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Review Article

Clinical implications of sagittal stratum damage: Laterality, neuroanatomical developmental considerations, and functional outcomes

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ABSTRACT

Background: The sagittal stratum (SS) is an important white matter (WM) structure that provides the anatomic substrate for cortico-cortical and cortico-subcortical axial interconnections necessary to overcome sensory, cognitive and motor processes. SS damage due to diseases or surgical lesions often results in significant functional losses, mainly involving serious language, visual processing, and cognitive deficits. These risks are maximized in older adults because of age-related WM degeneration.

Methods: In this comprehensive review, the research aims to synthesize research conducted on anatomy-functional roles that concern the SS, damage, and surgical outcomes. This would then separate studies that employed high neuroimaging advanced techniques, such as diffusion tensor imaging, combined with intraoperative mapping performed during awake surgery. Key attention areas will, therefore, be trajectories pointing toward lateralization of the SS tracts, age-related vulnerabilities, and the effectiveness of surgical strategies in preserving SS integrity.

Results: The review indicates that the pattern of SS damage is associated with lateralized deficits stemming from left-sided lesions, while language and vision are affected by right-sided. Older adults, already bearing significant WM degeneration, therefore, stand at a significantly greater risk of overall cognitive decline from compounding losses due to SS damage. However, advanced neuroimaging tools and refined surgical techniques have made the preservation of SS pathways much more effective, reducing long-term deficits.

Conclusion: Intraoperative preservation of SS integrity is crucial for the reduction of functional deficits and enhancement of the outcomes. Customized surgical techniques that consider tract lateralization and age-related changes are required. Further research in this area is needed.

Keywords: Cognitive functions, Neuroimaging, Sagittal stratum, Surgical outcomes, White matter tracts

INTRODUCTION

The sagittal stratum (SS) fills a very impressive crossing of neural pathways—refined in the nexus between the brain's white matter (WM) architecture and the orchestration of many cognitive and sensory processes. Having a location on crossroads, basically, of polygon shape, the SS is formed by inferior frontal-occipital fasciculus (IFOF), Optic radiation (OR), middle longitudinal fascicle (MdlF), and other associational fibers to guarantee communication between the disparate regions of the brain's ipsilateral hemisphere.[8] Though it is an important structure, little has been known about the SS until recent times, with many of its functional implications illuminated through advanced anatomical and imaging techniques. A better understanding of the SS is not merely an academic pursuit but a clinical imperative, given its role in key processes such as language comprehension, visual processing, and memory consolidation.

Recent research has underscored the profound clinical ramifications of SS damage, especially in neurosurgical contexts. The SS is a structure of interest and concern during surgical interventions since complex, multi-layered organization can lead to inadvertent damage with serious postoperative deficits, such as visual field cuts, language impairments, and disruptions in cognitive functions, which all argue for scrupulous surgical planning and execution.[21] The direct electrical stimulation (DES) of the SS during awake surgeries established more about its functions and showed that the stratum is implicated in more vital activities than simple sensory processing. For instance, the deficit in semantic paraphasia and other high-order linguistic functions related to surgical damage of the SS during the resection of brain tumors suggests a possible critical role for this stratum in both verbal and nonverbal human communication.[28] Furthermore, the SS itself is dynamic across the lifespan. The effects of aging-related changes on the structural integrity of the SS can be deep on its functional output; hence, the SS is one of the important targets for understanding the neurobiological substrate underlying cognitive decline in aging populations. An embryological perspective provides more about these changes, which allows for anticipating vulnerabilities that may predispose an individual to certain neurological conditions or a higher likelihood of their occurrence later in life. Essentially, the crossroad of anatomical, functional, and developmental perspectives provides an overarching framework, not only in disease but also in the whole spectrum of human development and aging, for understanding the SS.[8,21,28] The present paper seeks to delve deep into the clinical implications of SS damage and how this complex structure impacts functional outcomes in view of age-related transformations. In this respect, the current study gathers insights from anatomical dissections, clinical case studies, and embryological theories while seeking to provide an inside view into the SS with its complexities, vulnerabilities, and other key features that play a central role in the overall functioning of the brain.

METHODS

Search strategy

In this context, a critical review is given of the clinical implications due to the damage to the SS in terms of functional outcomes and considerations of age. Either published research, blended in data from case literature, was coordinated to offer views across the topic. A comprehensive search was conducted across multiple databases, including PubMed, Scopus, and Web of Science. The search strategy was developed to capture a broad range of studies about the anatomy and its functional roles, the clinical significance of SS, and different neurological conditions. The keywords used to search the literature on the SS, WM tracts, inferior frontal-occipital fasciculus, OR, MdlF, clinical implication, functional outcome, parallel processing, and age-related change involved Boolean operators for the critical refining of the search in order to ensure all relevant literature was included.

Inclusion and exclusion criteria

The inclusion criteria in this umbrella review were chosen so that only the studies that provided relevant and high-quality insights regarding the position of the SS were included. Specifically, those using human subjects or human brain specimens were covered in order to have direct general applicability to all potential clinical practices. The studies included were human subject studies investigating the structure of the SS, its functional significance, and its clinical implications, with a focus on disruption to this structure and the ensuing effects on cognitive and sensory functions.

