant results					Non-significant results					References
				FA	MD	RD	AD	NSL	FA	MD	RD	AD	NSL	
Left UF	Stroke	Auditory comprehension	WAB - comprehension						*					Breier et al. (2008)
	Stroke	Auditory word comprehension	WPV	+										Harvey et al. (2013)
	PPA		PPVT			-		+						Catani et al. (2013)
	PPA		PPVT			-								Marcotte et al. (2017)
	Stroke		WR + WPV	+	-	-	-							Xing et al. (2017)
	Stroke	Auditory sentence comprehension	Composite score **						-	-	-	-		Xing et al. (2017)
	Stroke	Association	PPTT (spoken word)	+										Harvey et al. (2013)
	PPA	Naming	BNT					+						Catani et al. (2013)
	PPA (sv)		BNT	*										Powers et al. (2013)
	PPA (sv)	Semantic fluency	SFT	*										Powers et al. (2013)
Left ILF	Stroke	Auditory word comprehension	WPV						+					Harvey et al. (2013)
Anterior-middle	Stroke		WPV	+++										Ivanova et al. (2016)
	PPA		PPVT		-									Agosta et al. (2010)
Middle	PPA		PPVT	+										Mandelli et al. (2014)
	PPA		PPVT			-								Marcotte et al. (2017)
Posterior	Stroke		WR + WPV						+	-	-	-		Xing et al. (2017)
	Stroke	Auditory sentence comprehension	SPV/command execution	+++										Ivanova et al. (2016)
	Stroke		Composite score**		-	-	-		+					Xing et al. (2017)
	Stroke	Non-verbal association	PPTT						+					Harvey et al. (2013)
	PPA		PPTT							-				Agosta et al. (2010)
	PPA		PPTT	+										Mandelli et al. (2014)
	Stroke	Naming	Picture naming	+					++					Ivanova et al. (2016)
	PPA		BNT							-				Agosta et al. (2010)
	PPA (lv)		BNT	*										Powers et al. (2013)
	PPA	Semantic fluency	SFT							-				Agosta et al. (2010)
	PPA (lv)		SFT	*										Powers et al. (2013)
	PPA	Language production: semantic features	Topic-directed interview			-								Marcotte et al. (2017)
Left IFOF	Stroke	Auditory word comprehension	WPV						+					Harvey et al. (2013)
Anterior-middle	Stroke		WPV	+++										Ivanova et al. (2016)
	Stroke		WR + WPV	+	-	-	-							Xing et al. (2017)
Middle	Stroke	Auditory sentence comprehension	SPV + command execution	+++										Ivanova et al. (2016)
	Stroke		Composite score **	+	-	-	-							Xing et al. (2017)
Posterior	Stroke	Semantic knowledge	Yes/no questions	+										Rolheiser et al. (2011)
	Stroke	Association	PPTT (spoken word)						-					Harvey et al. (2013)
	Stroke	Naming	Picture naming	+					++					Ivanova et al. (2016)
	PPA (lv)		BNT	*										Powers et al. (2013)
	Stroke		Picture naming	+										Rolheiser et al. (2011)

(continued on next page)

Table 5 (*continued*)

Fasciculus	Population	Semantic measures	Semantic assessment tool	Significant correlation(s)					Non-significant correlation(s)					References
				FA	MD	RD	AD	NSL	FA	MD	RD	AD	NSL	
Left AF	Stroke	Auditory comprehension	WAB-comprehension						*					Breier et al. (2008)
Frontal	Stroke	Auditory word comprehension	WPV	+					++					Ivanova et al. (2016)
Parietal	PPA		PPVT		-									Agosta et al. (2010)
	Stroke		WR + WPV						-	+	+	+		Xing et al. (2017)
Temporal	Stroke	Auditory sentence comprehension	SPV/command execution	+					++					Ivanova et al. (2016)
	Stroke		Composite score **						+	-	-	-		Xing et al. (2017)
	PPA	Non-verbal association	PPTT							-				Agosta et al. (2010)
	Stroke	Naming	Picture naming	++					+					Ivanova et al. (2016)
	PPA		BNT							-				Agosta et al. (2010)
	PPA	Semantic fluency	SFT							-				Agosta et al. (2010)
Left SLF	Stroke	Auditory comprehension	WAB - comprehension						*					Breier et al. (2008)
	PPA (lv)	Naming	BNT	*										Powers et al. (2013)
	PPA (lv)	Semantic fluency	SFT	*										Powers et al. (2013)
Left FAT	PPA	Auditory word comprehension	PPVT						-		+		-	Catani et al. (2013)
	PPA		PPVT						-					Mandelli et al. (2014)
	PPA	Non-verbal association	PPTT						-					Mandelli et al. (2014)
	PPA	Naming	BNT						+		-		+	Catani et al. (2013)
Left FST	PPA	Auditory word comprehension	PPVT						+					Mandelli et al. (2014)
	PPA	Non-verbal association	PPTT						-					Mandelli et al. (2014)
Right UF	Stroke	Auditory comprehension	WAB-comprehension						*					Breier et al. (2008)
	PPA (sv)	Naming	BNT	*										Powers et al. (2013)
	PPA	Speech production: semantic features	Topic-directed interview			-								Marcotte et al. (2017)
Right SLF	Stroke	Auditory comprehension	WAB-comprehension						*					Breier et al. (2008)
Right AF	Stroke	Auditory comprehension	WAB-comprehension						*					Breier et al. (2008)
	Stroke		WPV						x					Ivanova et al. (2016)
	Stroke	Auditory sentence comprehension	SPV/command execution						x					Ivanova et al. (2016)
Right ILF	Stroke	Auditory word comprehension	WPV						x					Ivanova et al. (2016)
	Stroke	Auditory sentence comprehension	SPV/command execution						x					Ivanova et al. (2016)
	PPA	Speech production: semantic features	Topic-directed interview			-								Marcotte et al. (2017)
Right IFOF	Stroke	Auditory word comprehension	WPV						x					Ivanova et al. (2016)
	Stroke	Auditory sentence comprehension	SPV/command execution						x					Ivanova et al. (2016)
	Stroke	Naming	Picture naming						x					Ivanova et al. (2016)

Note: + and – refer to the results from correlation analyses, * refers to the results from an ANOVA or a regression model; x = unclear whether correlation was positive or negative; FA= fractional anisotropy; MD = mean diffusivity; RD= radial diffusivity; AD= axial diffusivity; NSL = number of streamlines; PPA = primary progressive aphasia; WAB=Western Aphasia Battery; WPV= word-picture verification; PPVT = Peabody Picture Vocabulary Test; WR = word recognition; SPV=sentence picture verification; ** composite score of WAB-subtests (auditory verbal comprehension yes/no, and sequential commands) and Boston Diagnostic Aphasia Examination subtests (complex ideational materials, semantic probe and embedded sentences); PPTT = Pyramids and Palm Trees Test; BNT = Boston Naming Test; SFT = semantic fluency test.

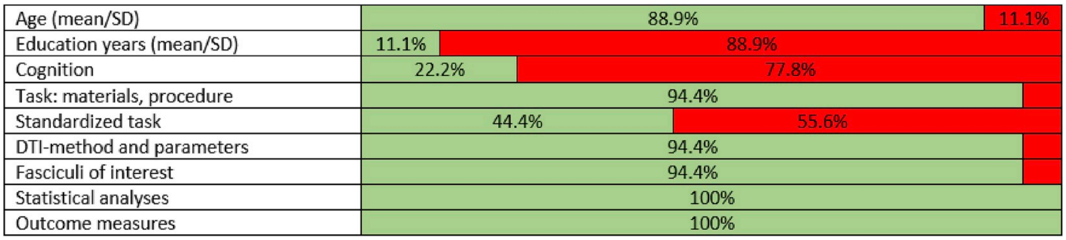

Fig. 5. Overview of the quality parameters of the 9 included studies on diffusion tensor imaging in healthy individuals. We refer to Appendix 4 for the detailed terms and weighted distribution of points for each row header. Green = high quality, red = low quality (SD: standard deviation; DTI = diffusion tensor imaging). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

1992). Similar to the results on the left IFOF, the authors proposed that the left ILF does not mediate semantic control. Unfortunately, correlations between non-verbal association abilities in patients with PPA and microstructural values of the left ILF neither support nor disprove the findings of Harvey and colleagues due to contradictory results (Agosta et al., 2010; Mandelli et al., 2014).

Focusing on the right ILF, no significant correlations with auditory comprehension scores were found in stroke patients (Ivanova et al., 2016), whereas RD values predicted the amount of semantic features during speech production in PPA patients (Marcotte et al., 2017).

Arcuate fasciculus (AF) – Correlations between DTI-parameters of the left AF and behavioral semantic performance were reported in 40% of the studies (4/10). In general, auditory word and sentence comprehension, non-verbal association, naming or semantic fluency abilities were not correlated with FA values of the left AF (Breier et al., 2008; Ivanova et al., 2016; Agosta et al., 2010; Xing et al., 2017). Nevertheless, taking different segments of the AF into account, FA (+) or MD values (−) of the temporal portion significantly correlated with word and sentence comprehension (Agosta et al., 2010; Ivanova et al., 2016), whereas for the parietal portion a correlation with picture naming performance occurred (Ivanova et al., 2016). No significant relationships were found concerning the right AF (Breier et al., 2008; Ivanova et al., 2016).

Remaining pathways – In a minority of studies, correlations between microstructural changes of the SLF (22.2%, 2/9), FAT (22.2%, 2/9) or FST (11.1%, 1/9) and language measures were investigated. In Powers et al. (2013), scores on picture naming and semantic fluency tasks were predicted by changes in FA of the left SLF in patients with the logopenic variant of PPA, whereas no association was found with auditory comprehension abilities in stroke patients (Breier et al., 2008). Regarding the left FAT, the left FST and the right SLF, associations with auditory comprehension, non-verbal association or picture naming scores were not significant (Catani et al., 2013; Mandelli et al., 2014; Breier et al., 2008).

Summary – Anatomo-functional correlations in patients with stroke-related and primary progressive aphasia revealed an important involvement of the left UF, IFOF and ILF in receptive and expressive tasks that require semantic operations. Interestingly, a semantic control function of the left IFOF and ILF was explicitly questioned by Harvey et al. (2013). For the left AF, no associations with semantic performance were reported, although results may vary regarding the specific segment under investigation. Concerning the left SLF, evidence for a role in semantic processing was very limited. Finally, the FAT and SFT did not seem to subserve functions of semantic nature.

3.4. Diffusion tensor imaging (DTI) in healthy individuals: anatomo-functional correlations

Quality of evidence – Fig. 5 shows the quality parameters of the nine DTI-studies in healthy individuals. The age (mean and standard deviation) of the subjects was clearly reported in 88.9% of the studies (8/9). Similar to results in awake surgery studies, the limited reporting of education levels is the most striking shortcoming (1/9–11.1%). In addition, there was a limited use of a standardized test to assess normal cognitive function, namely in 22.2% of the studies (2/9). Further, the used language tasks, materials and procedures were accurately described in all of the studies (8.5/9–94.4%). Nevertheless, a standardized semantic task was used in only 44.4% of the studies (4/9). Finally, the DTI-parameters and analysis methods, fasciculi of interest, statistical analyses and outcome measures were properly described.

In the paragraphs below, results on the anatomo-functional correlations between DTI-metrics of white matter tracts and healthy subjects' behavioral scores on tasks that require semantic processing are reported. An overview of the results is presented in Table 6.

Uncinate fasciculus (UF) – In 44.4% of the included studies (4/9), the relationship between DTI-metrics of the UF and (lexico)semantic task performance was described. In 75% of these studies (3/4), either no contribution in noun-based verb generation[3] (Nugiel et al., 2016) and reading comprehension (Welcome and Joanisse, 2014) or a detrimental contribution during rapid object naming (Rollans et al., 2017) was reported for the left UF. However, performance on a cross-situational learning task, in which correct associations had to be learned between spoken nonwords and pictures, was significantly correlated with RD values (−) (Ripollés et al., 2017). No (beneficial) contributions of the right UF were found (Nugiel et al., 2016; Ripollés et al., 2017; Rollans et al., 2017; Welcome and Joanisse, 2014).

