

## Short Communication

White matter in aphasia: A historical review of the Dejerines' studies<sup>☆</sup>Heinz Krestel<sup>a,b,\*</sup>, Jean-Marie Annoni<sup>c</sup>, Caroline Jagella<sup>d,\*</sup><sup>a</sup> Department of Neurology, Inselspital, Bern University Hospital, University of Bern, Switzerland<sup>b</sup> Department of Neuropediatrics, Inselspital, Bern University Hospital, University of Bern, Switzerland<sup>c</sup> Department of Neurology, Hôpital de Fribourg, Fribourg, Switzerland<sup>d</sup> Department of Neurology, Kantonsspital Baden, Baden, Switzerland

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## ABSTRACT

The Objective was to describe the contributions of Joseph Jules Dejerine and his wife Augusta Dejerine-Klumpke to our understanding of cerebral association fiber tracts and language processing.

The Dejerines (and not Constantin von Monakow) were the first to describe the superior longitudinal fasciculus/arcuate fasciculus (SLF/AF) as an association fiber tract uniting Broca's area, Wernicke's area, and a visual image center in the angular gyrus of a left hemispheric language zone. They were also the first to attribute language-related functions to the fasciculi occipito-frontalis (FOF) and the inferior longitudinal fasciculus (ILF) after describing aphasia patients with degeneration of the SLF/AF, ILF, uncinate fasciculus (UF), and FOF. These fasciculi belong to a functional network known as the Dejerines' language zone, which exceeds the borders of the classically defined cortical language centers.

The Dejerines provided the first descriptions of the anatomical pillars of present-day language models (such as the SLF/AF). Their anatomical descriptions of fasciculi in aphasia patients provided a foundation for our modern concept of the dorsal and ventral streams in language processing.

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## 1. Introduction

Joseph Jules Dejerine (1849–1917) and his wife, Augusta Dejerine-Klumpke (1859–1927), were both involved in aphasia research. He is primarily remembered for his description of alexia without agraphia (Catani & ffytche, 2005; Dejerine, 1892), while Augusta Dejerine-Klumpke is most famous for her discussion about the quadrilateral zone of Pierre Marie at the “hot summer of aphasiology” congress in Paris in 1908 (Klippel, 1908a; Lecours & Caplan, 1984; Lecours, Chain, Poncet, Nespoulous, & Joannette, 1992). Their knowledge of brain anatomy was very precise and led them to postulate a neuroanatomically founded concept of a language zone (Dejerine & Dejerine-Klumpke, 1901, pp. 247–252; Mirailhé, 1896, pp. 106–119). Their concept also integrated clinical information, which led to the introduction of an aphasia

classification (Mirailhé, 1896, p. 102ff). Biographical data about Dejerine-Klumpke and Dejerine can be found elsewhere (Bogousslavsky, 2005; Bogousslavsky, 2011; Creese, 2004; Ellis, 2010; Lecours & Caplan, 1984; Lecours et al., 1992; Sartran, 1974; Shojá & Tubbs, 2007; Sorrel-Dejerine, 1959; Ulgen, Brumblay, Yang, Doyle, & Chung, 2008; Yildirim & Sarikcioglu, 2008; Broussolle, Poirier, Clarac, & Barbara, 2012; Anonymous, 1969; Bassetti & Jagella, 2006; Gauckler, 1922; Henderson, 1984; Heuyer, 1963; Paciaroni & Bogousslavsky, 2011).

In the outgoing 19th century, a variety of these models existed, which were categorized as either localizationistic or associationistic, based on whether they focused on language processing as being locally specialized or highly distributed, respectively. The Paris congress in 1908 marked a climax in this controversy regarding aphasiology. At that time, several questions could not be explained with the then existing models, including that of the Dejerines. For example, the existing models could not explain why injury to anatomically distinct language regions could give rise to unpredictable and overlapping symptoms. Because of these issues, the existing models were progressively replaced by a more non-localizationistic or holistic view (Freud, 1891; Goldstein, 1910; Head, 1926; Marie, 1906; von Monakow, 1905). The deployment of individual models was of course not strictly sequential, but partially overlapping and coincidental. Holistic models were marked by their refusal to allocate language functions to distinct brain regions. However, the localizationistic models experienced a renaissance

**Abbreviations:** SLF/AF, superior longitudinal fasciculus/arcuate fasciculus; ILF, inferior longitudinal fasciculus; UF, uncinate fasciculus; FOF, fronto-occipital fasciculus.

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with Norman Geschwind (1926–1984; 1965) and his work on disconnection syndromes and the neo-associationist school he founded.