The preferential selection has focused on original research, case reports, retrospective studies, systematic reviews, as well as other relevant observational studies, through which many SSs and related WM tracts' insights could be better uncovered. Specifically preferred are studies that provide data on the functional outcomes associated with SS damage in general and age-related changes, visual, language, and cognitive impairments. Exclusion criteria were applied for relevance and applicability to ensure only studies conducted on matter tracing the SS or its related deep WM tracts. Furthermore, included were studies that focused on this area rather than more general studies looking at it as an entity. Studies published in another language that did not offer an English version for translation were also ruled out to remove the possibility of flawed interpretation and to conduct an exhaustive review. Finally, studies performed exclusively in animals will be excluded, as there should be a clear relation in content to human anatomy or clinical practice, so it will be applicable for the important aim of offering knowledge that will be useful for understanding human neurological function and clinical outcomes.

Data extraction and analysis

The extraction of data was done very systematically, aiming at a full and accurate representation of the study findings from the selected studies. The extracted data included characteristics of the main studies, such as the author, year of publication, country, design, populations under study, and patient demographics, which formed a general background for each study. More so, comprehensive information was acquired regarding the point of focus anatomically, which, in this case, was centered on WM tracts within the SS and their interconnectivity in an attempt to understand the structural and functional role of these tracts.

Further, the functional roles of the SS and its related WM tracts were another critical section with regard to data extraction and allowed the identification of contributions that the SS made to various cognitive and sensory processes. These contributed to establishing relationships between anatomical structures and clinical outcomes.

Consequently, there were carefully documented, in many articles, a number of clinical implications of damage to the SS, particularly regarding visual, language, and cognitive functions, along with age-related changes that could exacerbate noted effects. Besides that, it was also documented which neuroimaging and intraoperative techniques the studies used in order to determine the methodologies that went into the investigation of the SS. This was an important piece of information since it would tell how the anatomical and functional data were obtained and the obtained findings' reliability.

Two researchers independently reviewed the analysis for accuracy and appropriateness. Any disparity in the reflections regarding the reviews was discussed, and mutual consent led to the production of the final synthesis, which rests on the foundation of accurate and agreed-upon data. Qualitative synthesis was performed with an emphasis on the identification of common themes and patterns such that the results of all these studies could be comprehensively understood in terms of the role of the SS in neurological function and the clinical implications of damage to the SS.

Quality assessment

The tool Risk of bias in non-randomized studies(ROBINS-I) was used to determine that the studies included do not have a biased nature so that the findings can be generalized and have validity. The quality assessment is attached in Table 1. Two independent assessors evaluated the quality of the included studies using the ROBINS-I tool. Any discrepancy in quality between the reviewers was resolved by discussion among themselves. These evaluations assigned every study to the low, moderate, severe, or critical categories of risk of bias. Only the studies judged to have a low or, at most, moderate risk of bias were carried forward for the final syntheses so that the conclusions were based on the most reliable evidence.

Synthesis of results

These findings were synthesized into common themes and patterns across the data in a qualitative manner. Studies were grouped with respect to functional outcomes, such as visual, language, and cognitive, and the effects of damage to SS, with special emphasis on age-related considerations. The synthesis would establish a deep understanding of the role SS plays in neurological functioning and the clinical implications of its damage in relation to neurosurgical interventions.

Ethical considerations

Since this was a review of available literature, no new data was to be collected from human subjects; therefore, no ethical approvals were needed. The included studies were checked for reporting that they had adhered to ethical standards.

RESULTS

Demographic and clinical characteristics

The studies included in this review span a diverse demographic range, encompassing patients of various ages, genders, and clinical conditions, all of which provide a broad basis for understanding the implications of SS damage [Table 2].[1-4,6,7,9-17,20,22,23,25-27,30,31] The demographic data reveal that most patients involved in the studies were middle-aged adults, with mean ages ranging from 38 to 45 years across different studies. This age bracket was considered of particular interest because it covered that time window in life when the interplay between changes due to WM aging and those due to damage from disease is at its peak. Most of the patients in both populations were right-handed, with few being left-handed, and included both males and females; therefore, generalization of the findings would go for all subgroups.

These demographic findings are important, as they suggest that age, handedness, and baseline cognitive function could all be critical modifiers of the functional outcomes after SS damage and may affect the effectiveness of surgical interventions. Older patients, in particular, could be more sensitive to long-term risks for chronic cognitive decline due to added effects from the degeneration of WM with aging on top of disease-induced damage.

Anatomical organization and connectivity

The SS contains some WM tracts of key interest in cognitive and sensory processing. Among these, OR assumes a special position in relation to visual processing [Figure 1]. They

Table 1: Risk of bias assessment using ROBINS-I tool of the included studies.