Inferior fronto-occipital fasciculus (IFOF) – In 55.6% of the studies (5/9) microstructural differences of the IFOF were investigated and correlated with performance on tasks requiring semantic processing. In 60% of these studies (3/5), individual behavioral differences in rapid object naming (Rollans et al., 2017), vocabulary learning (Xiang et al., 2012) and noun-based verb generation (Nugiel et al., 2016) were significantly related to the FA, number of streamlines and MD of the left IFOF respectively. Nevertheless, the left IFOF was not identified as a key pathway in semantic learning, neither in a contextual learning task (deriving the meaning of nonwords based upon sentential contexts) nor in a cross-situational learning task (learning the association between nonwords and pictures). Hence, no evidence was found for a contribution of the left IFOF in word-to-meaning mapping (Ripollés et al., 2017), which is contradictory to findings of Xiang et al. (2012). Finally, no significant contributions of the right IFOF in the aforementioned tasks were found (Rollans et al., 2017; Nugiel et al., 2016; Ripollés et al., 2017).

Inferior longitudinal fasciculus (ILF) – In 55.6% of the studies (5/9), healthy participants' performance on various receptive and expressive tasks was correlated with DTI-scalars of the ILF. In 80% of these studies (4/5), a significant correlation between left ILF RD (−), AD (−) or MD (−) values and performance on contextual semantic learning, rapid object naming, noun-based verb generation or the amount of recalled semantic details in autobiographical memory (ABM) was reported (Ripollés et al., 2017; Rollans et al., 2017; Nugiel et al., 2016; Hodgetts

[3] Nugiel et al. (2016) considered the performance on a noun-based verb generation task as a specific behavioral measure of semantic control.

Table 6
An overview of the anatomo-functional correlations between DTI-parameters and behavioral semantic measures in healthy individuals.

Fasciculus	Semantic measures	Semantic assessment tool	Significant correlation(s)					Non-significant correlation(s)					References
			FA	MD	RD	AD	NSL	FA	MD	RD	AD	NSL	
Left UF	Reading comprehension	Nelson-Denny RC subtest						+					Welcome and Joanisse (2014)
	Semantic learning	Contextual learning								–			Ripollés et al. (2017)
		Cross-situational learning			–								Ripollés et al. (2017)
	Naming (reaction time)	RAN	+	–									Rollans et al. (2017)
	Semantic control (association strength)	Noun-based verb generation						*	*	*	*		Nugiel et al. (2016)
Left ILF	Reading comprehension	Nelson-Denny RC subtest						–					Welcome and Joanisse (2014)
	Semantic learning	Contextual learning			–								Ripollés et al. (2017)
		Cross-situational learning								–			Ripollés et al. (2017)
	Naming (reaction time)	RAN				–							Rollans et al. (2017)
	Semantic control (association strength)	Noun-based verb generation		*				*		*	*		Nugiel et al. (2016)
L/R ILF	Language production: semantic features	Galton-Crovitz cues		–				+					Hodgetts et al. (2017)
Left IFOF	Reading comprehension	Nelson-Denny RC subtest						+					Welcome and Joanisse (2014)
	Semantic learning	Contextual learning								–			Ripollés et al. (2017)
		Cross-situational learning								–			Ripollés et al. (2017)
		Vocabulary learning					*						Xiang et al. (2012)
	Naming (reaction time)	RAN	–										Rollans et al. (2017)
	Semantic control (association strength)	Noun-based verb generation		*				*		*	*		Nugiel et al. (2016)
Left AF	Auditory word comprehension	PPVT						*				*	Allendorfer et al. (2016)
	Auditory sentence comprehension	Complex ideation (BDAE)						*				*	Allendorfer et al. (2016)
	Reading comprehension	Nelson-Denny RC subtest	+										Welcome and Joanisse (2014)
	Semantic learning	Contextual learning								–			Ripollés et al. (2017)
		Cross-situational learning								–			Ripollés et al. (2017)
	Naming	RAN						x	x	x	X		Rollans et al. (2017)
		BNT						*				*	Allendorfer et al. (2016)
	Semantic fluency	SFT					*	*					Allendorfer et al. (2016)
Left SLF	Reading comprehension	Nelson-Denny RC subtest						+					Welcome and Joanisse (2014)
	Semantic fluency	SFT						x					Spalletta et al. (2014)
MdLF	Imageability	Reading event sentences + viewing event pictures					+						Jouen et al. (2015)
Right UF	Reading comprehension	Nelson-Denny RC subtest						+					Welcome and Joanisse (2014)
	Semantic learning	Contextual learning								–			Ripollés et al. (2017)
		Cross-situational learning								–			Ripollés et al. (2017)
	Naming (reaction time)	RAN		–									Rollans et al. (2017)
	Semantic control (association strength)	Noun-based verb generation						*	*	*	*		Nugiel et al. (2016)
Right ILF	Reading comprehension	Nelson-Denny RC subtest						–					Welcome and Joanisse (2014)
	Semantic learning	Contextual learning								–			Ripollés et al. (2017)
		Cross-situational learning								–			Ripollés et al. (2017)
	Naming (reaction time)	RAN									–		Rollans et al. (2017)
	Semantic control (association strength)	Noun-based verb generation	*						*	*	*		Nugiel et al. (2016)
Right IFOF	Reading comprehension	Nelson-Denny RC subtest						+					Welcome and Joanisse (2014)
	Semantic learning	Contextual learning								–			Ripollés et al. (2017)
		Cross-situational learning								–			Ripollés et al. (2017)
	Naming (reaction time)	RAN						–					Rollans et al. (2017)
	Semantic control (association strength)	Noun-based verb generation						*	*	*	*		Nugiel et al. (2016)
Right AF	Semantic learning	Contextual learning								–			Ripollés et al. (2017)
		Cross-situational learning								–			Ripollés et al. (2017)
	Naming	RAN						x	x	x	x		Rollans et al. (2017)
Right SLF	Reading comprehension	Nelson-Denny RC subtest						+					Welcome and Joanisse (2014)

Note: + and – refer to results from correlation analysis, * refers to the results from an ANOVA or a regression model; x = unclear whether correlation was positive or negative; FA = fractional anisotropy; MD = mean diffusivity; RD = radial diffusivity; AD = axial diffusivity; NSL = number of streamlines; RC = reading comprehension; RAN = rapid automatized naming; BDAE = Boston Diagnostic Aphasia Examination; BNT = Boston Naming Test; SFT = semantic fluency test.

et al., 2017). Interestingly, no significant inter-hemispheric differences were yielded for MD values in their relation with the amount of semantic ABM details, suggesting a bilateral contribution of the ILF (Hodgetts et al., 2017). The latter finding is supported by Nugiel et al. (2016) who found that higher FA in the right ILF led to slower reaction times in the noun-based verb generation task.

Middle longitudinal fasciculus (MdLF) – In an unique experiment among the included studies (11.1% - 1/9), subjects were asked to process event pictures of individuals performing daily activities (e.g. eating) and read sentences describing these actions (e.g. "The man is eating"). Afterwards, imageability ratings of the presented sentences were collected. Correlation analyses revealed that these ratings were associated with the fiber density of the bilateral MdLF (Jouen et al., 2015).

Arcuate fasciculus (AF) – DTI-scalars of the AF were correlated with performance on semantic tasks in 44.4% of the studies (4/9). No significant relationship between auditory comprehension, naming or semantic learning on the one hand and microstructural properties of the left (Allendorfer et al., 2016; Ripollés et al., 2017; Rollans et al., 2017) or the right AF (Ripollés et al., 2017; Rollans et al., 2017) on the other hand could be established in 75% of these studies (3/4). Contrarily, one study (25% - 1/4) revealed that FA values of the posterior segment of the left AF predicted reading comprehension abilities (Welcome and Joanisse, 2014).

Remaining pathways – In 22.2% of the studies (2/9), correlations between the integrity of the left or right superior longitudinal fasciculus (SLF) and semantic performance were investigated. No significant relationship between the behavioral scores on reading comprehension (Welcome and Joanisse, 2014) or semantic fluency tasks (Spalletta et al., 2014) and FA values were found. Finally, correlations between the microstructure of the frontal aslant tract or fronto-striatal tract have not been investigated.

Summary – Anatomo-functional correlations in healthy individuals revealed a contributive role of both the left IFOF and ILF in semantic processing, whereas evidence for a contribution of the left UF was very limited. Finally, preliminary results suggest that the left MdLF and the posterior segment of the left AF may underlie the neural semantic network as well.

4. Discussion

In this manuscript, we aimed to delineate the white matter architecture underlying semantic processing. Hence, we made an inventory of the current knowledge on this topic by means of a systematic review. The results of this review suggest that semantic processing is subserved by specific white matter tracts. However, the quality of the included studies as well as some limitations of the methodological techniques of interest should be considered when interpreting the results.

Quality of evidence – Both in the awake surgery and the DTI-studies, important limitations were detected by the study quality assessments. In the awake surgery studies, there was often a vague description of the tumor localization, regarding the involved grey and white matter (20/48–41.7%). Moreover, a precise description of intra-operatively stimulated areas was not always provided (34/48–70.8%). These anatomical details are crucial aspects in order to answer our research question. More specifically, our language connectome contains multiple white matter "bottlenecks" with fibers from several tracts (such as the frontal operculum, temporal stem and claustrum), making it difficult to determine which specific tract was stimulated and therefore contributed to the investigated language function (Turken and Dronkers, 2011). Furthermore, the lack of information on education levels is a common limitation in both the awake surgery studies (4/24–16.7%) and in DTI studies in healthy individuals (1/9 or 11.1%). This aspect compromises generalizability of the reported findings, as there is no guarantee that the tested subjects are representative for the entire population. Finally, there was a limited use of standardized tests to assure normal cognition (e.g. Mini-Mental State Examination) in healthy subjects (2/9–22.2%). No formal investigation of cognitive performance might have led to the inclusion of participants with mild cognitive impairment, in which white matter alterations have been described (Fellgiebel et al., 2004; Medina et al., 2006; Pievani et al., 2010). Concerning DTI-studies in patients with aphasia, an accurate description of the lesion localization was lacking in the majority of studies (6/10–60%) and cortical lesion volumes were often not included as covariates in statistical analyses (7/10–70%). This aspect might hinder the verification that white matter tracts, rather than the severity of cortical damage, account for the reported findings.

General methodological limitations – Both techniques that were used in the included studies are characterized by certain limitations. First, results from direct electrostimulation during awake surgery are limited to specific stimulation areas surrounding the tumor, which prohibits the investigation of individual relationships between different tract segments and their language functions. Investigating the latter is only possible by indirect anatomo-functional correlations, performed in healthy or brain-damaged subjects. Moreover, plastic changes in the language circuit, induced by a slow growing tumor (Herbet et al., 2016) might possibly influence the obtained intra-operative results. Nonetheless, anatomo-functional correlations in brain-damaged individuals (patients with aphasia) are subject to neuroplasticity as well.

In a healthy population, the interpretation of correlations between DTI-parameters and behavioral measures can be equally challenging. For example, FA values are often decreased in areas where multiple fibers cross (i.e. white matter "bottlenecks") (Oouchi et al., 2007) and RD or AD measures might be misleading due to their sensitivity to noise and partial volume effects (Wheeler-Kingshott and Cercignani, 2009). In this context, Alexander et al. (2007) discourage the reliance on single DTI-measures in order to obtain a reliable estimate of microstructural properties and emphasize that at least FA and MD values should be considered to maximize the specificity.

It is beyond any doubt that these limitations complicate the interpretation of the obtained results. Hence, it is valuable to compare and integrate results from different techniques and populations in order to shed light on the involvement of specific white matter tracts in semantic processing. In the sections below, the results are discussed for each tract separately in the context of one or multiple hypothesized function(s) based upon the anatomical connectivity.