Historical overviews of the research on white matter anatomy and the association fiber tracts involved in language processing have been published previously (Catani, 2010; Catani & Mesulam, 2008; Catani & Thiebaut de Schotten, 2008). The Dejerines categorized association fibers as either short or long. Neighboring convolutions were interconnected by the short intracortical association fibers, tangential fibers, and U-fibers (Klippel, 1908, p. 1002; Mirailhé, 1896, p. 112), while long association fibers connected more remote convolutions. Long association fibers belonging to the Dejerines' language zone were listed, described, and discussed in the Neuroanatomy Atlas "Anatomie des Centres Nerveux" (Dejerine & Dejerine-Klumpke, 1895, p. 749ff) and in the doctorate thesis of Mirailhé (1896, p. 112ff).

Lesion studies including serial sectioning in autopsy patients, as they were performed by the Dejerines and others, are nowadays rare. Diffusion tensor imaging (DTI) plus tractography, a 3D modeling technique used to visually represent fiber tracts, enable us by their non-invasiveness to perform neuroanatomical studies at larger patient numbers. Functional magnetic resonance imaging (fMRI) can localize the activity of brain areas during certain tasks. DTI/tractography together with fMRI can thus replace the former lesion studies. Current limitations in DTI resolution particularly arise with signal interpretation at fiber endings (where fibers enter grey matter), and at loci where fiber tracts overlap (Mori & Zhang, 2006). Here, technical development will probably contribute to the improvement of resolution comparable to the level of lesion studies. An extra motivation for DTI/tractography will be, to set the new data into historical perspective. Examination of earlier findings obtained with invasive techniques including the anatomical overlap of fiber endings from the superior longitudinal fasciculus/arcuate fasciculus (SLF/AF), inferior longitudinal fasciculus (ILF), and uncinate fasciculus (UF) in the anterior temporal lobe; the course of language related fibers through the external capsule; and the composition of the SLF/AF may yield interesting comparisons (Supplemental text).

Although the influence of anatomical data is well documented in the Dejerines' literature, it remains unknown how their language processing theory was influenced by the combination of neuroanatomy and functional data from aphasia patients. In the present manuscript, we review primary and secondary sources in order to elucidate the relationship between the Dejerines' neuroanatomical knowledge, language, and aphasia.

## 2. Methods

Systematic review of primary and secondary literature. The search strategy was to screen literature from and about the Dejerines for their content of language-related white matter anatomy, patients with aphasia, and the concept of a language zone. Their most important books were found online and were freely accessible at the Bibliothèque nationale de France and Open Library (initiative of the Internet Archive). Primary and secondary literature was ordered via the University Bern library service or photocopied from library books in France (e.g. Klippel protocols by JMA). PubMed was searched with the terms "superior longitudinal fasciculus", "arcuate fasciculus", "inferior longitudinal fasciculus", "uncinate fasciculus", and "fronto-occipital fasciculus" for more recent publications, in order to put the Dejerines' knowledge of white matter anatomy into context with today's views. Who was first in describing association fiber tracts in relation to language and aphasia was verified by tracing citations in secondary literature back to their first publication. In analogy to the strategy

how to study the history of white matter anatomy, we collected previously published data from primary and secondary literature about the Dejerines' language zone and contemporary models. All French or German literature, required for the preparation of this manuscript, was translated into English by HK.

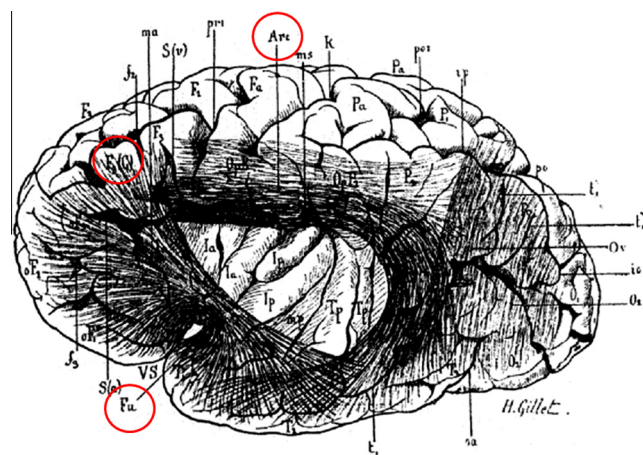
## 3. Results

### 3.1. The superior longitudinal or arcuate fasciculus

The most well studied and canonical dorsal language pathway is the SLF/AF (Fig. 1). The SLF/AF consists of association fibers passing from the frontal lobe through the white matter of the frontal operculum to the posterior end of the Sylvian fissure. There, the fibers radiate into the parietal and occipital lobes and other fibers turn downward and anterior to radiate to anterior portions of the temporal lobe. In humans, the SLF is composed of four components, the SLF I–III and AF, which are bundled together, even though they are functionally separate (Makris et al., 2005). Of these, the AF was described first by Johann Christian Reil (1759–1813) (Catani & Mesulam, 2008). Recent work suggests that the AF may connect posterior receptive areas with premotor/motor areas, but not directly with Broca's area (Bernal & Ardila, 2009). By contrast, the Dejerines suggested that the SLF and the AF were the same tract rather than separate entities. They attributed its first anatomical description to Friedrich Burdach (1776–1847) and not to Reil (Dejerine & Dejerine-Klumpke, 1895, pp. 756, 758).