	Risk of bias assessment						
Authors	**Confounding**	**Selection of patients**	**Classification of interventions**	**Deviations from intended interventions**	**Missing data**	**Measurement of outcomes**	**Selection of reported results**
Wedeen *et al.* (2012)	Moderate	Moderate	Low	Low	Moderate	Low	Moderate
Robles *et al.* (2022)	Serious	Moderate	Low	Low	Moderate	Moderate	Serious
Di Carlo *et al.* (2019)	Low	Moderate	Low	Low	Low	Low	Moderate
Chan-Seng *et al.* (2014)	Moderate	Moderate	Low	Low	Moderate	Low	Moderate
Wu *et al.* (2016)	Moderate	Moderate	Low	Low	Low	Low	Moderate
Herbet *et al.* (2017)	Moderate	Moderate	Low	Low	Moderate	Low	Moderate
Chen *et al.* (2020)	Moderate	Moderate	Low	Low	Low	Moderate	Moderate
Duffau *et al.*, (2005)	Moderate	Moderate	Low	Low	Low	Low	Moderate
Duffau *et al.*, (2008)	Moderate	Moderate	Low	Low	Low	Low	Moderate
Maldonado *et al.* (2011)	Moderate	Moderate	Low	Low	Low	Low	Moderate
Giedd *et al.* (1999)	Moderate	Moderate	Low	Low	Low	Low	Moderate
Lebel *et al.* (2008)	Moderate	Moderate	Low	Low	Low	Low	Moderate
Mukherjee *et al.* (2001)	Moderate	Moderate	Low	Low	Low	Low	Moderate
Paus *et al.* (1999)	Moderate	Moderate	Low	Low	Low	Low	Moderate
Eichert *et al.* (2019)	Moderate	Moderate	Low	Low	Low	Low	Moderate
Hosoya *et al.* (1998)	Moderate	Moderate	Low	Low	Low	Low	Moderate
Gil-Robles *et al.* (2013)	Moderate	Moderate	Low	Low	Low	Low	Moderate
Latini *et al.* (2017)	Moderate	Moderate	Low	Low	Low	Low	Moderate
Berro *et al.* (2021)	Moderate	Moderate	Low	Low	Low	Low	Moderate

conduct visual information from the lateral geniculate nucleus to the visual cortex; the feature of laterality is notable here. In the left hemisphere, the OR processes information from the right visual field, and in the right hemisphere, that of the left. Lateralization, on the other hand, ensures that visual input from the contralateral visual field for both hemispheres is integrated in order to result in coherent visual perception.

Another critical tract in the SS is the inferior longitudinal fasciculus, which interconnects the occipital and temporal lobes. This kind of interconnection may be relevant to the procedures of visual identification and memory integration. Interestingly, the participation of the left ILF is overwhelmingly dominant in lexical access and linking faces to their names. In contrast, right ILF involvement can include nonverbal semantic processing and emotional recognition; it participates in face recognition and visual memory, predominantly across individuals with atypical linguistic lateralization, such as left-handers.[4]

The inferior frontal-occipital fasciculus forms the ventral pathway of visual stimulation and provides a critical route for the integration of visual stimuli with past experiences stored as conceptual knowledge. The IFOF subserves both verbal and nonverbal semantic processes, although it is dominant on the left side for language comprehension and visual-language integration. However, the right IFOF has a greater role in nonverbal tasks, interprets facial expressions, and recognizes objects.[2]

The other important constituents of the SS include the superior longitudinal fasciculus (SLF) and the arcuate fasciculus (AF). These tracts are fundamental ways of interconnecting language-related areas to support cognitive functions such as spatial working memory and social cognition. For example, the left SLF is heavily involved in language processing, specifically phonological and articulatory functions. In contrast, the right SLF is involved in social cognition and emotional regulation, with changes in this tract contributing to conditions such as social anxiety disorder.[2,29]

Functional implications of SS damage

Damage to the SS and its associated tracts can cause substantial functional impairments, although the specific outcomes often depend on the laterality of the affected tracts [Table 3].[1,2,4,13,29] The OR are part of the SS and are significant in visual processing by transmitting information from the lateral geniculate nucleus to the visual cortex. The left OR mainly processes the right visual field, and the right OR processes the left visual field. This lateralization is what ensures each hemisphere integrates the contralateral input to light for coherent visual perception. These tracts can be damaged to cause visual field deficits, such as quadrantanopia or hemianopia, depending on the side of the lesion.[1]

Table 2: Comprehensive data extraction and analysis of studies investigating SS damage: Anatomical, functional, and surgical outcomes.

Study ID	Author(s)	Country	Year
1	Fernández Coello *et al.*[12]	Spain, France, Italy, Japan	2013
2	Rolland *et al.*[27]	France	2018
3	Berro *et al.*[3]	France	2021
4	Robles *et al.*[26]	USA	2021
5	Chan-Seng *et al.*[6]	France	2014
6	Wu *et al.*[31]	China	2016
7	Latini *et al.*[17]	Sweden	2017
8	Herbet *et al.*[15]	France	2017
9	Chen *et al.*[7]	China	2020
10	Duffau *et al.*[9]	France	2005
11	Duffau *et al.*[10]	France	2008
12	Maldonado *et al.*[22]	France	2011
13	Eichert *et al.*[11]	United Kingdom	2019
14	Hosoya *et al.*[16]	Japan	1998
15	Gil-Robles *et al.*[14]	Spain	2013
16	Wedeen *et al.*[30]	USA	2012
17	Mukherjee *et al.*[23]	USA	2001
18	Lebel *et al.*[20]	Canada, UK, Belgium	2008
19	Paus *et al.*[25]	Canada, USA	1999
20	Giedd *et al.*[13]	USA, Canada	1999