Uncinate fasciculus (UF) - The UF originates from the anterior temporal lobe, parahippocampal gyrus and amygdala, and enters the external capsule after a U-turn. Afterwards the UF continues towards the basal frontal area, the cingulate gyrus, the frontal pole (Catani and Thiebaut de Schotten, 2012) and the inferior frontal cortex (Peuskens et al., 2004; Schmahmann et al., 2007). The structural connectivity between the anterior temporal lobe and the inferior frontal lobe, regions that have been linked to the storage and retrieval/selection of semantic representations respectively (Badre et al., 2005; Badre and Wagner, 2007; Patterson et al., 2007), postulate the UF as a good candidate to support semantic control processes.

An important contribution of the left UF in tasks requiring semantic control is demonstrated by correlations between behavioral semantic measures and DTI-metrics in patients with aphasia. Within this population, performance on multiple receptive (auditory word-picture verification and nonverbal association) and expressive semantic tasks (picture naming and semantic fluency) was significantly correlated with microstructural properties of the left UF (Harvey et al., 2013; Catani et al., 2013; Marcotte et al., 2017; Xing et al., 2017; Powers et al., 2013). In word-picture matching and nonverbal association tests, relevant semantic representations and relationships respectively need to be activated, while irrelevant information should be inhibited (Noonan et al., 2010). Likewise, picture naming and semantic fluency tasks depend on the activation and selection of semantic knowledge that is specific enough for given concepts, followed by the lexical retrieval stage. Hence, performance on the aforementioned tasks extensively relies on the ability to regulate intact semantic representations/relationships or "semantic control" (Noonan et al., 2010). However, it is important to note that the observed relationship between the left UF and semantic control might only be valid in older individuals, since the patients under investigation had mean ages ranging between 60 and 68 years. This finding corresponds with previous research emphasizing that semantic memory in older adults relies on both the left IFOF and UF (de Zubicaray et al., 2011).

Regarding DTI studies in healthy (younger) individuals and awake surgery studies, a semantic (control) function of the left UF was not supported. In healthy individuals, greater dependence on the UF was considered inefficient during rapid object naming (Rollans et al., 2017) and no relationship between noun-based verb generation performance and integrity (FA) of the left UF was found (Nugiel et al., 2016). In patients with glioma, stimulation of the language dominant UF did not induce (reliable) naming errors (Duffau et al., 2009; Vassal et al., 2013). These findings correspond to the dynamic hodotopical model of Duffau et al. (2014), in which the authors propose an indirect ventral route, constituted by the UF (and the anterior part of the ILF), that is functionally compensable by its direct counterpart (the IFOF). Therefore, the contribution of the UF is considered as not essential in semantic computations (Duffau et al., 2014). Importantly, these results only apply to language production tasks. Regarding comprehension, radial diffusivity (RD) of the left UF was associated with better cross-situational semantic learning in healthy subjects (Ripolles et al., 2017). These findings highlight a possible contribution of the left UF in word-to-meaning mapping. However, the direct interpretation of RD values requires some cautiousness (Wheeler-Kingshott and Cercignani, 2009). Hence, these preliminary findings should be confirmed by future research, in which performance on semantic learning and on other receptive tasks, such as word-picture matching and nonverbal association, are correlated with several DTI-metrics of the UF, including at least FA and MD (Alexander et al., 2007).

Hence, a semantic control function of the left UF can neither be confirmed nor be refuted due to the limited amount of studies, the methodological differences and the heterogeneous results. This seems surprising, since the UF is proposed to project towards the inferior frontal lobe (Peuskens et al., 2004; Schmahmann et al., 2007), a core region in semantic retrieval and selection (Badre and Wagner, 2007). However, Von Der Heide, Skipper, Klobusicky, and Olson (2013) pointed out that most anatomical studies fail to detect terminations of the UF in the inferior frontal gyrus (BA45/47) and instead report fiber projections to the orbitofrontal cortex (OFC). This anatomical detail could have important implications for the interpretation of the above-mentioned results. The OFC is generally not linked to linguistic functions, but is considered to be a core component of the neural decision-making circuit (Broche-Perez et al., 2016). Through direct connections with the amygdala (Barbas, 2007), the OFC processes reward values and guides decision-making by inhibiting responses that are not rewarding (Krawczyk, 2002). It is the UF that provides the direct structural connection between both structures and the anterior temporal lobe. Interestingly, this connectivity pattern has been proposed to underlie reward-based decision making in previous research towards the neural correlates of social cognition (for a review, see Olson et al. (2013)). This in mind, significant correlations between microstructural properties of the left UF and behavioral semantic measures might be driven by the fact that the language tasks under investigation required adequate decision-making, in which the generation of a correct answer might be experienced as a positive reward. This, however, is highly speculative and should be investigated in future research.

Altogether, results of this systematic review provide no clear answer to the question whether the left UF is essential in semantic processing. In order to obtain more clarity on this topic, future research should aim to accurately determine the frontal terminations of this fiber bundle by means of fiber dissections and DTI tractography. In addition, more DTI and awake surgery research is needed in which both semantic comprehension and production tasks are considered in order to gain new insights along the divergent findings currently available in the literature.

Inferior fronto-occipital fasciculus (IFOF) - The IFOF is the longest associative pathway consisting of a superficial/dorsal and a deep/ventral subcomponent, as revealed by fiber dissection methods. The superficial layer connects BA44/45 to the posterior superior temporal gyrus (STG), the superior parietal lobe and the superior and middle occipital gyri. The deep layer connects the dorsolateral prefrontal cortex, middle frontal gyrus and orbito-frontal cortex to the posterior medial and basal temporal cortex, ending in the inferior occipital gyrus (Bajada et al., 2015; Catani and Thiebaut de Schotten, 2012; Sarubbo et al., 2013). More recently, DTI tractography data disclosed a subdivision in five subcomponents (Wu et al., 2016). Based on its widespread anatomical course, the IFOF might serve as the subcortical architecture underlying the hub and spoke model (Ralph et al., 2017) as this fiber bundle provides a structural connection between modality-specific association areas/spokes in the four cerebral lobes and amodal concept storage area(s) in the anterior temporal lobe (Patterson et al., 2007) and the posterior temporo-parietal areas (Binder and Desai, 2011). Moreover, the IFOF projects towards regions that have been linked to semantic control, namely the inferior frontal gyrus (BA45/47) (Badre and Wagner, 2007) and the posterior middle temporal gyrus (Davey et al., 2016; Noonan et al., 2013; Whitney et al., 2011). Hence, the IFOF could provide an information transfer between areas implied in the organization, integration, retrieval and selection of semantic features, which favors an important contribution in semantic processing. The majority of results on the linguistic contribution of the IFOF arises from awake surgery studies. Along its entire course, intra-operative stimulation of the language dominant (left) IFOF consistently elicited semantic paraphasias. Similarly, significant anatomo-functional correlations between DTI-metrics of the IFOF and naming performance were reported, both in healthy and aphasic individuals (Rollans et al., 2017; Ivanova et al., 2016; Rolheiser et al., 2011; Powers et al., 2013). These results are in line with the dynamic hodotopical model of Duffau et al. (2014) in which the IFOF is considered as the direct ventral route, being essential for semantic computations during picture naming. Importantly, picture naming is a complex process including several stages, namely 1) early visual processing and recognition, 2) the retrieval and selection of semantic knowledge, 3) lexical retrieval and 4) the coordination and execution of motor plans for the articulators (Levelt et al., 1999). Hence, one cannot be sure that the correlation between DTI-metrics of the IFOF and performance on picture naming tasks is (purely) driven by semantic operations. Likewise, semantic paraphasias might reflect deficits at stage two or three, since they can arise due to disorders in the semantic system or due to a lexical retrieval deficit (Cloutman et al., 2009). Although a semantic function of the IFOF is likely, it cannot be confirmed during picture naming. However, the finding that intra-operative stimulation of the left and right IFOF induced deficits in non-verbal association performance (Moritz-Gasser et al., 2013; Herbet et al., 2017) suggest that the IFOF is indeed essential for pure semantic operations. Unfortunately, no studies in healthy or aphasic individuals investigated correlations between non-verbal association abilities and DTI-metrics of the IFOF. Thus, whether the non-verbal semantic system is underpinned by the bilateral IFOF should be confirmed in future research.

In two studies, semantic control was explicitly targeted in a group of stroke patients and of healthy subjects respectively (Harvey et al., 2013; Nugiel et al., 2016). Regarding FA values of the left IFOF, no significant correlations with performance on the spoken word Pyramids and Palm Tree Test (Howard and Patterson, 1992), auditory word-picture matching and noun-based verb generation were found. These results are rather unexpected since the performance of patients with aphasia on auditory comprehension and property knowledge tests, which all require a certain amount of semantic control, did yield significant correlations with FA values of the left IFOF (Ivanova et al., 2016; Xing et al., 2017; Rolheiser et al., 2011). Moreover, authors considering MD values of the left IFOF did find significant correlations with semantic control measures, in both healthy subjects (Nugiel et al., 2016) and in patients with PPA (Xing et al., 2017). Although only two studies inventoried MD, such values contribute to a more specific characterization of white matter microstructure and, in pathological conditions, MD is highly sensitive to edema, cellularity and necrosis, whereas FA is not very specific to the type of microstructural change (Alexander et al., 2007). Therefore, correlations between semantic control performance and MD measures do support the hypothesis of a semantic control function of the left IFOF.

In order to (dis)confirm this hypothesis, future research should address both comprehension and production tasks comprising multiple conditions in which the semantic selection and retrieval demands are manipulated. Behavioral performance in the different conditions should be correlated with diffusion tensor measures, including at least the FA and MD of the IFOF.

Inferior longitudinal fasciculus (ILF) - The ILF runs inferior to the IFOF and connects the ventro-anterior temporal lobes, through the temporal pole, hippocampus, amygdala and middle and inferior temporal gyrus, to several occipital regions (fusiform gyrus, lingual gyrus and dorsolateral occipital cortex) (Bajada et al., 2015; Catani and Thiebaut de Schotten, 2012). Similar to the IFOF, the ILF may provide a bidirectional information flow between modality-specific areas/spokes in the temporal and occipital areas (Pulvermuller and Fadiga, 2010; Ralph et al., 2017), and the amodal hub(s) in the ATL (Patterson et al., 2007) and posterior temporo-parietal areas (Binder and Desai, 2011). Based on the anatomical connections, the ILF might mediate the organization and integration of semantic features. A semantic control function might also be possible, regarding its terminations in the posterior middle temporal gyrus (Noonan et al., 2013).

Although limited, results from awake surgery studies do not suggest a contribution of the left ILF in semantic processing, albeit for production tasks only. During picture naming, no reliable language disturbances could be observed due to direct electrical stimulation (Mandonnet et al., 2007; Vassal et al., 2013). These results substantiate the dynamic hodotopical model of Duffau, in which the anterior part of the ILF, along with the UF, is supposed to be part of the compensable ventral route for semantic computations. However, in a recent paper Herbet et al. (2018a) highlighted that the direct ventral route (IFOF) only compensates for language functions of the ILF when the ATL is damaged. The latter structure, often referred to as the semantic hub (Patterson et al., 2007; Ralph et al., 2017), is highly sensitive for neuroplasticity in the context of slow-growing tumors (Herbet et al., 2016). Hence, the authors proposed that the ILF might lose his function when the function of the ATL is reorganized. This hypothesis was supported during an intra-operative picture naming task. DES of the left ILF did not result in naming errors when the tumor infiltrated the ATL, whereas patients with preserved anterior temporal structures presented with anomia. The latter symptom was considered to reflect a phonological-lexical retrieval deficit since ILF stimulation induced no semantic errors during nonverbal association (Herbet, Moritz-Gasser et al., 2018a). Whether or not anomia truly reflects a phonological-lexical deficit, rather than a semantic deficit has been questioned by Hope and Price (2016) and remains a topic of debate. Nevertheless, Herbet and colleagues emphasize the importance of considering damage of the ATL in order to confirm or to refute a linguistic function of the ILF. This important finding provides clear directions for future research, as it might be applicable for the uncinate fasciculus as well, since this pathway also projects from and towards the ATL.

Results from awake surgery studies do not allow to formulate a clear answer to the question whether the ILF subserves a semantic function. However, associations between changes in DTI measures in the left ILF and (lexico)semantic performance in healthy and aphasic individuals put the intra-operative findings somewhat in perspective.