The first publication mentioning the SLF/AF as the tract connecting Broca's and Wernicke's areas has been ascribed to von Monakow (Catani & Mesulam, 2008), by referring to Geschwind's commented translation (1967, p. 454) of "Der aphasische Symptomenkomplex" by Carl Wernicke (1848–1905) (see also second paragraph of the present manuscript's discussion). Geschwind describes among other things Wernicke's realization that there must be a "psychic reflex arc" connecting motor articulation and sound areas. Wernicke assumed that the anatomical substrate for this arc was the *fibrae propriae*, association fibers running through the insular cortex, and not the AF (Wernicke, 1874, p. 19). Later, Wernicke (1908) modified his view to accept von Monakow's assertion that the path did indeed run in the AF.

Von Monakow's first monographs about aphasia (1897b) and association fibers (1900) did not contain any description of the



**Fig. 1.** Drawing by H. Gillet that shows the insula and the retro-insular region of the left hemisphere, after the borders of the sylvian fissure had been removed. Abbreviations of selected structures are explained: Arc (red circle: SLF/AF), Fu (red circle: UF), F3(C) (red circle: pars triangularis of F3) and Fa (anterior central gyrus) (Dejerine & Dejerine-Klumpke, 1895, p. 757). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

association fiber tracts related to language/aphasia. However, the figure legend 136 in von Monakow's first edition of "Gehirnpathologie" contained the following text:

"Frontal section through the left cerebral hemisphere at the level of the third frontal convolution and the anterior central convolution [...]. D) Associational connection between T1 (first temporal convolution), J (insula) and F3 (third frontal convolution), running in the so-called fasciculus arcuatus (red field); this tract (see d and d1 in Fig. 137) mediates the interaction of T1 with F3." (von Monakow, 1897a).

This figure legend was contained in a chapter entitled "Die Sprachregion" (language zone), in which von Monakow (1897a) explicitly referred to Dejerine for his concept of inner language and the term language zone. The reference to Dejerine seems to extend to the whole chapter, including the remark about the AF, as it was not indicated otherwise.

In 1895, the Dejerines' first volume of "Anatomie des centres nerveux" was published. This publication contained a detailed anatomical description of the white matter anatomy of the cerebral hemispheres including association fibers. In 1895, von Monakow did research for his book "Gehirnpathologie" in Paris, where he also visited the Dejerines in their laboratory and attended the clinical rounds of J.J. Dejerine. Von Monakow remembered that there always were at least 12 aphasia patients hospitalized (Gubser & Ackerknecht, 1970; Jagella, Isler & Hess, 1994). In 1896, the first historical description appeared that the SLF/AF, FOF, and ILF belong to the language zone and unite Broca's and Wernicke's areas and the gyrus angularis. This description was published in the Dejerines' doctoral student C. Mirailhé's thesis "de l'aphasie sensorielle." Mirailhé set the following passage in citation marks indicating that this was an original statement by him and his doctoral supervisor.

"[...] These centers (Broca, Wernicke, visual image center in the angular gyrus, annotation ours) are intimately united among each other by association fibers as anatomy shows us, building an inextricably united ensemble, a unique zone with three secondary centers. [...]" (Mirailhé, 1896, p. 99).

With reference to Dejerine and Dejerine-Klumpke (1895), Mirailhé further described the Dejerines' concept of a language zone and the normal and pathological anatomy of the language zone. The anatomy chapter listed the SLF/AF, FOF, and ILF as association fibers belonging to the language zone, and described their anatomical course including their endings (Mirailhé, 1896, pp. 112–115). Mirailhé also mentioned the UF, but more in anatomical relation to other association fiber tracts. The SLF/AF endings were in the superior and medial temporal gyri and in the Rolandic and inferior frontal gyrus operculum. Taken together, the Dejerines' first publication stated that the SLF/AF, FOF, and ILF unite Broca's area, Wernicke's area, and a visual image center in the gyrus angularis to comprise a left hemispheric language zone.