Study ID	Author(s)	Study type	Patient demographics
1	Fernández Coello *et al.*[12]	Case Report	41-year-old male right-handed with a low-grade glioma in the right basal temporo-occipital region.
2	Rolland *et al.*[27]	Case Series	14 patients (9 men, 5 women); Mean age: 44 years (range 17–67); all underwent awake surgery for right IPL gliomas. All patients but 1 were right handed
3	Berro *et al.*[3]	Retrospective observational study	17 patients (6 males, 11 females); Mean age: 38 years (range 31–52); All underwent awake surgery for diffuse low-grade gliomas involving the right SS. 14 right-handed, 2 lest-handed and one ambidextrous
4	Robles *et al.*[26]	Cohort Study	109 participants (46 females, 63 males); Ages 18–77 (Mean age: 40±17 years); All had mild TBI and were assessed within~1 week and~6 months postinjury.

(Contd...)

Table 2: *(Continued)*

Study ID	Author(s)	Study type	Patient demographics
5	Chan-Seng *et al.*[6]	Case Series	8 patients (6 males, 2 females); Mean age: 41.7 years (range 32–61 years); all had WHO Grade II glioma involving the left SS.
6	Wu *et al.*[31]	Cross-sectional study	10 subjects (3 males, 7 females), aged 23–40; NTU -90 template of 90 subjects, aged 18–60.
7	Latini *et al.*[17]	Anatomical and DTI Study	14 postmortem human brains for dissection; 24 right-handed healthy volunteers for *in vivo* DTI; Age range: 21–28 years.
8	Herbet *et al.*[15]	Retrospective observational study	13 patients (8 males, 5 females); Mean age: 44.7 years (range 24–67 years); All had right low-grade gliomas affecting or near the IFOF.
9	Chen *et al.*[7]	Cross-sectional study	70 participants (23 healthy controls, 25 with WMH-normal cognition, 22 with WMH-MCI); Age range 50–80 years.
10	Duffau *et al.*[9]	Retrospective observational study	17 patients (11 males, 6 females, ages 17–52)
11	Duffau *et al.*[10]	Retrospective cohort study	115 patients (69 males, 46 females); Mean age: 35 years (range 17–60 years); All had WHO Grade II gliomas in the left dominant hemisphere
12	Maldonado *et al.*[22]	Retrospective case series	11 patients (4 males, 7 females), Mean age: 45±12.5 years; all had gliomas involving the SMG Right handed adult
13	Eichert *et al.*[11]	Comparative Neuroanatomy	Human: 25 subjects (ages 25–35) 22 right handed, Macaque: 4 subjects (1 female, age at death range 4e14 years)
14	Hosoya *et al.*[16]	Cross-sectional study	Eight normal volunteers (mean age 33 years) and seven patients with brain edema (mean age 57 years)
15	Gil-Robles *et al.*[14]	Case series	Three right-handed patients (37-year-old male, 64-year-old female, 60-year-old male) with brain lesions in the left basal posterotemporal region
16	Wedeen *et al.*[30]	Diffusion MRI Study	Human subjects, nonhuman primates (rhesus monkey, owl monkey, marmoset, and galago)
17	Mukherjee *et al.*[23]	Cross-sectional Retrospective Study	153 children (95 boys, 58 girls; age range, 1 day–11 years; mean age, 3.5 years)
18	Lebel *et al.*[20]	Cross-sectional Study	202 healthy individuals aged 5–30 years, including 98 females and 104 males
19	Paus *et al.*[25]	Cross-sectional Study	111 children and adolescents aged 4–17 years
20	Giedd *et al.*[13]	Longitudinal MRI Study	145 healthy children and adolescents (89 males) with ages ranging from 4.2 to 21.6 years
Study ID	**Author(s)**	**Scope of study**	**Anatomical focus**
1	Fernández Coello *et al.*[12]	To explore the role of the right inferior longitudinal fasciculus (ILF) in visual hemiagnosia during glioma surgery.	Right basal temporo-occipital region; Fusiform gyrus
2	Rolland *et al.*[27]	Investigating the functional connectivity of the right IPL during awake surgery for gliomas.	Right IPL
3	Berro *et al.*[3]	Investigation of the anatomo-functional organization of the right SS in patients undergoing awake brain surgery for low-grade glioma.	Right SS, including surrounding pathways
4	Robles *et al.*[26]	Investigates how age, sex, and CMBs contribute to WM degradation following TBI.	CC, Superior Longitudinal Fasciculus (SLF), Inferior Longitudinal Fasciculus (ILF), Middle Longitudinal Fasciculus (MdLF), Inferior Occipitofrontal Fasciculus (IOFF), Superficial Frontal and Temporal Fasciculi

(Contd...)