In the majority of studies in patients with aphasia, significant correlations were found between DTI-scalars of the left ILF and behavioral performance on auditory word and sentence comprehension, nonverbal association and picture naming. These results suggest that microstructural damage of the left ILF at least partly underlies (lexico) semantic deficits and hence, support the hypothesis of a (lexico)semantic contribution. Complementary information is provided by DTI-studies in healthy individuals in which negative correlations between RD and MD values of the left ILF were correlated with sensitive means of semantic processing, i.e. semantic learning (word-to-meaning mapping) performance (Ripollés et al., 2017) and the abundance of semantic autobiographical memory (ABM) (Hodgetts et al., 2017) respectively. Interestingly, no significant inter-hemispheric differences for MD values in their relation with the amount of semantic details in ABM were yielded (Hodgetts et al., 2017) and higher FA in the right ILF led to slower reaction times in a noun-based verb generation task (Nugiel et al., 2016). These findings are in line with a bilateral organization of the ventral semantic stream, as proposed in the dual-stream model of Hickok and Poeppel (2007).

In general, findings from DTI studies in healthy and aphasic subjects correspond to each other. However, divergent results are yielded in the two studies explicitly targeting semantic control. In healthy subjects, MD values of the left ILF significantly predicted semantic control performance, as measured in a noun-based verb generation task (Nugiel et al., 2016). However, no significant relationship was found between semantic control abilities in word-picture matching and FA measures in stroke-patients (Harvey et al., 2013). Besides the fact that MD values are not available in the latter study, the different modalities of stimulus presentation (i.e. orthographically in Nugiel et al. (2016) and auditorily in Harvey et al. (2013)) might be a possible explanation for these disparate results. The sensitivity of the ILF for visual input (verbal and nonverbal) processing has already been emphasized by previous research (for a recent review see Herbet et al. (2018b)). Through its terminations in visual association areas, this pathway has been linked to object recognition (Mandonnet et al., 2009; Ortibus et al., 2012), face recognition (Hodgetts et al., 2015) and reading processing (Epelbaum et al., 2008; Zemmoura et al., 2015). The latter is in line with the observed alexia during intra-operative stimulation (Chan-Seng et al., 2014; Gil-Robles et al., 2013; Sarubbo et al., 2014).

Altogether, results from DTI-studies in aphasic and healthy individuals strengthen the view of Herbet et al. (2018a), namely that a linguistic function of the left ILF should not be refuted. Unfortunately, the nature of this linguistic function – either lexical, semantic or lexico-semantic – remains unclear. In order to shed light on this topic, future research should investigate correlations between ILF-metrics and the behavioral performance on more sensitive tasks of semantic processing.

Arcuate fasciculus (AF) – The AF consists of a direct and an indirect pathway according to Catani et al. (2005). The direct pathway consists of the classical connection between Broca's and Wernicke's area, whereas the indirect pathway encompasses an anterior segment, connecting Broca's area and the inferior parietal lobe (IPL), and a posterior segment that connects Wernicke's area and the IPL. However, tractography results revealed that the cortical termination areas of the indirect anterior segment also encompass the ventral premotor cortex (BA 6), whereas the indirect posterior segment also projects towards the medial and inferior temporal gyrus (Rilling et al., 2008). In recent studies, the indirect tracts through the inferior parietal lobe are often considered as parts of the superior longitudinal fasciculi (Gierhan, 2013). Functionally, the direct segment of the AF has been postulated to subserve the dorsal phonological stream (Friederici and Gierhan, 2013), which has been linked to mapping acoustic features into articulatory representations (Hickok and Poeppel, 2007). This is supported by the fact that phonological paraphasias are the most common symptoms due to DES of the left AF during awake surgery (Almairac et al., 2015; Bello et al., 2006, 2007; Chan-Seng et al., 2014; Hamer et al., 2011; Duffau et al., 2008, 2009; Maldonado et al., 2011a, 2011b; Mandonnet et al., 2007; Sarubbo et al., 2015; Vassal et al., 2013; van Geemen et al., 2014). The indirect anterior segment has been associated with the vocalization of semantic content (Catani et al., 2005), which might provide an explanation of the semantic paraphasias in Leclercq et al. (2010) and Rofes et al. (2017). The latter suggestion can, however, not be verified since the specific stimulation areas along the AF were vaguely reported. Finally, the indirect posterior segment may support semantic comprehension (Catani et al., 2005), especially through its terminations in the medial temporal gyrus (Glasser and Rilling, 2008). Although results were limited, this hypothesis is supported by the anatomo-functional correlations in patients with aphasia (Agosta et al., 2010; Ivanova et al., 2016) and in healthy individuals (Welcome and Joanisse, 2014).

Middle longitudinal fasciculus (MdLF)- The MdLF originates in the superior temporal gyrus and projects towards the angular gyrus (AG) and the superior parietal lobe (Makris et al., 2013). Based on its anatomical course, this pathway has been linked to the language comprehension network (Turken and Dronkers, 2011) and might subserve the organization of semantic knowledge (Saur et al., 2010). The finding that imageability ratings were associated with the MdLF fiber density strengthens this view (Jouen et al., 2015). However, intra-operative stimulation of this fiber bundle failed to show any naming errors (Hamer et al., 2011). Altogether, the functional significance of the MdLF in semantic processing remains rather unclear.

Remaining pathways – The superior longitudinal fasciculus (SLF) is a complex fiber system consisting of a least three subcomponents (SLF I, SLF II and SLF III - Catani and Thiebaut de Schotten, 2012; Catani et al., 2012; Catani et al., 2005), of which SLF-II and SLF-III, connecting frontal areas with the angular and supramarginal gyrus respectively (Makris et al., 2005), have been linked to linguistic processing (Gierhan, 2013). However, the horizontal fibers of the SLF and the AF are not easily distinguishable, hence, the nomenclature SLF/AF is commonly used (Friederici and Gierhan, 2013). Intra-operative stimulation results (Maldonado et al., 2011a, 2011b; van Geemen et al., 2014; Vidorreta et al., 2011) are in line with previous research that emphasized a role of the SLF/AF in both articulatory (Sarubbo et al., 2015), phonological (Duffau, 2008) and syntactic processing (Antonenko et al., 2013; Friederici and Gierhan, 2013; Grossman et al., 2013; Wilson et al., 2011).

The frontal aslant tract (FAT) and fronto-striatal tract (FST) connect the caudate nucleus with the pre-supplementary motor area (pre-SMA) and SMA respectively (Catani et al., 2012). The latter structures seem to support speech processing aspects, more specifically initiation and timing mechanisms (Hertrich et al., 2016). Thus, the speech initiation disorders observed during intra-operative stimulation of the left FAT/FST are plausible symptoms (Vassal et al., 2013; Duffau et al., 2008; Kinoshita et al., 2015). In a limited amount of patients, stimulation of the left FST led to semantic paraphasias (Bello et al., 2006, 2007). A possible explanation for this observation might be an alteration of the striato-thalamo-cortical function. In a systematic review on the subcortical grey matter correlates of verbal-semantic processing, it has been shown that the caudate nucleus (as part of the striatum) supports the access of cortically represented semantic features, through the direct and indirect cortico-striato-thalamo-cortical loops (Cocquyt et al., 2019). Therefore, a temporary disruption of the FST might lead to the access of semantically related features, causing semantic paraphasias. Instead, Mandonnet, et al. (2019) found that stimulation of the white matter near the posteriosuperior head of the caudate nucleus results in verbal perseverations, possibly due to impaired updating of thalamic output. However, the authors acknowledged that it is quite rare to selectively stimulate the striatal input without the simultaneous disturbance of other fiber bundles (i.e. the IFOF), which prevents us to draw strong conclusions from the results of Bello et al. (2006) and Bello et al. (2007).

5. Conclusion

This systematic review provides an overview of the current knowledge on the white matter architecture underlying semantic processing. Results of the 43 included studies suggest that the left inferior fronto-occipital fasciculus contributes to the essential connectivity that allows semantic processing. However, it remains uncertain whether its contributive role is limited to the organization of semantic knowledge or extends to the level of semantic control. Moreover, the functionality of the left uncinate fasciculus, inferior longitudinal fasciculus and the posterior segment of the indirect arcuate fasciculus in semantic processing has to be confirmed by future research.

Declaration of competing interest

None known.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuropsychologia.2019.107182.

Appendix 1. Search strategies in Pubmed, Web of Science and Embase

Pubmed

1. “Semantics” [Mesh] OR semantic* [TIAB] OR “lexical-semantic” [TIAB] OR “lexico-semantic” [TIAB] OR “lexicosemantic” [TIAB] OR “grammar” [TIAB] OR grammatic* [TIAB] OR “syntaxis” [TIAB] OR syntactic* [TIAB] OR “morphosyntaxis” [TIAB] OR morphosyntactic* [TIAB] OR “morpho-syntaxis” [TIAB] OR morpho-syntactic* [TIAB] OR “language comprehension” [TIAB] OR “language production” [TIAB] OR “verbal input” [TIAB] OR “verbal output” [TIAB] OR “language input” [TIAB] OR “language output” [TIAB] OR “lexical retrieval” [TIAB] OR “word retrieval” [TIAB]
2. “white matter” [Mesh] OR “white matter” [TIAB] OR “fasciculus” [TIAB] OR “fasciculi” [TIAB] OR “fascicle” [TIAB] OR “fascicles” [TIAB] OR “fiber tract” [TIAB] OR “fiber tracts” [TIAB] OR “fibre tract” [TIAB] OR “fibre tracts” [TIAB] OR “fiber system” [TIAB] OR “fiber systems” [TIAB] OR “fibre system” [TIAB] OR “fibre systems” [TIAB] OR “language tract” [TIAB] OR “language tracts” [TIAB] OR “connectome” [TIAB] OR “language pathway” [TIAB] OR “language pathways” [TIAB] OR “fiber pathway” [TIAB] OR “fiber pathways” [TIAB] OR “fibre pathway” [TIAB] OR “fibre pathways” [TIAB] OR “fiber connection” [TIAB] OR “fiber connections” [TIAB] OR “fibre connection” [TIAB] OR “fibre connections” [TIAB] OR “language network” [TIAB] OR “language networks” [TIAB] OR “language circuit” [TIAB] OR “language circuits” [TIAB] OR “ventral route” [TIAB] OR “dorsal route” [TIAB] OR “ventral language route” [TIAB] OR “dorsal language route” [TIAB] OR “ventral stream” [TIAB] OR “dorsal stream” [TIAB] OR “ventral language stream” [TIAB] OR “dorsal language stream” [TIAB] OR “ventral tract” [TIAB] OR “dorsal tract” [TIAB] OR “ventral tracts” [TIAB] OR “dorsal tracts” [TIAB] OR “ventral language tract” [TIAB] OR “dorsal language tract” [TIAB] OR “ventral

language tracts” [TIAB] OR “dorsal language tracts” [TIAB] OR “ventral pathway” [TIAB] OR “dorsal pathway” [TIAB] OR “ventral pathways” [TIAB] OR “dorsal pathways” [TIAB] OR “ventral language pathway” [TIAB] OR “dorsal language pathway” [TIAB] OR “ventral language pathways” [TIAB] OR “dorsal language pathways” [TIAB] OR “tractography” [TIAB] OR “fiber tracking” [TIAB] OR “fibre tracking” [TIAB] OR “diffusion MRI” [TIAB] OR “diffusion weighted magnetic resonance imaging” [TIAB] OR “diffusion weighted MRI” [TIAB] OR “diffusion magnetic resonance imaging” [TIAB] OR “Diffusion Tensor Imaging” [Mesh] OR “diffusion tensor imaging” [TIAB] OR “DTI” [TIAB] OR “diffusion imaging” [TIAB] OR “awake surgery” [TIAB] OR “awake brain surgery” [TIAB] OR “awake operation” [TIAB] OR “tumor surgery” [TIAB] OR “tumour surgery” [TIAB] OR “glioma surgery” [TIAB] OR “glioma resection” [TIAB] OR “tumor resection” [TIAB] OR “tumour resection” [TIAB] OR “electrostimulation” [TIAB] OR “electro-stimulation” [TIAB] OR “electrical stimulation” [TIAB] OR “intraoperative stimulation” [TIAB] OR “intra operative stimulation” [TIAB] OR “intra-operative stimulation” [TIAB] OR “language mapping” [TIAB] OR “brain mapping” [TIAB] OR “stimulation mapping” [TIAB] OR “IFOF” [TIAB] OR “aslant” [TIAB] OR “fronto-striatal” [TIAB] OR “striato-frontal” [TIAB] OR “thalamocortical” [TIAB] OR “thalamo-cortical” [TIAB]
3. 1 AND 2