### 3.2. The fronto-occipital fasciculus

The FOF (Fig. 2) passes backward from the frontal lobe along the lateral border of the caudate nucleus and on the medial aspect of the corona radiata. It radiates in a fan-like manner (tapetum) lateral to the posterior and inferior cornua of the lateral ventricles into the occipital and temporal lobes. The first description of the FOF has been attributed to Burdach (Catani, 2010, p. 6). However, the history of the FOF is apparently more complex (Schmahmann & Pandya, 2007). Even if Burdach was the first to describe direct connections between the frontal and occipital lobes (Catani, 2010), it apparently were the Dejerines who first described the correct anatomical course of the FOF (except for two mistakes about

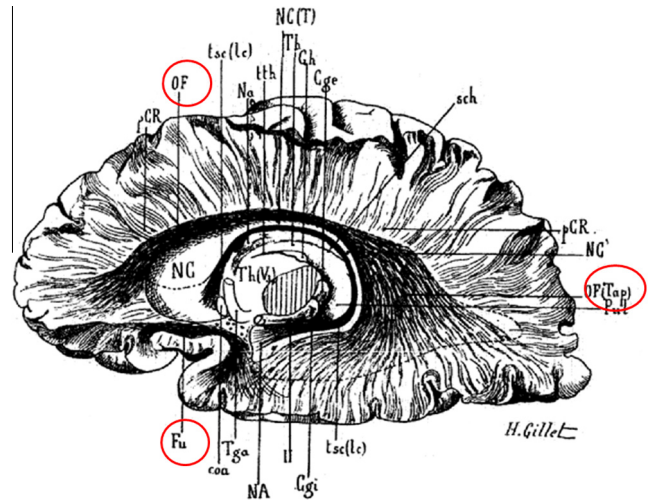


Fig. 2. The corpus callosum and the cingulum were omitted on this drawing of a dissected brain to show the FOF (OF, red circle), the tapetum [OF (Tap), red circle] which is part of the FOF and the UF (Fu, red circle) (Dejerine & Dejerine-Klumpke, 1895, p. 762). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the description of the Muratoff bundle and the tapetum). The expression "fronto-occipital association bundle" may have been coined by Auguste Forel (1848–1931) and his student Wladislaus Onufrowicz (1854–1899). Even the Dejerines named the FOF after Forel and Onufrowicz (Dejerine & Dejerine-Klumpke, 1895, p. 758). Forel and Onufrowicz however confused rostro-caudal fibers in a callosal agenesis brain with the SLF/AF and suggested to name this fiber bundle the true superior longitudinal fasciculus. Second, the "fronto-occipital association bundle" of Forel and Onufrowicz corresponds in reality to the Sachs-Probst bundle and both designations correspond to misguided callosal fibers in the particular case of agenesis of the corpus callosum, but it is not to be found in the normal brain (Schmahmann & Pandya, 2007). The inferior fasciculus occipito-frontalis (IFOF) appears to be a component of the FOF that runs ventrally along the extreme capsule and is arguably the only direct connection between the occipital and frontal cortex in the human brain (Catani & Mesulam, 2008). It is considered as part of the mirror neuron system. Recently, the IFOF was posited to be an additional part of the ventral stream. Electrical stimulation of the IFOF can result in semantic paraphasias (Martino, Brogna, Robles, Vergani, & Duffau, 2010). The existence of the IFOF is however disputed. From a historical point of view, there may be confusion of the IFOF with the Muratoff bundle, a corticostriatal fiber tract (Schmahmann & Pandya, 2007, p. 373).

Several elements of their publications suggest that the Dejerines were likely the first to pioneer the association between the FOF and language and aphasia. First, they observed that the FOF connects subregions of the Dejerines' language zone with more remote cortical regions (Mirailhé, 1896, p. 112f), in particular the anterior language zone with the occipital lobe. A lesioned tract disconnected the language zone from remote cortices and caused pure or conduction aphasia (see Section 3.7.). Second, the Dejerines knew that temporal lobe lesions (which possibly involved Wernicke's area; annotation ours) led to the degeneration of FOF fibers. Third, the Dejerines reported a patient, "Moriceau," who had Broca's aphasia and fiber degeneration, including those of the FOF (Table 1). In fact, Moriceau had a cortical lesion in the frontal lobe, which in turn affected the FOF, UF, and SLF/AF. Note that many patients were published in "Anatomie des centres nerveux" but only the three aphasia patients presented in Table 1 had autopsy results that revealed secondary degeneration caused by circumscribed



**Table 1**

Description of clinical symptoms, brain lesions and degenerated structures, found post mortem in 3 aphasia patients with limited cortical lesions. Case Moriceau (p. 147) had Broca's aphasia, due to a cortical lesion of the left frontal lobe. Case Leudot (p. 125) had Wernicke's aphasia, due to a cortical lesion of the left parietal lobe. Case Heudebert (p. 138) had global aphasia due to cortical lesions of the left temporo-occipital lobe (Dejerine & Dejerine-Klumpke, 1901).