Table 2: *(Continued)*

Study ID	Author(s)	Scope of study	Anatomical focus
5	Chan-Seng *et al.*[6]	Explores the functional anatomy and surgical outcomes of gliomas involving the left SS.	Left SS
6	Wu *et al.*[31]	Investigates the subcomponents and connectivity of the Inferior Fronto-Occipital Fasciculus (IFOF) using DSI and tractography.	Inferior Fronto-Occipital Fasciculus (IFOF)
7	Latini *et al.*[17]	Investigates the segmentation and connectivity of the Inferior Longitudinal Fasciculus (ILF).	Inferior Longitudinal Fasciculus (ILF)
8	Herbet *et al.*[15]	Investigates the role of the right Inferior Fronto-Occipital Fasciculus (IFOF) in nonverbal semantic cognition.	Right Inferior Fronto-Occipital Fasciculus (IFOF)
9	Chen *et al.*[7]	Investigates the microstructural disruption in the right inferior fronto-occipital fasciculus (IFOF) and inferior longitudinal fasciculus (ILF) related to WMH and cognitive impairment.	Right inferior fronto-occipital fasciculus (IFOF) and inferior longitudinal fasciculus (ILF)
10	Duffau *et al.*[9]	Investigating the anatomo-functional connectivity of the semantic system using cortico-subcortical electrostimulations during glioma surgery	Dominant hemisphere (frontal, temporal, insular lobes)
11	Duffau *et al.*[10]	Examines the role of intraoperative subcortical stimulation mapping in preserving language pathways during the resection of Grade II gliomas in the left dominant hemisphere	The left dominant hemisphere, particularly areas involved in language
12	Maldonado *et al.*[22]	Investigated whether the left superior longitudinal fasciculus (SLF) is involved in language semantics using intraoperative brain mapping during glioma resection	Left superior longitudinal fasciculus (SLF), particularly under the SMG
13	Eichert *et al.*[11]	Analysis of the AF in humans and macaques	AF
14	Hosoya *et al.*[16]	Investigating the MRI anatomy of WM layers around the trigone of the lateral ventricle, including the SS	WM around the trigone of the lateral ventricle
15	Gil-Robles *et al.*[14]	Investigating the functional anatomy of visual recognition and picture naming by combining tractography with intraoperative brain stimulation	BPTC
16	Wedeen *et al.*[30]	Investigating the geometric structure of brain fiber pathways across multiple species using DSI	Cerebral WM, with a focus on the SS and related tracts
17	Mukherjee *et al.*[23]	Characterizing the maturational changes in water diffusion within central gray matter nuclei and WM pathways during childhood using DTI	CC, Internal Capsule
18	Lebel *et al.*[20]	Examining the trajectory of microstructural brain development from childhood to adulthood.	WM tracts across the brain, including those within the SS
19	Paus *et al.*[25]	Investigating the structural maturation of neural pathways in children and adolescents using *in vivo* MRI techniques	WM tracts, with a focus on the internal capsule and AF, relevant to the SS
20	Giedd *et al.*[13]	Investigating the structural maturation of the brain during childhood and adolescence using longitudinal MRI data	WM tracts, with relevance to the SS
Study ID	**Author(s)**	**Specific WM Tracts**	**Laterality of the Tract (Right/Left/Bilateral)**
1	Fernández Coello *et al.*[12]	Inferior Longitudinal Fasciculus (ILF)	Right

(Contd...)

Table 2: *(Continued)*

Study ID	Author(s)	Specific WM Tracts	Laterality of the Tract (Right/Left/Bilateral)
2	Rolland *et al.*[27]	Superior Longitudinal Fasciculus (SLF II and III), Inferior Fronto-Occipital Fasciculus (IFOF), ORs	Right
3	Berro *et al.*[3]	ORs, Inferior Longitudinal Fasciculus (ILF), Inferior Fronto-Occipital Fasciculus (IFOF), Superior Longitudinal Fasciculus/AF (SLF/AF), Thalamocortical radiations, Auditory radiations	Right
4	Robles *et al.*[26]	ILF, MdLF, IOFF, CC (Genu, Body, Splenium), Superficial Frontal and Temporal Fasciculi	Bilateral
5	Chan-Seng *et al.*[6]	Inferior Fronto-Occipital Fasciculus (IFOF), Inferior Longitudinal Fasciculus (ILF), ORs, AF	Left
6	Wu *et al.*[31]	IFOF subcomponents I-V	Bilateral
7	Latini *et al.*[17]	Three primary ILF components: Fusiform branch, Lingual branch, Dorsolateral-occipital branch	Right
8	Herbet *et al.*[15]	Right IFOF	Right
9	Chen *et al.*[7]	Right IFOF and ILF	Right
10	Duffau *et al.*[9]	Inferior fronto-occipital fasciculus, STS	Dominant Hemisphere (likely Left)
11	Duffau *et al.*[10]	AF, Inferior Fronto-Occipital Fasciculus (IFOF), Subcallosal fasciculus, Frontoparietal phonological loop, Ventral premotor cortex fibers	Left
12	Maldonado *et al.*[22]	SLF, AF	Left
13	Eichert *et al.*[11]	AF, Inferior fronto-occipital fasciculus (IFOF), Extreme capsule	Left
14	Hosoya *et al.*[16]	Tapetum, Internal SS, External SS, Central Sagittal Lamina	Bilateral
15	Gil-Robles *et al.*[14]	Inferior Longitudinal Fasciculus (ILF), Inferior Fronto-Occipital Fasciculus (IFOF)	Left
16	Wedeen *et al.*[30]	SS, Superior Longitudinal Fasciculus (SLF), CC, CB, FX, AC	Bilateral
17	Mukherjee *et al.*[23]	CC (Genu, Splenium), Internal Capsule (Anterior, Posterior limbs)	Bilateral
18	Lebel *et al.*[20]	Inferior Longitudinal Fasciculus (ILF), Inferior Fronto-Occipital Fasciculus (IFOF), Splenium and Genu of the CC	Bilateral
19	Paus *et al.*[25]	Internal Capsule, AF, Inferior Longitudinal Fasciculus (ILF)	Left (emphasis), but primarily Bilateral
20	Giedd *et al.*[13]	WM tracts	Bilateral
Study ID	**Author(s)**	**Connectivity and pathways**	**Functional roles**
1	Fernández Coello *et al.*[12]	Connects occipital visual input to higher-level processing areas in the temporal lobe, including the hippocampus, parahippocampal gyrus, and amygdala.	ILF: Critical for object recognition, face perception, and visual memory integration.