Web of Science

1. TS = (“semantic*“) OR TS = (“lexical-semantic”) OR TS = (“lexico-semantic”) OR TS = (“lexicosemantic”) OR TS = (“grammar”) OR TS = (“grammatic*“) OR TS = (“syntaxis”) OR TS = (“syntactic*“) OR TS = (“morphosyntaxis”) OR TS = (“morphosyntactic*“) OR TS = (“morpho-syntaxis”) OR TS = (“morpho-syntactic*“) OR TS = (“language comprehension”) OR TS = (“language production”) OR TS = (“verbal input”) OR TS = (“verbal output”) OR TS = (“language input”) OR TS = (“language output”) OR TS = (“lexical retrieval”) OR TS = (“word retrieval”)
2. TS = (“white matter”) OR TS = (“fasciculus”) OR TS = (“fasciculi”) OR TS = (“fascicle”) OR TS = (“fascicles”) OR TS = (“fiber tract”) OR TS = (“fiber tracts”) OR TS = (“fibre tract”) OR TS = (“fibre tracts”) OR TS = (“fiber system”) OR TS = (“fiber systems”) OR TS = (“fibre system”) OR TS = (“fibre systems”) OR TS = (“language tract”) OR TS = (“language tracts”) OR TS = (“connectome”) OR TS = (“language pathway”) OR TS = (“language pathways”) OR TS = (“fiber pathway”) OR TS = (“fiber pathways”) OR TS = (“fibre pathway”) OR TS = (“fibre pathways”) OR TS = (“fiber connection”) OR TS = (“fiber connections”) OR TS = (“fibre connection”) OR TS = (“fibre connections”) OR TS = (“language network”) OR TS = (“language networks”) OR TS = (“language circuit”) OR TS = (“language circuits”) OR TS = (“ventral route”) OR TS = (“dorsal route”) OR TS = (“ventral language route”) OR TS = (“dorsal language route”) OR TS = (“ventral stream”) OR TS = (“dorsal stream”) OR TS = (“ventral language stream”) OR TS = (“dorsal language stream”) OR TS = (“ventral tract”) OR TS = (“dorsal tract”) OR TS = (“ventral tracts”) OR TS = (“dorsal tracts”) OR TS = (“ventral language tract”) OR TS = (“dorsal language tract”) OR TS = (“ventral language tracts”) OR TS = (“dorsal language tracts”) OR TS = (“ventral pathway”) OR TS = (“dorsal pathway”) OR TS = (“ventral pathways”) OR TS = (“dorsal pathways”) OR TS = (“ventral language pathway”) OR TS = (“dorsal language pathway”) OR TS = (“ventral language pathways”) OR TS = (“dorsal language pathways”) OR TS = (“tractography”) OR TS = (“fiber tracking”) OR TS = (“fibre tracking”) OR TS = (“diffusion MRI”) OR TS = (“diffusion weighted magnetic resonance imaging”) OR TS = (“diffusion weighted MRI”) OR TS = (“diffusion magnetic resonance imaging”) OR TS = (“diffusion tensor imaging”) OR TS = (“DTI”) OR TS = (“diffusion imaging”) OR TS = (“awake surgery”) OR TS = (“awake brain surgery”) OR TS = (“awake operation”) OR TS = (“tumor surgery”) OR TS = (“tumour surgery”) OR TS = (“glioma surgery”) OR TS = (“glioma resection”) OR TS = (“tumor resection”) OR TS = (“tumour resection”) OR TS = (“electrostimulation”) OR TS = (“electro-stimulation”) OR TS = (“electrical stimulation”) OR TS = (“intraoperative stimulation”) OR TS = (“intra operative stimulation”) OR TS = (“intra-operative stimulation”) OR TS = (“language mapping”) OR TS = (“brain mapping”) OR TS = (“stimulation mapping”) OR TS = (“IFOF”) OR TS = (“aslant”) OR TS = (“fronto-striatal”) OR TS = (“striato-frontal”) OR TS = (“thalamocortical”) OR TS = (“thalamo-cortical”)
3. 1 AND 2

Embase

1. ‘Semantics’/de OR semantic*:ti,ab OR ‘lexical-semantic’:ti,ab OR ‘lexico-semantic’:ti,ab OR ‘lexicosemantic’:ti,ab OR ‘grammar’/de OR ‘grammar’:ti,ab OR grammatic*:ti,ab OR ‘syntaxis’:ti,ab OR syntactic*:ti,ab OR ‘morphosyntaxis’:ti,ab OR ‘morpho-syntaxis’:ti,ab OR morpho-syntactic*:ti,ab OR ‘morpho-syntactic’:ti,ab OR ‘language comprehension’:ti,ab OR ‘language production’:ti,ab OR ‘verbal input’:ti,ab OR ‘verbal output’:ti,ab OR ‘language input’:ti,ab OR ‘language ouput’:ti,ab OR ‘lexical retrieval’:ti,ab OR ‘word retrieval’:ti,ab
2. ‘White matter’/exp OR ‘medial longitudinal fasciculus’/de OR ‘thalamocortical tract’/de OR ‘white matter’:ti,ab OR ‘fasciculus’:ti,ab OR ‘fasciculi’:ti,ab OR ‘fascicle’:ti,ab OR ‘fascicles’:ti,ab OR ‘fiber tract’:ti,ab OR ‘fiber tracts’:ti,ab OR ‘fibre tract’:ti,ab OR ‘fibre tracts’:ti,ab OR ‘fiber system’:ab,ti OR ‘fiber sytems’:ab,ti OR ‘fibre system’:ab,ti OR ‘fibre systems’:ab,ti OR ‘language tract’:ti,ab OR ‘language tracts’:ti,ab OR ‘connectome’:ti,ab OR ‘language pathway’:ti,ab OR ‘language pathways’:ti,ab OR ‘fiber pathway’:ti,ab OR ‘fiber pathways’:ti,ab OR ‘fibre pathway’:ti,ab OR ‘fibre pathways’:ti,ab OR ‘fiber connection’:ti,ab OR ‘fiber connections’:ti,ab OR ‘fibre connection’:ti,ab OR ‘fibre connections’:ti,ab OR ‘language network’:ti,ab OR ‘language networks’:ti,ab OR ‘language circuit’:ti,ab OR ‘language circuits’:ti,ab OR ‘ventral route’:ti,ab OR ‘dorsal route’:ti,ab OR ‘ventral language route’:ti,ab OR ‘dorsal language route’:ti,ab OR ‘ventral stream’:ti,ab OR ‘dorsal stream’:ti,ab OR ‘ventral language stream’:ti,ab OR ‘dorsal language stream’:ti,ab OR ‘ventral tract’:ti,ab OR ‘dorsal tract’:ti,ab OR ‘ventral language tract’:ti,ab OR ‘dorsal language tract’:ti,ab OR ‘ventral language tracts’:ti,ab OR ‘dorsal language tracts’:ti,ab OR ‘ventral pathway’:ti,ab OR ‘dorsal pathway’:ti,ab OR ‘ventral pathways’:ti,ab OR ‘dorsal pathways’:ti,ab OR ‘ventral language pathway’:ti,ab OR ‘dorsal language pathway’:ti,ab OR ‘ventral language pathways’:ti,ab OR ‘dorsal language pathways’:ti,ab OR ‘tractography’:ti,ab OR ‘fiber tracking’:ti,ab OR ‘fibre tracking’:ti,ab OR ‘diffusion MRI’:ti,ab OR ‘diffusion weighted magnetic resonance imaging’:ab,ti OR ‘diffusion weighted MRI’:ab,ti OR ‘diffusion magnetic resonance imaging’:ti,ab OR ‘diffusion tensor imaging’/de OR ‘diffusion tensor imaging’:ti,ab OR ‘DTI’:ti,ab OR ‘diffusion imaging’:ti,ab OR ‘awake surgery’:ti,ab OR ‘awake brain surgery’:ti,ab OR ‘awake operation’:ti,ab OR ‘tumor surgery’:ti,ab OR ‘tumour surgery’:ti,ab OR ‘glioma surgery’:ti,ab OR ‘glioma resection’:ti,ab OR ‘tumor resection’:ti,ab OR ‘tumour resection’:ti,ab OR ‘electrostimulation’:ti,ab OR ‘electro-stimulation’:ti,ab OR ‘electrical stimulation’:ti,ab OR ‘intraoperative stimulation’:ti,ab OR ‘intra operative stimulation’:ti,ab OR ‘intra-operative stimulation’:ti,ab OR ‘language mapping’:ti,ab OR ‘brain mapping’:ti,ab OR ‘stimulation mapping’:ti,ab OR ‘IFOF’:ti,ab OR ‘aslant’:ti,ab OR ‘fronto-striatal’:ti,ab OR ‘striato-frontal’:ti,ab OR ‘thalamocortical’:ti,ab OR ‘thalamo-cortical’:ti,ab
3. 1 AND 2

Appendix 2. QUALITY LABEL AWAKE SURGERY - Detailed terms and weighted distribution of points

1) Was the study population clearly specified and defined?	/6
• Age (mean - SD)	/1
• Education years (mean, SD)	/1
• Tumor localization (grey + white matter)	/2
• Pre-operative language dominance	/1
• Pre-operative language deficits	/1
2) Were the exposure measures clearly defined, valid, reliable and implemented consistently across all study participants?	/5
• Is there a clear description and argumentation of the semantic task(s) (including the materials and procedure) which are used during surgery?	/3
• Is there a clear description of the stimulation sites?	/2
• Left/right hemisphere	
• (Sub)cortical regions	
3) Were the outcome measures (language deficits due to stimulation) clearly defined, valid and reliable?	/2
• Qualitative error analysis	
TOTAL	/13

Appendix 3. QUALITY LABEL DTI (PATIENTS WITH APHASIA) - Detailed terms and weighted distribution of points

1) Was the study population clearly specified and defined?	/5
• Age (mean - SD)	/1
• Education years (mean, SD)	/1
• Type of aphasia/PPA phenotype	/1
• Lesion localization	/1
• Duration of disease	/1
2) Were the exposure measures clearly defined, valid, reliable and implemented consistently across all study participants?	/7
• Is there a clear description and argumentation of the semantic task (including the materials and procedure)?	/2
• Is the semantic task standardized?	/1
• Is there a clear description of the DTI-method and parameters?	/2
• Is there a clear description of the fasciculi of interest?	/2
• Left/right hemisphere	
• Anatomical regions	
3) Is there a clear description and argumentation of the statistical analysis? Are confounding variables implemented as covariates?	/2
4) Were the outcome measures clearly defined, valid and reliable?	/1
TOTAL	/15

Note: PPA = primary progressive aphasia.