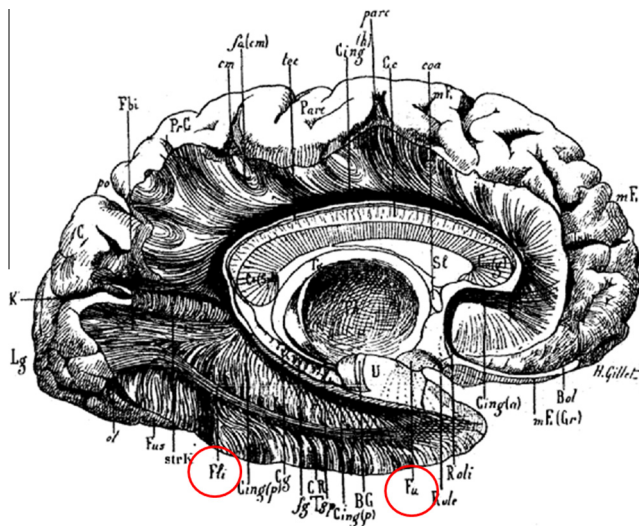
Symptoms	Lesions	Degeneration	Conclusion
<i>Case "Moriceau": cortical lesion of the left frontal lobe</i>			
<ul style="list-style-type: none"> <li>• Right hander, transient Broca aphasia with a little alexia and without word deafness (Wernicke aphasia; annotation ours)</li> <li>• Back to normal within 5 months</li> </ul>	<ul style="list-style-type: none"> <li>• Yellow plaque in the anterior two third of the left inferior frontal gyrus with minimal involvement of adjacent medial frontal gyrus</li> <li>• Foot of left corona radiata</li> <li>• Anterior extremity of right medial and superior frontal gyri</li> </ul>	<ul style="list-style-type: none"> <li>• Short regional association fibers</li> <li>• Commissural fibers from F3 cape (gyrus triangularis of inferior frontal gyrus, annotation ours)</li> <li>• Fasciculus occipitofrontalis</li> <li>• Fasciculus uncinatus</li> <li>• Fasciculus arcuatus</li> <li>• Fibers in anterior limb of internal capsule</li> <li>• Internal and external thalamic nuclei</li> </ul>	<ul style="list-style-type: none"> <li>• The fasciculi arcuatus and occipito-frontalis are affected in both hemispheres</li> <li>• The lesion of the left inferior frontal gyrus only affects the fasciculus uncinatus and fibers of the corpus callosum rostrum and genu</li> <li>• "In good order are the lenticular and caudate nucleus and the temporo-occipital lobe. My (J.J. Dejerine's, annotation ours) cases show that Broca aphasia, i.e. motor aphasia with impaired inner language but preserved understanding is caused by a lesion of the anterior language zone, i.e. the Broca zone, and no lesions are found neither in the posterior Wernicke language region nor in the basal ganglia (Klippel protocols 1908, p. 1009)"</li> </ul>
<i>Case "Leudot": cortical lesion of the left parietal lobe</i>			
<ul style="list-style-type: none"> <li>• 73 yrs. old patient with sensory aphasia and pronounced paraphasia, alexia</li> <li>• Agraphia in dictation and spontaneous writing, very erroneous copying of script (each letter appears drawn)</li> <li>• Probably hemianopia to the right</li> </ul>	<ul style="list-style-type: none"> <li>• Angular gyrus, inferior parietal lobule</li> <li>• Inferior two third of the postcentral gyrus</li> <li>• Posterior part of the insular convolution</li> <li>• Posterior part of the superior and medial temporal gyri</li> </ul>	<ul style="list-style-type: none"> <li>• Retrolenticular and posterior limb of the internal capsule</li> <li>• Tapetum</li> <li>• Forceps posterior and splenium of corpus callosum</li> <li>• Pulvinar, external thalamic nucleus corpus geniculatum laterale, partial degeneration of the corpus geniculatum mediale</li> <li>• Corpora quadrigemina</li> <li>• Superior and anterior part of the ruber nucleus</li> <li>• External two fifth of the pes pedunculi</li> </ul>	<ul style="list-style-type: none"> <li>• The parietal lobe contains cortico-rubral projection fibers that partially run through the retrolenticular segment and partially through the posterior limb of the internal capsule</li> <li>• The parietal lobe also radiates cortico-thalamic projection fibers</li> <li>• A parietal lobe lesion causes degeneration of short parietal association fibers and long association fibers such as the fasciculus longitudinalis inferior (whose degenerated fibers can be traced into the superior temporal gyrus) and the tapetum (whose degenerated fibers are found within the fasciculus occipito-frontalis)</li> </ul>
<i>Case "Heudebert": cortical lesion of the left temporo-occipital lobe</i>			
<ul style="list-style-type: none"> <li>• Mutistic patient with total [global] aphasia</li> <li>• Full agraphia and alexia</li> </ul>	<ul style="list-style-type: none"> <li>• Two inferior quarters of the precentral gyrus</li> <li>• Left occipito-temporal lesion with destruction of the middle and posterior parts of the medial and inferior temporal gyri, the inferior part of the angular gyrus, the external side of the temporal lobe until the fusiform lobe and medially until the ventricular ependyma</li> <li>• Posterior and inferior segments of the corona radiata</li> </ul>	<ul style="list-style-type: none"> <li>• Anterior two fifth of the posterior limb of the internal capsule</li> <li>• Medial two fifth of the pes pedunculi</li> <li>• Retro- and sublenticular segments of the internal capsule and the temporo-pontine tract</li> <li>• Stratum zonale of the superior and posterior part of the external thalamic nucleus, the pulvinar, the posterior and superior part of the internal thalamic nucleus, corpus geniculatum laterale</li> <li>• Fasciculus temporo-thalamicus Arnold</li> <li>• Fasciculus Türck in its course through the internal capsule</li> <li>• Fasciculus uncinatus till the anterior insular convolution and the frontal <i>facies orbitalis</i></li> </ul>	<ul style="list-style-type: none"> <li>• Degeneration of the cortico-thalamic fibers to the pulvinar</li> <li>• Degeneration of the projection fibers from the cortex until the corpus geniculatum laterale</li> <li>• Degeneration of the fibers of the lateral one fifth of the pes pedunculi</li> </ul>