(Contd...)

Table 2: *(Continued)*

Study ID	Author(s)	Connectivity and pathways	Functional roles
2	Rolland *et al.*[27]	The IPL connects various regions, including the SLF, IFOF, and OR, contributing to spatial awareness, language processing, and visual functions.	SLF III: Articulatory functions; SLF II: Spatial awareness; IFOF: Nonverbal semantic cognition; OR: Visual processing.
3	Berro *et al.*[3]	The SS is a polygonal neural crossroad deep on the lateral surface of the hemisphere, with significant connectivity across the occipital, temporal, and parietal lobes, linking visual, auditory, and semantic processing centers.	ORs: Visual field processing; ILF: Object recognition, face perception, visual memory; IFOF: Visual-semantic processing; SLF/AF: Spatial awareness, spatial working memory; Thalamocortical Radiations: Sensory relay, proprioception, tactile perception; Auditory Radiations: Sound localization, auditory processing.
4	Robles *et al.*[26]	Connects frontal, parietal, temporal, and occipital lobes; facilitates interhemispheric communication, visual and auditory processing, and sensorimotor integration.	ILF: Visual recognition and object identification; MdLF: Language comprehension, audiovisual integration, attentional processes; IFOF: Supports semantic processing and motor pathways; CC: Interhemispheric communication, motor coordination, sensory integration.
5	Chan-Seng *et al.*[6]	The SS is a critical region linking the occipital, temporal, and parietal lobes with the frontal lobe. The IFOF connects the frontal lobe to the occipital and temporal lobes, the ILF links the occipital and temporal lobes, the OR transmits visual information from the lateral geniculate nucleus to the visual cortex, and the AF connects the temporal lobe with the frontal regions involved in language.	IFOF: Semantic processing and visual-language integration; ILF: Visual recognition, reading, object identification; OR: Visual field processing; AF: Phonological processing, language articulation.
6	Wu *et al.*[31]	The IFOF connects various regions of the frontal lobe (superior, middle, and inferior frontal gyrus, orbito-frontal cortex, and frontal pole) with the occipital lobe (inferior, middle, and superior occipital gyrus, occipital pole, pericalcarine, fusiform gyrus), superior parietal lobe, angular gyrus, and postcentral gyrus.	IFOF-I: High-level visual processing and spatial cognition; IFOF-II: In OCD, changes in this pathway are linked to cognitive issues like executive function deficits and impaired decision-making; IFOF-III: Language processing, particularly phonological and semantic aspects; IFOF-IV and the IFOF-V might take part in the semantic processing of language, visual conceptualization, and recognition.
7	Latini *et al.*[17]	The ILF connects the occipital lobe (visual processing regions) with the anterior temporal lobe, including the fusiform gyrus, parahippocampal gyrus, and amygdala, integrating visual information with memory and emotion.	Fusiform Branch: Supports facial recognition and processing of visual stimuli related to objects; Lingual Branch: Recognition of complex visual scenes and processing visual memory; and identification of emotional facial expressions, especially in the nondominant hemisphere; Dorsolateral-Occipital Branch: Integrates visual information with spatial orientation.
8	Herbet *et al.*[15]	The right IFOF connects the occipital lobe with the frontal lobe via the temporal and parietal lobes, interfacing with areas involved in visual and semantic processing, including the fusiform gyrus, IPL, and dorsolateral prefrontal cortex.	Right IFOF: Nonverbal semantic processing, including visual-semantic associations, integrating visual stimuli with semantic knowledge, and supporting interpretation of nonverbal cues such as facial expressions and object recognition.
9	Chen *et al.*[7]	The right IFOF and ILF are major WM tracts connecting the occipital lobe to the frontal and temporal lobes. The IFOF connects frontal, parietal, and occipital regions, while the ILF connects occipital and temporal regions, integrating visual and cognitive functions.	Right IFOF: Involved in visual-semantic processing and memory integration. Right ILF: Plays a key role in visual recognition, memory, and processing of emotional and semantic content.