Appendix 4. QUALITY LABEL DTI (HEALTHY INDIVIDUALS) - Detailed terms and weighted distribution of points

1) Was the study population clearly specified and defined?	/3
• Age (mean - SD)	/1
• Education years (mean, SD)	/1
• Cognition	/1
2) Were the exposure measures clearly defined, valid, reliable and implemented consistently across all study participants?	/7
• Is there a clear description and argumentation of the semantic task(s) (including the materials and procedure)?	/2
• Is the semantic task standardized?	/1
• Is there a clear description of the DTI-method and parameters?	/2
• Is there a clear description of the fasciculi of interest?	/2
• Left/right hemisphere	
• Anatomical regions	
3) Is there a clear description and argumentation of the statistical analysis?	/1
4) Were the outcome measures clearly defined, valid and reliable?	/1
TOTAL	/12

References

Acosta-Cabronero, J., Patterson, K., Fryer, T.D., Hodges, J.R., Pengas, G., Williams, G.B., Nestor, P.J., 2011. Atrophy, hypometabolism and white matter abnormalities in semantic dementia tell a coherent story. Brain : J. Neurol. 134, 2025–2035.
Agosta, F., Henry, R.G., Migliaccio, R., Neuhaus, J., Miller, B.L., Dronkers, N.F., Brambati, S.M., Filippi, M., Ogar, J.M., Wilson, S.M., Gorno-Tempini, M.L., 2010. Language networks in semantic dementia. Brain 133, 286–299.
Agrawal, A., Kapfhammer, J.P., Kress, A., Wichers, H., Deep, A., Feindel, W., Sonntag, V.K., Spetzler, R.F., Preul, M.C., 2011. Josef Klingler's models of white matter tracts: influences on neuroanatomy, neurosurgery, and neuroimaging. Neurosurgery 69, 238–254.
Alexander, A.L., Lee, J.E., Lazar, M., Field, A.S., 2007. Diffusion tensor imaging of the brain. Neurotherapeutics : J. Am. Soc. Exp. Neurother. 4, 316–329.
Allendorfer, J.B., Hernando, K.A., Hossain, S., Nenert, R., Holland, S.K., Szaflarski, J.P., 2016. Arcuate fasciculus asymmetry has a hand in language function but not handedness. Human Brain Mapping. https://doi.org/10.1002/hbm.23241.
Almairac, F., Herbet, G., Moritz-Gasser, S., de Champfleur, N.M., Duffau, H., 2015. The left inferior fronto-occipital fasciculus subserves language semantics: a multilevel lesion study. Brain Struct. Funct. 220 (4), 1983–1995. https://doi.org/10.1007/s00429-014-0773-1.
Antonenko, D., Brauer, J., Meinzer, M., Fengler, A., Kerti, L., Friederici, A.D., Floel, A., 2013. Functional and structural syntax networks in aging. Neuroimage 83, 513–523.
Badre, D., Poldrack, R.A., Pare-Blagoev, E.J., Insler, R.Z., Wagner, A.D., 2005. Dissociable controlled retrieval and generalized selection mechanisms in ventrolateral prefrontal cortex. Neuron 47, 907–918.
Badre, D., Wagner, A.D., 2007. Left ventrolateral prefrontal cortex and the cognitive control of memory. Neuropsychologia 45, 2883–2901.
Bajada, C.J., Lambon Ralph, M.A., Cloutman, L.L., 2015. Transport for language south of the Sylvian fissure: the routes and history of the main tracts and stations in the ventral language network. Cortex; a journal devoted to the study of the nervous system and behavior 69, 141–151.
Barbas, H., 2007. Flow of information for emotions through temporal and orbitofrontal pathways. J. Anat. 211, 237–249.
Bello, L., Acerbi, F., Giussani, C., Baratta, P., Taccone, P., Songa, V., ... Gaini, S.M., 2006. Intraoperative language localization in multilingual patients with gliomas. Neurosurgery 59 (1), 115–123. https://doi.org/10.1227/01.NEU.0000219241.92246.FB.
Bello, L., Gallucci, M., Fava, M., Carrabba, G., Giussani, C., Acerbi, F., ... Gaini, S.M., 2007. Intraoperative subcortical language tract mapping guides surgical removal of gliomas involving speech areas. Neurosurgery 60 (1), 67–80. https://doi.org/10.1227/01.NEU.0000249206.58601.DE.
Bello, L., Gambini, A., Castellano, A., Carrabba, G., Acerbi, F., Fava, E., Casarotti, A., 2008. Motor and language DTI Fiber Tracking combined with intraoperative subcortical mapping for surgical removal of gliomas. Neuroimage 39 (1), 369–382.
Berwick, R.C., Friederici, A.D., Chomsky, N., Bolhuis, J.J., 2013. Evolution, brain, and the nature of language. Trends Cogn. Sci. 17, 89–98.
Binder, J.R., Desai, R.H., 2011. The neurobiology of semantic memory. Trends Cogn. Sci. 15, 527–536.
Binder, J.R., Desai, R.H., Graves, W.W., Conant, L.L., 2009. Where is the semantic system? A critical review and meta-analysis of 120 functional neuroimaging studies. Cerebr. Cortex 19, 2767–2796.
Breier, J.I., Hasan, K.M., Zhang, W., Men, D., Papanicolaou, A.C., 2008. Language dysfunction after stroke and damage to white matter tracts evaluated using diffusion tensor imaging. Am. J. Neuroradiol. 29, 483–487.
Broche-Perez, Y., Herrera Jimenez, L.F., Omar-Martinez, E., 2016. Neural substrates of decision-making. Neurologia 31, 319–325.
Burks, J.D., Boettcher, L.B., Conner, A.K., Glenn, C.A., Bonney, P.A., Baker, C.M., Briggs, R.G., Pittman, N.A., O'Donoghue, D.L., Wu, D.H., 2017. White matter connections of the inferior parietal lobule: a study of surgical anatomy. Brain and behavior 7, e00640.
Burks, J.D., Conner, A.K., Bonney, P.A., Glenn, C.A., Baker, C.M., Boettcher, L.B., Briggs, R.G., O'Donoghue, D.L., Wu, D.H., Sughrue, M.E., 2018. Anatomy and white matter connections of the orbitofrontal gyrus. J. Neurosurg. 128, 1865–1872.
Catani, M., Thiebaut de Schotten, M.T., 2012. Atlas of Human Brain Connections. Oxford University Press.
Catani, M., Dell'acqua, F., Vergani, F., Malik, F., Hodge, H., Roy, P., Valabregue, R., Thiebaut de Schotten, M., 2012. Short frontal lobe connections of the human brain. Cortex; a journal devoted to the study of the nervous system and behavior 48, 273–291.
Catani, M., Howard, R.J., Pajevic, S., Jones, D.K., 2002. Virtual in vivo interactive dissection of white matter fasciculi in the human brain. Neuroimage 17, 77–94.
Catani, M., Jones, D.K., ffytche, D.H., 2005. Perisylvian language networks of the human brain. Ann. Neurol. 57, 8–16.
Catani, M., Mesulam, M.M., Jakobsen, E., Malik, F., Martersteck, A., Wieneke, C., Thompson, C.K., Thiebaut De Schotten, M., Dell'Acqua, F., Weintraub, S., Rogalski, E., 2013. A novel frontal pathway underlies verbal fluency in primary progressive aphasia. Brain 136, 2619–2628.
Chan-Seng, E., Moritz-Gasser, S., Duffau, H., 2014. Awake mapping for low-grade gliomas involving the left sagittal stratum: anatomofunctional and surgical considerations. J. Neurosurg. 120 (5), 1069–1077. https://doi.org/10.3171/2014.1.jns132015.
Cloutman, L., Gottesman, R., Chaudhry, P., Davis, C., Kleinman, J.T., Pawlak, M., Herskovits, E.H., Kannan, V., Lee, A., Newhart, M., Heidler-Gary, J., Hillis, A.E., 2009. Where (in the brain) do semantic errors come from? Cortex; a journal devoted to the study of the nervous system and behavior 45, 641–649.
Cocquyt, E.-M., Coffé, C., van Mierlo, P., Duyck, W., Mariën, P., Szmalec, A., Santens, P., De Letter, M., 2019. The involvement of subcortical grey matter in verbal semantic comprehension: a systematic review and meta-analysis of fMRI and PET studies. J. Neurolinguistics 51, 278–296.
Cochrane Collaboration, 2011. Cochrane Handbook for Systematic Reviews of Interventions. [updated March 2011] Available at: www.cochrane-handbook.org, version 5.1. 0 (Date of access: 01/03/2015).
Davey, J., Thompson, H.E., Hallam, G., Karapanagiotidis, T., Murphy, C., De Caso, I., Krieger-Redwood, K., Bernhardt, B.C., Smallwood, J., Jefferies, E., 2016. Exploring the role of the posterior middle temporal gyrus in semantic cognition: integration of anterior temporal lobe with executive processes. Neuroimage 137, 165–177.
De Witte, E., Satoer, D., Colle, H., Robert, E., Visch-Brink, E., Mariën, P., 2015. Subcortical language and non-language mapping in awake brain surgery: the use of multimodal tests. Acta Neurochir. 157 (4), 577–588.
de Zubicaray, G.I., Rose, S.E., McMahon, K.L., 2011. The structure and connectivity of semantic memory in the healthy older adult brain. Neuroimage 54, 1488–1494.
Devlin, J.T., Matthews, P.M., Rushworth, M.F., 2003. Semantic processing in the left inferior prefrontal cortex: a combined functional magnetic resonance imaging and transcranial magnetic stimulation study. J. Cogn. Neurosci. 15, 71–84.
Dick, A.S., Bernal, B., Tremblay, P., 2014. The language connectome: new pathways, new concepts. The Neuroscientist : a review journal bringing neurobiology, neurology and psychiatry 20, 453–467.
Dominey, P.F., Inui, T., 2009. Cortico-striatal function in sentence comprehension: insights from neurophysiology and modeling. Cortex 45, 1012–1018.
Duffau, H., Gatignol, P., Mandonnet, E., Peruzzi, P., Tzourio-Mazoyer, N., Capelle, L., 2005. New insights into the anatomo-functional connectivity of the semantic system: a study using cortico-subcortical electrostimulations. Brain 128 (4), 797–810. https://doi.org/10.1093/brain/awh423.
Duffau, H., Gatignol, P., Moritz-Gasser, S., Mandonnet, E., 2009. Is the left uncinate fasciculus essential for language? : AA cerebral stimulation study. J. Neurol. 256 (3), 382–389. https://doi.org/10.1007/s00415-009-0053-9.
Duffau, H., Gatignol, P., Mandonnet, E., Capelle, L., Taillandier, L., 2008. Intraoperative subcortical stimulation mapping of language pathways in a consecutive series of 115 patients with Grade II glioma in the left dominant hemisphere. J. Neurosurg. 109 (3), 461–471. https://doi.org/10.3171/jns/2008/109/9/0461.
Duffau, H., 2005. Lessons from brain mapping in surgery for low-grade glioma: insights into associations between tumour and brain plasticity. Lancet Neurol. 4, 476–486.
Duffau, H., 2008. The anatomo-functional connectivity of language revisited. New insights provided by electrostimulation and tractography. Neuropsychologia 46, 927–934.
Duffau, H., 2015. Stimulation mapping of white matter tracts to study brain functional connectivity. Nat. Rev. Neurol. 11, 255–265.
Duffau, H., Moritz-Gasser, S., Mandonnet, E., 2014. A re-examination of neural basis of language processing: proposal of a dynamic hodotopical model from data provided by brain stimulation mapping during picture naming. Brain Lang. 131, 1–10.
Epelbaum, S., Pinel, P., Gaillard, R., Delmaire, C., Perrin, M., Dupont, S., Dehaene, S., Cohen, L., 2008. Pure alexia as a disconnection syndrome: new diffusion imaging evidence for an old concept. Cortex; a journal devoted to the study of the nervous system and behavior 44, 962–974.
Fellgiebel, A., Wille, P., Muller, M.J., Winterer, G., Scheurich, A., Vucurevic, G., Schmidt, L.G., Stoeter, P., 2004. Ultrastructural hippocampal and white matter alterations in mild cognitive impairment: a diffusion tensor imaging study. Dement. Geriatr. Cognit. Disord. 18, 101–108.
Ford, A.A., Triplett, W., Sudhyadhom, A., Gullett, J., McGregor, K., Fitzgerald, D.B., Mareci, T., White, K., Crosson, B., 2013. Broca's area and its striatal and thalamic connections: a diffusion-MRI tractography study. Front. Neuroanat. 7, 8.
Friederici, A.D., 2002. Towards a neural basis of auditory sentence processing. Trends Cogn. Sci. 6, 78–84.
Friederici, A.D., Gierhan, S.M., 2013. The language network. Curr. Opin. Neurobiol. 23, 250–254.
Gierhan, S.M., 2013. Connections for auditory language in the human brain. Brain Lang. 127, 205–221.
Gil-Robles, S., Carvallo, A., Jimenez, M.D.M., Gomez Caicoya, A., Martinez, R., Ruiz-Ocaña, C., Duffau, H., 2013. Double dissociation between visual recognition and picture naming: a study of the visual language connectivity using tractography and brain stimulation. Neurosurgery 72 (4), 678–686. https://doi.org/10.1227/NEU.0b013e318282a361.
Glasser, M.F., Rilling, J.K., 2008. DTI tractography of the human brain's language pathways. Cerebr. Cortex 18, 2471–2482.
Gold, B.T., Balota, D.A., Kirchhoff, B.A., Buckner, R.L., 2005. Common and dissociable activation patterns associated with controlled semantic and phonological processing: evidence from FMRI adaptation. Cerebr. Cortex 15, 1438–1450 New York, N.Y. : 1991.
Gorno-Tempini, M.L., Dronkers, N.F., Rankin, K.P., Ogar, J.M., Phengrasamy, L., Rosen, H.J., Johnson, J.K., Weiner, M.W., Miller, B.L., 2004. Cognition and anatomy in three variants of primary progressive aphasia. Ann. Neurol. 55, 335–346.
Gorno-Tempini, M.L., Hillis, A.E., Weintraub, S., Kertesz, A., Mendez, M., Cappa, S.F., Ogar, J.M., Rohrer, J.D., Black, S., Boeve, B.F., Manes, F., Dronkers, N.F., Vandenberghe, R., Rascovsky, K., Patterson, K., Miller, B.L., Knopman, D.S., Hodges, J.R., Mesulam, M.M., Grossman, M., 2011. Classification of primary progressive aphasia and its variants. Neurology 76, 1006–1014.
Griffis, J.C., Nenert, R., Allendorfer, J.B., Szaflarski, J.P., 2017. Damage to white matter bottlenecks contributes to language impairments after left hemispheric stroke. Neuroimage: Clinical 14, 552–565.
Grossman, M., Powers, J., Ash, S., McMillan, C., Burkholder, L., Irwin, D., Trojanowski, J.Q., 2013. Disruption of large-scale neural networks in non-fluent/agrammatic