cortical lesions in the left hemisphere (Dejerine & Dejerine-Klumpke, 1901). The IFOF was not explicitly described by the Dejerines, even though they noted that fibers of the FOF passed through the external capsule.

### 3.3. The inferior longitudinal fasciculus

The ILF (Fig. 3) connects the temporal and occipital lobes, running along the lateral walls of the inferior and posterior cornua of the lateral ventricle. Its first description is attributed to Burdach (Catani, 2010, p. 6; Dejerine & Dejerine-Klumpke, 1895, p. 765). The ILF transports visual information from the occipital region to the temporal lobe and probably plays an important role in visual object recognition and in the association of visual object representations with their lexical labels (Catani & Mesulam, 2008). The existence of the ILF in humans that is independent from a putative occipito-temporal fasciculus (fibers in the fusiform gyrus) remains controversial, with some favoring the term “occipitotemporal projection” over ILF (Bergmann & Affi, 2005).

The ILF was listed in the Dejerines' anatomy book (Dejerine & Dejerine-Klumpke, 1895, p. 765ff) and in the chapter detailing the long association fibers that unite the Dejerines' language zone with more remote cortices (Mirailhé, 1896, p. 114ff) The ILF was described as the tract that unites the occipital with the temporal lobe, and the ILF belongs to the language zone only with those fibers that project to the first temporal convolution. It was also written that the ILF is affected in pure alexia (Mirailhé, 1896, p. 115). Interestingly, descriptions of trajectories to the angular gyrus are missing from the chapters about the ILF (Dejerine & Dejerine-Klumpke, 1895; Mirailhé, 1896, p. 765ff). Only on online-page 768 (Dejerine & Dejerine-Klumpke, 1895), the crests of the ILF's convex face at the level of the angular gyrus are mentioned without saying that the ILF releases fibers into it. This is remarkable, because the angular gyrus was seen as the visual center for words and letters and its lesion was considered responsible for alexia with agraphia (Dejerine, 1891). Pure alexia, i.e., alexia without agraphia, was attributed to lesions in the lingual lobe, fusiform lobe, cuneus, and the tip of the occipital lobe as well as a strongly marked atrophy of the optical radiations in the fold of the corpus callosum (Dejerine, 1892;



**Fig. 3.** Drawing of an alcohol-fixed and dissected brain in which the cortices of the limbic lobe and the fusiform lobule were removed to show the ILF (Flī, red circle) and the UF (Fu, red circle). For better orientation, further abbreviations such as U (uncinate gyrus), K (calcarine sulcus) and Fus (fusiform lobule) are given (Dejerine & Dejerine-Klumppke, 1895, p. 750). For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Dejerine & Dejerine-Klumpke, 1895, Figs. 396 and 397 in p. 798) leading to the disconnection of the left and right visual areas from the visual verbal center (i.e. the angular gyrus) and also affected the optic radiation inputs to the left visual area. In conclusion, the ILF was part of the Dejerines' language zone but inconsistencies exist concerning the ILF's role in pure alexia with its apparently missing trajectories to the angular gyrus.