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Table 2: *(Continued)*

Study ID	Author(s)	Connectivity and pathways	Functional roles
10	Duffau *et al.*[9]	Connections between the posterior superior temporal regions and the IFC/DLPFC	Inferior Fronto-Occipital Fasciculus (IFOF): Facilitates the integration of visual and auditory semantic information, playing a crucial role in the comprehension of complex linguistic and nonlinguistic stimuli. STS: Involved in the processing of social and linguistic cues, contributing to the understanding of verbal and nonverbal communication. IFC/DLPFC Connection: Supports higher-level cognitive processes such as decision-making, problem-solving, and language production, particularly in the context of semantic content.
11	Duffau *et al.*[10]	These pathways connect cortical language areas, such as Broca's area, with subcortical structures and other language-related cortical regions, forming a complex network that supports language production and comprehension.	AF: Supports phonemic processing, connecting Broca's area to Wernicke's area, essential for speech production and phonological processing. Inferior Fronto-Occipital Fasciculus (IFOF): Involved in semantic processing, linking the frontal, temporal, and occipital lobes, crucial for the comprehension of meaning and integration of semantic information. Subcallosal Fasciculus: Involved in the initiation and execution of speech, particularly influencing motor planning of language. Frontoparietal Phonological Loop: Supports articulatory planning and execution, connecting Broca's area to the parietal regions involved in phonological processing. Ventral Premotor Cortex Fibers: Critical for speech motor planning, facilitating the articulation of speech sounds.
12	Maldonado *et al.*[22]	The SLF connects the frontal, parietal, and temporal lobes, including connections between the SMG and ventral premotor cortex.	SLF: Involved in phonological processing, particularly linking the SMG to the premotor cortex, supporting articulatory processing. AF: Facilitates phonemic processing, connecting Broca's and Wernicke's areas, but no role in semantics was found.
13	Eichert *et al.*[11]	The AF connects Broca's area (frontal lobe) with Wernicke's area (temporal lobe), supporting the integration of auditory and motor processes required for speech production and comprehension. The IFOF and extreme capsule are involved in linking frontal and temporal areas associated with higher-level cognitive functions.	AF: Integral for phonological processing, supporting the transformation of auditory information into articulatory movements necessary for speech. It also plays a key role in syntactic processing, allowing for the construction and understanding of complex sentence structures. The lateralization of the AF, particularly in the left hemisphere, is crucial for efficient language processing, enabling the dominance of language functions in one hemisphere, which is thought to enhance processing speed and accuracy. Inferior Fronto-Occipital Fasciculus (IFOF): Supports the integration of visual information with semantic content, contributing to the comprehension of language that involves visual cues, such as reading and interpreting gestures. Extreme Capsule: Facilitates rapid communication between Broca's and Wernicke's areas, playing a role in the real-time processing of speech sounds and the generation of appropriate verbal responses.
14	Hosoya *et al.*[16]	The tapetum, internal SS, and external SS form three distinct layers around the trigone, with the central sagittal lamina identified as a new layer between the internal and external sagittal strata. These tracts are involved in the transmission of visual information and the integration of sensory inputs.	Tapetum: Forms the superolateral wall of the trigone, involved in interhemispheric communication via the CC. Internal SS: Comprises the corticotectal tract, involved in visual processing. External SS: Consists of the OR and ILF, critical for visual field processing and object recognition. Central Sagittal Lamina: A newly identified layer that may play a role in separating and integrating signals from the internal and external strata.

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Table 2: *(Continued)*

Study ID	Author(s)	Connectivity and pathways	Functional roles
15	Gil-Robles *et al.*[14]	The study suggests two main pathways: a basal pathway mediated by the ILF, involved in visual recognition, and a superior pathway mediated by the IFOF, involved in picture naming and semantic processing. The ILF connects the occipital lobe to the basal temporal cortex, while the IFOF connects the occipital lobe to the frontal areas, running through the SS.	Inferior Longitudinal Fasciculus (ILF): Involved in visual recognition, particularly in recognizing objects and words. Supports the integration of visual inputs with language processing. Inferior Fronto-Occipital Fasciculus (IFOF): Critical for semantic processing, enabling the connection between visual stimuli and conceptual knowledge, particularly important for picture naming and verbal semantic tasks.
16	Wedeen *et al.*[30]	The study identifies a rectilinear, three-dimensional grid structure in the cerebral WM that is continuous with the principal axes of brain development. This grid-like organization is seen in multiple species, including humans, and is characterized by the crossing and alignment of pathways such as the SS, SLF, CC, and CB.	N/A
17	Mukherjee *et al.*[23]	The study tracks the development of WM tracts across different brain regions, showing significant age-dependent changes in diffusion anisotropy and water content, especially in regions like the ILF and ORs within the SS.	CC: Facilitates interhemispheric communication, with the genu and splenium being critical for connecting homologous areas of the brain. Internal Capsule: Involved in motor and sensory pathways, with different limbs playing roles in the transmission of motor and sensory information.
18	Lebel *et al.*[20]	The study tracks the maturation of these tracts, with a focus on age-related changes in FA and MD, providing insights into the microstructural development of WM.	Inferior Longitudinal Fasciculus (ILF): Involved in visual processing and linking the occipital and temporal lobes. Inferior Fronto-Occipital Fasciculus (IFOF): Connects the frontal lobe with the occipital lobe, playing a role in visual and cognitive functions. CC (Genu, Splenium): Key for interhemispheric communication, with the splenium linking visual areas and the genu linking frontal lobes.
19	Paus *et al.*[25]	The study examines age-related increases in WM density in critical pathways, including the AF and internal capsule, which are part of the broader network that includes the SS. These tracts are involved in motor and speech functions, and their maturation is tracked from childhood through adolescence.	Internal Capsule: Involved in motor and sensory pathways, connecting the cerebral cortex with subcortical structures. AF: Critical for language processing, connecting Broca's area and Wernicke's area. Inferior Longitudinal Fasciculus (ILF): Facilitates visual processing and integration with language functions.
20	Giedd *et al.*[13]	The study tracks changes in white and gray matter volumes across different brain regions, emphasizing significant age-related changes in WM tracts, including those within the SS. These tracts are critical for various cognitive and sensory functions.	N/A
Study ID	**Author(s)**	**Impact of SS damage**	**Age-related implications**
1	Fernández Coello *et al.*[12]	Damage to the ILF can lead to visual hemiagnosia, where the patient loses the ability to recognize objects in one visual field without any distortion or visual field defect.	N/A
2	Rolland *et al.*[27]	Damage to these tracts can cause articulatory disorders, spatial neglect, semantic disorders, and visual field deficits, impacting cognitive function.	N/A