variant primary progressive aphasia associated with frontotemporal degeneration pathology. Brain Lang. 127, 106–120.
Hagoort, P., 2005. On Broca, brain, and binding: a new framework. Trends Cogn. Sci. 9, 416–423.
Hamer, P., Moritz-Gasser, S., Gatignol, P., Duffau, H., 2011. Is the human left middle longitudinal fascicle essential for language? A brain electrostimulation study. Hum. Brain Mapp. 32 (6), 962–973. https://doi.org/10.1002/hbm.21082.
Han, Z., Ma, Y., Gong, G., He, Y., Caramazza, A., Bi, Y., 2013. White matter structural connectivity underlying semantic processing: evidence from brain damaged patients. Brain 136, 2952–2965.
Hart Jr., J., Maguire, M.J., Motes, M., Mudar, R.A., Chiang, H.-S., Womack, K.B., Kraut, M.A., 2013. Semantic memory retrieval circuit: role of pre-SMA, caudate, and thalamus. 126, 89–98.
Harvey, D.Y., Wei, T., Ellmore, T.M., Hamilton, A.C., Schnur, T.T., 2013. The functional role of the uncinate fasciculus in semantic control: converging evidence from structural and functional connectivity measures. J. Cogn. Neurosci 137-137.
Hau, J., Sarubbo, S., Houde, J.C., Corsini, F., Girard, G., Deledalle, C., Crivello, F., Zago, L., Mellet, E., Jobard, G., Joliot, M., Mazoyer, B., Tzourio-Mazoyer, N., Descoteaux, M., Petit, L., 2017. Revisiting the human uncinate fasciculus, its subcomponents and asymmetries with stem-based tractography and microdissection validation. Brain Struct. Funct. 222, 1645–1662.
Herbet, G., Moritz-Gasser, S., Duffau, H., 2017. Direct evidence for the contributive role of the right inferior fronto-occipital fasciculus in non-verbal semantic cognition. Brain Struct. Funct. 222 (4), 1597–1610. https://doi.org/10.1007/s00429-016-1294-x.
Herbet, G., Maheu, M., Costi, E., Lafargue, G., Duffau, H., 2016. Mapping neuroplastic potential in brain-damaged patients. Brain : J. Neurol. 139, 829–844.
Herbet, G., Moritz-Gasser, S., Lemaitre, A.L., Almairac, F., Duffau, H., 2018a. Functional compensation of the left inferior longitudinal fasciculus for picture naming. Cogn. Neuropsychol. 1–18.
Herbet, G., Zemmoura, I., Duffau, H., 2018b. Functional anatomy of the inferior longitudinal fasciculus: from historical reports to current hypotheses. Front. Neuroanat. 12, 77.
Hertrich, I., Dietrich, S., Ackermann, H., 2016. The role of the supplementary motor area for speech and language processing. Neurosci. Biobehav. Rev. 68, 602–610.
Hickok, G., Poeppel, D., 2007. The cortical organization of speech processing. Nat. Rev. Neurosci. 8, 393–402.
Hodgetts, C.J., Postans, M., Shine, J.P., Jones, D.K., Lawrence, A.D., Graham, K.S., 2015. Dissociable roles of the inferior longitudinal fasciculus and fornix in face and place perception. eLife 4.
Hodgetts, C.J., Postans, M., Warne, N., Varnava, A., Lawrence, A.D., Graham, K.S., 2017. Distinct contributions of the fornix and inferior longitudinal fasciculus to episodic and semantic autobiographical memory. Cortex 94, 1–14. https://doi.org/10.1016/j.cortex.2017.05.010.
Hope, T.M.H., Price, C.J., 2016. Why the left posterior inferior temporal lobe is needed for word finding. Brain : J. Neurol. 139, 2823–2826.
Howard, D., Patterson, K., 1992. The Pyramids and Palm Trees Test: A Test of Semantic Access from Words and Pictures. Thames Valley Test Company.
Ivanova, M.V., Isaev, D.Y., Dragoy, O.V., Akinina, Y.S., Petrushevskiy, A.G., Fedina, O.N., Shklovsky, V.M., Dronkers, N.F., 2016. Diffusion-tensor imaging of major white matter tracts and their role in language processing in aphasia. Cortex 85, 165–181.
Johansen-Berg, H., Behrens, T.E., 2013. Diffusion MRI: from Quantitative Measurement to in Vivo Neuroanatomy. Academic Press.
Jouen, A.L., Ellmore, T.M., Madden, C.J., Pallier, C., Dominey, P.F., Ventre-Dominey, J., 2015. Beyond the word and image: characteristics of a common meaning system for language and vision revealed by functional and structural imaging. Neuroimage 106, 72–85. https://doi.org/10.1016/j.neuroimage.2014.11.024.
Kinoshita, M., de Champfleur, N.M., Deverdun, J., Moritz-Gasser, S., Herbet, G., Duffau, H., 2015. Role of fronto-striatal tract and frontal aslant tract in movement and speech: an axonal mapping study. Brain Struct. Funct. 220, 3399–3412.
Knibb, J.A., Xuereb, J.H., Patterson, K., Hodges, J.R., 2006. Clinical and pathological characterization of progressive aphasia. Ann. Neurol. 59, 156–165.
Krawczyk, D.C., 2002. Contributions of the prefrontal cortex to the neural basis of human decision making. Neurosci. Biobehav. Rev. 26, 631–664.
Leclercq, D., Duffau, H., Delmaire, C., Capelle, L., Gatignol, P., Ducros, M., ... Lehéricy, S., 2010. Comparison of diffusion tensor imaging tractography of language tracts and intraoperative subcortical stimulations: clinical article. J. Neurosurg. 112 (3), 503–511. https://doi.org/10.3171/2009.8.JNS09558.
Levelt, W.J., Roelofs, A., Meyer, A.S., 1999. A theory of lexical access in speech production. Behav. Brain Sci. 22, 1–38 discussion 38-75.
Maffei, C., Soria, G., Prats-Galino, A., Catani, M., 2015. Imaging white-matter pathways of the auditory system with diffusion imaging tractography. In: Handbook of Clinical Neurology, vol. 129. Elsevier, pp. 277–288.
Makris, N., Kennedy, D.N., McInerney, S., Sorensen, A.G., Wang, R., Caviness Jr., V.S., Pandya, D.N., 2005. Segmentation of subcomponents within the superior longitudinal fascicle in humans: a quantitative, in vivo, DT-MRI study. Cerebr. Cortex 15, 854–869 New York, N.Y. : 1991.
Makris, N., Preti, M.G., Wassermann, D., Rathi, Y., Papadimitriou, G.M., Yergatian, C., Dickerson, B.C., Shenton, M.E., Kubicki, M., 2013. Human middle longitudinal fascicle: segregation and behavioral-clinical implications of two distinct fiber connections linking temporal pole and superior temporal gyrus with the angular gyrus or superior parietal lobule using multi-tensor tractography. Brain imaging and behavior 7, 335–352.
Maldonado, I.L., Moritz-Gasser, S., de Champfleur, N.M., Bertram, L., Moulinié, G., Duffau, H., 2011b. Surgery for gliomas involving the left inferior parietal lobule: new insights into the functional anatomy provided by stimulation mapping in awake patients. J. Neurosurg. 115 (4), 770–779.
Maldonado, I.L., Moritz-Gasser, S., Duffau, H., 2011a. Does the left superior longitudinal fascicle subserve language semanticsNS A brain electrostimulation study. Brain Struct. Funct. 216 (3), 263–274. https://doi.org/10.1007/s00429-011-0309-x.
Mandelli, M.L., Caverzasi, E., Binney, R.J., Henry, M.L., Lobach, I., Block, N., Amirbekian, B., Dronkers, N., Miller, B.L., Henry, R.G., Gorno-Tempini, M.L., 2014. Frontal white matter tracts sustaining speech production in primary progressive aphasia. J. Neurosci. 34, 9754–9767.
Mandonnet, E., Nouet, A., Gatignol, P., Capelle, L., Duffau, H., 2007. Does the left inferior longitudinal fasciculus play a role in language? A brain stimulation study. Brain 130 (3), 623–629. https://doi.org/10.1093/brain/awl361.
Mandonnet, E., Gatignol, P., Duffau, H., 2009. Evidence for an occipito-temporal tract underlying visual recognition in picture naming. Clin. Neurol. Neurosurg. 111, 601–605.
Mandonnet, E., 2017. A surgical approach to the anatomo-functional structure of language. Neurochirurgie 63, 122–128.
Mandonnet, E., Herbet, G., Moritz-Gasser, S., Poisson, I., Rheault, F., Duffau, H., 2019. Electrically induced verbal perseveration: a striatal deafferentation model. Neurology 92, e613–e621.
Marcotte, K., Graham, N.L., Fraser, K.C., Meltzer, J.A., Tang-Wai, D.F., Chow, T.W., Freedman, M., Leonard, C., Black, S.E., Rochon, E., 2017. White matter disruption and connected speech in non-fluent and semantic variants of primary progressive aphasia. Dementia and Geriatric Cognitive Disorders Extra 7, 52–73.
Martino, J., De Lucas, E.M., 2014. Subcortical anatomy of the lateral association fascicles of the brain: a review. Clin. Anat. 27, 563–569.
Martino, J., De Witt Hamer, P.C., Berger, M.S., Lawton, M.T., Arnold, C.M., de Lucas, E.M., Duffau, H., 2013. Analysis of the subcomponents and cortical terminations of the perisylvian superior longitudinal fasciculus: a fiber dissection and DTI tractography study. Brain Struct. Funct. 218, 105–121.
McKinnon, E., Glenn, R., Wabnitz, A., Jensen, J., Helpern, J., Bonilha, L., Fridriksson, J., 2017. Therapy-related structural plasticity of temporal white matter is related to naming recovery in aphasia. Stroke 48.
Medina, D., DeToledo-Morrell, L., Urresta, F., Gabrieli, J.D., Moseley, M., Fleischman, D., Bennett, D.A., Leurgans, S., Turner, D.A., Stebbins, G.T., 2006. White matter changes in mild cognitive impairment and AD: a diffusion tensor imaging study. Neurobiol. Aging 27, 663–672.
Mesulam, M., Wicklund, A., Johnson, N., Rogalski, E., Leger, G.C., Rademaker, A., Weintraub, S., Bigio, E.H., 2008. Alzheimer and frontotemporal pathology in subsets of primary progressive aphasia. Ann. Neurol. 63, 709–719.
Mirman, D., Chen, Q., Zhang, Y., Wang, Z., Faseyitan, O.K., Coslett, H.B., Schwartz, M.F., 2015. Neural organization of spoken language revealed by lesion-symptom mapping. Nat. Commun. 6.
Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G., 2009. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. PLoS Med. 6, e1000097.
Moritz-Gasser, S., Herbet, G., Duffau, H., 2013. Mapping the connectivity underlying multimodal (verbal and non-verbal) semantic processing: a brain electrostimulation study. Neuropsychologia 51 (10), 1814–1822. https://doi.org/10.1016/j.neuropsychologia.2013.06.007.
Murdoch, B.E., 2009. Speech and Language Disorders Associated with Subcortical Pathology. John Wiley & Sons.
Noonan, K.A., Jefferies, E., Corbett, F., Lambon Ralph, M.A., 2010. Elucidating the nature of deregulated semantic cognition in semantic aphasia: evidence for the roles of prefrontal and temporo-parietal cortices. J. Cogn. Neurosci. 22, 1597–1613.
Noonan, K.A., Jefferies, E., Visser, M., Lambon Ralph, M.A., 2013. Going beyond inferior prefrontal involvement in semantic control: evidence for the additional contribution of dorsal angular gyrus and posterior middle temporal cortex. J. Cogn. Neurosci. 25, 1824–1850.
Nugiel, T., Alm, K.H., Olson, I.R., 2016. Individual differences in white matter microstructure predict semantic control. Cognit. Affect Behav. Neurosci. 16 (6), 1003–1016.
Olson, I.R., McCoy, D., Klobusicky, E., Ross, L.A., 2013. Social cognition and the anterior temporal lobes: a review and theoretical framework. Soc. Cogn. Affect. Neurosci. 8, 123–133.
Oouchi, H., Yamada, K., Sakai, K., Kizu, O., Kubota, T., Ito, H., Nishimura, T., 2007. Diffusion anisotropy measurement of brain white matter is affected by voxel size: underestimation occurs in areas with crossing fibers. AJNR. American journal of neuroradiology 28, 1102–1106.
Ortibus, E., Verhoeven, J., Sunaert, S., Casteels, I., de Cock, P., Lagae, L., 2012. Integrity of the inferior longitudinal fasciculus and impaired object recognition in children: a diffusion tensor imaging study. Dev. Med. Child Neurol. 54, 38–43.
Patterson, K., Nestor, P.J., Rogers, T.T., 2007. Where do you know what you know? The representation of semantic knowledge in the human brain. Nat. Rev. Neurosci. 8, 976–987.
Peuskens, D., van Loon, J., Van Calenbergh, F., van den Bergh, R., Goffin, J., Plets, C., 2004. Anatomy of the anterior temporal lobe and the frontotemporal region demonstrated by fiber dissection. Neurosurgery 55, 1174–1184.
Pievani, M., Agosta, F., Pagani, E., Canu, E., Sala, S., Absinta, M., Geroldi, C., Ganzola, R., Frisoni, G.B., Filippi, M., 2010. Assessment of white matter tract damage in mild cognitive impairment and Alzheimer's disease. Hum. Brain Mapp. 31, 1862–1875.
Powers, J.P., McMillan, C.T., Brun, C.C., Yushkevich, P.A., Zhang, H., Gee, J.C., Grossman, M., 2013. White matter disease correlates with lexical retrieval deficits in primary progressive aphasia. Front. Neurol. 4 DEC.
Pulvermuller, F., Fadiga, L., 2010. Active perception: sensorimotor circuits as a cortical basis for language. Nat. Rev. Neurosci. 11, 351–360.
Ralph, M.A., Jefferies, E., Patterson, K., Rogers, T.T., 2017. The neural and computational