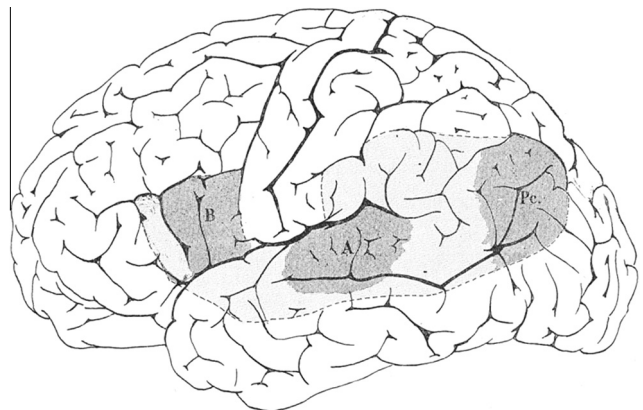
### 3.4. The uncinata fasciculus

The UF was discovered by Reil (Catani, 2010, p. 6; Dejerine & Dejerine-Klumpke, 1895, p. 753), and it connects the temporal lobe with the orbitofrontal region including the inferior frontal gyrus. The UF likely plays an important role in language processing, particularly lexical retrieval, semantic associations, and aspects of naming (e.g., naming of actions) (Catani & Mesulam, 2008).

Only indirect evidence suggests that the Dejerines may have considered the UF as a part of their language zone concept. They found a degenerated UF in patients with Broca's (Table 1: case Moriceau, pp. 147) and global aphasia (Table 1: case Heudebert; Dejerine & Dejerine-Klumpke, 1901, pp. 138). They also described the tract's course as a connection between the pars triangularis of the third frontal convolution (F3) and the temporal lobe pole together with the anterior parts of the medial and superior temporal gyri (Fig. 1). Therefore, the Dejerines may have assumed that this tract participated in language processing, as they claimed that any lesion of fibers going to or from the pars triangularis and opercularis could cause aphasic symptoms.

### 3.5. The Dejerines' concept of the "zone de langage"

The Dejerines understood that the association fibers in the left hemisphere formed an intricate network that could not be separated from the cortical language centers, including Broca's area [F3, Brodmann area (BA) 44], Wernicke's area (BA 22), and the angular gyrus (BA 39) (Mirail , 1896, p. 112). Apparently, the name "zone de langage" was adapted by the Dejerines from Sigmund Freud (1856–1939) (Mirail , 1896, p. 93). The "zone de langage" (Fig. 4) extended beyond the classical language centers described by Broca and Wernicke, adopted the form of a horseshoe around the rolandic operculum, and extended into the second frontal and temporal gyri (Mirail , 1896, pp. 107–110). The concept of an interconnected language zone separated the Dejerines from the doctrine of Jean-Martin Charcot (1825–1893), who postulated the existence of largely autonomous centers for different language modes (Mirail , 1896, p. 90).



**Fig. 4.** The Dejerines' language zone of 1901: (A) Wernickés area or auditive image center; and (B) Broca's area or motor articulation image center; Pc, visual image center of words (Dejerine & Dejerine-Klumpke, 1901, p. 247).

### 3.6. What is language?

The Dejerines understood that “*langage interieur*” (the silent thinking of sound, motor articulation, and visual word images) arises as a network function, rather than from a distinct cortical area. The recall of all three types of language processes is indispensable for intact inner language. The entire word image (“*la notion du mot*”) can only arise if all three aspects are simultaneously recalled, and if information was quickly exchanged between image centers. If one aspect is lost, the entire image was altered, and inner language was impaired (Dejerine & Dejerine-Klumpke, 1901, pp. 247–252).

### 3.7. What was aphasia for the Dejerines?

The Dejerines' concept of aphasia consisted of total (global) aphasia if the entire language zone was destroyed. Partial aphasia was divided into motor or sensory aphasia, depending on the lesion location in the anterior or posterior part of the language zone. Motor and sensory aphasia were further subdivided into cortical or non-cortical aphasias based on whether the lesion was localized in the convolutions portion of the language zone (i.e., cortical grey matter + intracortical association and tangential fibers + projection, commissural and association fibers belonging to the convolutions). A. Dejerine-Klumpke explained:

*“The definition of a cortical lesion was never exclusively applied to the grey matter, i.e. the cortex, but to the convolution, i.e. the cortex and the underlying white matter. The term cortical lesion refers to the whole convolution, in contrast to subcortical lesions that affect the centrum ovale and the central lesions that affect the basal ganglia. It is these cortical lesions that were named peripheral lesions by Charcot”* (Klippel, 1908, p. 999).

The Dejerines noted that a lesion at any point within their defined language zone did not cause restricted language impairment. Instead, it hampered all language modes, particularly the mode whose anatomical image center was closest to the lesion site. A subcortical or pure aphasia was caused by lesions to the association fibers underneath the convolutions. The division between cortical and pure aphasia could also be made on clinical terms. Patients with pure aphasia could think with their word images, i.e., the inner language was preserved (tested with Lichtheim's way by letting the patient squeeze the hand of the examiner as often as the number of syllables that were contained in the requested word). Patients with lesions in their language zone (cortical aphasia) could think with ideas (or perhaps concepts, comment ours) but not with word images (Dejerine & Dejerine-Klumpke, 1901, p. 249).

## 4. Discussion

The Dejerines first described degenerations of the SLF/AF, UF, ILF, and FOF in aphasia patients. Meynert, the great white matter anatomist who also published about the ILF and FOF before the Dejerines, did not mention any fiber tracts in his publications related to aphasia (1866, 1868). Wernicke described his *fibrae propriae* as the anatomical link between Broca's and Wernicke's areas in 1874, but let the fibers converge in the insula and was not to correct their anatomical course before 1908. While the Dejerines were not the first to describe the dorsal and ventral pathway concept of language (e.g. Friederici & Gierhan, 2013), their description of the circular arrangement of fasciculi around the insula affected in aphasia patients (see also Figs. 1–3) is reminiscent of the dorsal and ventral pathways connecting frontal and temporo-parietal language regions.

The notion that von Monakow was the first to publish that the (SLF)/AF connects Broca's and Wernicke's areas may have arisen because of the wider distribution of Nothnagel's work in German-speaking countries (*Specielle Pathologie und Therapie*, 1895–1905, 24 volumes), which contained von Monakow's first edition “*Gehirnpathologie*.” Wernicke cited von Monakow's drawings, in which von Monakow illustrated what the Dejerines had said about the language zone. Wernicke (1908) was subsequently cited by Geschwind (1967, p. 453), who attributed the AF description in relation to language to von Monakow. This assignment was later adopted by other authors including Catani and Mesulam (2008).

Wernicke compared the cortical extension of the Dejerines' language zone with the zone described by von Monakow. This comparison illustrated how tightly related the concepts of von Monakow and the Dejerines were. This is an interesting observation from an historical perspective because J.J. Dejerine was perceived as a localizationalist, while von Monakow was perceived as a holist. This difference in perception may have contributed to the Dejerines' minor reception in 20th century aphasia research. In this regard, the “hot summer of aphasiology” meeting in 1908 in Paris is worth mentioning, because it was initially perceived to emphasize the differences between holistic and localizationistic aphasia models. For example, the anatomic aphasia model of Pierre Marie (1853–1940), another famous protagonist of holistic views, differed at first sight from the Dejerines' language zone because Marie denied a role of F3 and assigned importance to the middle third of the (left) hemisphere in the genesis of aphasia (Klippel, 1908, p. 977). However, Marie's and the Dejerines' language zone concepts had significant commonalities because both emphasized on the role of subcortical structures, mainly white matter, in the genesis of aphasia. By excluding Broca's area from aphasia (Marie) and admitting that lesions in subcortical structures can also cause symptoms of Broca's aphasia (Dejerines), both opponents also clearly limited the role of Broca's area (BA 44). Commonalities also arose between the Dejerines' language zone and other holistic language zone models, such as the one by S. Freud. Freud (1891) criticized the Wernicke-Lichtheim scheme (p. 10), the classification into cortical and conduction aphasia (p. 19), the concept of inner language (p. 20), and the explanation that the variety of aphasias can be explained by different localizations of destructive lesions (pp. 20, 31). However, he accepted that lesions at any point within the language zone affected all language functions but to a different extent. He was herewith in concordance with the Dejerines' and with the current view, of a functional network of language-related brain regions. An interesting overview over the metamorphose of the language zone from Franz Joseph Gall (1758–1828) to Wilder Penfield (1891–1976) is given elsewhere (Lecours & Lhermitte, 1979, p. 297ff).

In conclusion, the Dejerines' first description of the (SLF)/AF as the fasciculus uniting Broca's area, Wernicke's area, and a visual image center in the angular gyrus, as well as the degeneration of an ensemble of fasciculi in aphasia patients should be acknowledged. The turn of the 20th century saw various language models incorporating interconnected brain areas. However, the Dejerines included precise language- and aphasia-related anatomical descriptions that represented an expansion of pure localizationistic models while retaining a functional aspect. The pendular discussion about holistic versus localizationistic views in the 20th century somewhat obstructed a clear vision of aphasia concepts. Indeed, despite the inaccuracies of the Dejerines and their contemporaries, these conflicting models contain more agreement than disagreement over the importance of subcortical structures, the limited importance of cortical Brodmann area 44 in aphasia, and the current network approach of language-related brain regions.



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## Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.bandl.2013.05.019>.

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