bases of semantic cognition. Nat. Rev. Neurosci. 18, 42–55.
Rilling, J.K., Glasser, M.F., Preuss, T.M., Ma, X., Zhao, T., Hu, X., Behrens, T.E., 2008. The evolution of the arcuate fasciculus revealed with comparative DTI. Nat. Neurosci. 11, 426–428.
Ripollés, P., Biel, D., Penaloza, C., Kaufmann, J., Marco-Pallares, J., Noesselt, T., Rodriguez-Fornells, A., 2017. Strength of temporal white matter pathways predicts semantic learning. J. Neurosci. https://doi.org/10.1523/jneurosci.1720-17.2017.
Rofes, A., Spena, G., Talacchi, A., Santini, B., Miozzo, A., Miceli, G., 2017. Mapping nouns and finite verbs in left hemisphere tumors: a direct electrical stimulation study. Neurocase 23 (2), 105–113. https://doi.org/10.1080/13554794.2017.1307418.
Rolheiser, T., Stamatakis, E.A., Tyler, L.K., 2011. Dynamic processing in the human language system: synergy between the arcuate fascicle and extreme capsule. J. Neurosci. 31, 16949–16957.
Rollans, C., Cheema, K., Georgiou, G.K., Cummine, J., 2017. Pathways of the inferior frontal occipital fasciculus in overt speech and reading. Neuroscience 364, 93–106. https://doi.org/10.1016/j.neuroscience.2017.09.011.
Sarubbo, S., De Benedictis, A., Maldonado, I.L., Basso, G., Duffau, H., 2013. Frontal terminations for the inferior fronto-occipital fascicle: anatomical dissection, DTI study and functional considerations on a multi-component bundle. Brain Struct. Funct. 218, 21–37.
Sarubbo, S., De Benedictis, A., Merler, S., Mandonnet, E., Balbi, S., Granieri, E., Duffau, H., 2015. Towards a functional atlas of human white matter. Hum. Brain Mapp. 36, 3117–3136.
Saur, D., Schelter, B., Schnell, S., Kratochvil, D., Kupper, H., Kellmeyer, P., Kummerer, D., Kloppel, S., Glauche, V., Lange, R., Mader, W., Feess, D., Timmer, J., Weiller, C., 2010. Combining functional and anatomical connectivity reveals brain networks for auditory language comprehension. Neuroimage 49, 3187–3197.
Schmahmann, J.D., Pandya, D.N., Wang, R., Dai, G., D'Arceuil, H.E., de Crespigny, A.J., Wedeen, V.J., 2007. Association fibre pathways of the brain: parallel observations from diffusion spectrum imaging and autoradiography. Brain : J. Neurol. 130, 630–653.
Sierpowska, J., Gabarrós, A., Fernandez-Coello, A., Camins, T., Castañer, S., Juncadella, M., ... Rodríguez-Fornells, A., 2015. Morphological derivation overflow as a result of disruption of the left frontal aslant white matter tract. Brain Lang. 142, 54–64. https://doi.org/10.1016/j.bandl.2015.01.005.
Spalletta, G., Piras, F., Fagioli, S., Caltagirone, C., Piras, F., 2014. Brain microstructural changes and cognitive correlates in patients with pure obsessive compulsive disorder. Brain and Behavior 4 (2), 261–277. https://doi.org/10.1002/brb3.212.
Thiebaut de Schotten, M., Bizzi, A., Dell'Acqua, F., Allin, M., Walshe, M., Murray, R., Williams, S.C., Murphy, D.G., Catani, M., 2011. Atlasing location, asymmetry and inter-subject variability of white matter tracts in the human brain with MR diffusion tractography. Neuroimage 54, 49–59.
Thompson-Schill, S.L., Bedny, M., Goldberg, R.F., 2005. The frontal lobes and the regulation of mental activity. Curr. Opin. Neurobiol. 15, 219–224.
Trinh, V.T., Fahim, D.K., Shah, K., Tummala, S., McCutcheon, I.E., Sawaya, R., Suki, D., Prabhu, S.S., 2013. Subcortical injury is an independent predictor of worsening neurological deficits following awake craniotomy procedures. Neurosurgery 72, 160–169.
Tu, S., Leyton, C.E., Hodges, J.R., Piguet, O., Hornberger, M., 2016. Divergent longitudinal propagation of white matter degradation in logopenic and semantic variants of primary progressive aphasia. J. Alzheimer's Dis. 49, 853–861.
Turken, A.U., Dronkers, N.F., 2011. The neural architecture of the language comprehension network: converging evidence from lesion and connectivity analyses. Front. Syst. Neurosci. 5, 1.
Vassal, F., Schneider, F., Sontheimer, A., Lemaire, J.J., Nuti, C., 2013. Intraoperative visualisation of language fascicles by diffusion tensor imaging-based tractography in glioma surgery. Acta Neurochir. 155 (3), 437–448. https://doi.org/10.1007/s00701-012-1580-1.
van Geemen, K., Herbet, G., Moritz-Gasser, S., Duffau, H., 2014. Limited plastic potential of the left ventral premotor cortex in speech articulation: evidence from intraoperative awake mapping in glioma patients. Hum. Brain Mapp. 35 (4), 1587–1596.
Vidorreta, J.G., Garcia, R., Moritz-Gasser, S., Duffau, H., 2011. Double dissociation between syntactic gender and picture naming processing: a brain stimulation mapping study. Hum. Brain Mapp. 32 (3), 331–340. https://doi.org/10.1002/hbm.21026.
Vigneau, M., Beaucousin, V., Herve, P.Y., Duffau, H., Crivello, F., Houde, O., Mazoyer, B., Tzourio-Mazoyer, N., 2006. Meta-analyzing left hemisphere language areas: phonology, semantics, and sentence processing. Neuroimage 30, 1414–1432.
Von Der Heide, R.J., Skipper, L.M., Klobusicky, E., Olson, I.R., 2013. Dissecting the uncinate fasciculus: disorders, controversies and a hypothesis. Brain 136, 1692–1707.
Welcome, S.E., Joanisse, M.F., 2014. Individual differences in white matter anatomy predict dissociable components of reading skill in adults. Neuroimage 96, 261–275. https://doi.org/10.1016/j.neuroimage.2014.03.069.
Wheeler-Kingshott, C.A., Cercignani, M., 2009. About "axial" and "radial" diffusivities. Magn. Reson. Med. 61, 1255–1260.
Whitney, C., Kirk, M., O'Sullivan, J., Lambon Ralph, M.A., Jefferies, E., 2011. The neural organization of semantic control: TMS evidence for a distributed network in left inferior frontal and posterior middle temporal gyrus. Cerebr. Cortex 21, 1066–1075.
Wilson, S.M., Galantucci, S., Tartaglia, M.C., Rising, K., Patterson, D.K., Henry, M.L., Ogar, J.M., DeLeon, J., Miller, B.L., Gorno-Tempini, M.L.J.N., 2011. Syntactic processing depends on dorsal language tracts. 72, 397–403.
Wu, Y., Sun, D., Wang, Y., Wang, Y., 2016. Subcomponents and connectivity of the inferior fronto-occipital fasciculus revealed by diffusion spectrum imaging fiber tracking. Front. Neuroanat. 10, 88.
Xiang, H.D., Dediu, D., Roberts, L., van Oort, E., Norris, D.G., Hagoort, P., 2012. The structural connectivity underpinning language aptitude, working memory, and IQ in the perisylvian language network. Lang. Learn. 62, 110–130. https://doi.org/10.1111/j.1467-9922.2012.00708.x.
Xing, S.H., Lacey, E.H., Skipper-Kallal, L.M., Zeng, J.S., Turkeltaub, P.E., 2017. White Matter correlates of auditory comprehension Outcomes in chronic Post-stroke aphasia. Front. Neurol. 8.
Zemmoura, I., Herbet, G., Moritz-Gasser, S., Duffau, H., 2015. New insights into the neural network mediating reading processes provided by cortico-subcortical electrical mapping. Hum. Brain Mapp. 36, 2215–2230.