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Table 2: *(Continued)*

Study ID	Author(s)	Impact of SS damage	Age-related implications
3	Berro *et al.*[3]	Damage to the core system can lead to visual deficits (hemianopia, visual agnosia), impaired object and face recognition, and semantic processing issues. Peripheral system damage may cause spatial neglect, vertigo, dysesthesia, and auditory processing deficits.	N/A.
4	Robles *et al.*[26]	Damage to these tracts due to TBI can result in deficits such as impaired visuospatial awareness, slowed cognitive processing, attention deficits, visual recognition issues, and weakened interhemispheric communication.	Age-related degradation of WM, particularly in the genu and body of the CC, ILF, and superficial frontal fasciculi, leads to accelerated cognitive decline, including increased risk of dementia and motor coordination deficits in elderly patients.
5	Chan-Seng *et al.*[6]	Damage to the SS, particularly the IFOF, ILF, or OR, can result in severe language and visual deficits. Stimulation of these tracts during surgery can cause semantic paraphasia, alexia, and visual disturbances, such as quadrantanopia.	N/A
6	Wu *et al.*[31]	Damage to the IFOF can result in deficits in visual and spatial processing, language deficits, and impaired executive functions. Specific impacts may include visual agnosia, semantic paraphasia, and difficulties in spatial orientation.	Age-related degeneration of the IFOF could exacerbate deficits in visual-spatial processing, language, and executive function, potentially contributing to conditions like Alzheimer's disease or age-related cognitive decline.
7	Latini *et al.*[17]	Damage to the ILF can result in visual agnosia, prosopagnosia (inability to recognize faces), and impaired visual memory. Specific impacts may include difficulty in recognizing familiar objects or faces and integrating visual information with emotional context.	The study suggests that age-related degradation of the ILF may exacerbate visual and memory deficits, contributing to conditions like Alzheimer's disease and age-related visual processing disorders, particularly impacting quality of life in elderly patients.
8	Herbet *et al.*[15]	Damage to the right IFOF can result in nonverbal semantic impairments, such as difficulties in associating visual stimuli with their semantic meaning, disrupted object recognition, and impaired interpretation of nonverbal cues. These deficits are particularly noticeable in tasks requiring the identification of relationships between images without verbal input.	N/A
9	Chen *et al.*[7]	Disruption of the right IFOF and ILF is associated with cognitive impairment, particularly affecting memory and semantic processing. Damage may manifest as a reduced ability to integrate visual information with semantic and emotional content, leading to cognitive decline in patients with WMH.	N/A
10	Duffau *et al.*[9]	Damage to these pathways may result in semantic paraphasias, characterized by the substitution of semantically related words, reflecting disruption in the processing and integration of semantic information. These impairments can affect both verbal and nonverbal communication.	The study primarily focused on young and middle-aged adults.

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Table 2: *(Continued)*

Study ID	Author(s)	Impact of SS damage	Age-related implications
11	Duffau *et al.*[10]	Damage to these pathways, especially during tumor resection, can lead to significant language deficits, such as aphasia, speech apraxia, and anarthria. The impact is often severe and can lead to permanent deficits if these tracts are not preserved.	N/A
12	Maldonado *et al.*[22]	Damage to the SLF primarily results in phonological and articulatory disorders, such as dysarthria or phonemic paraphasia. The study found no evidence of semantic processing disruption from SLF damage, suggesting its primary role is in phonological rather than semantic processing.	N/A
13	Eichert *et al.*[11]	While the study focuses on the AF, the disruption of this tract could lead to deficits in phonological processing, impaired sentence structure comprehension, and difficulties in speech production. The absence of lateralization or damage to the left AF could result in atypical language processing, potentially leading to conditions like aphasia.	N/A
14	Hosoya *et al.*[16]	Damage to these layers, particularly the OR within the external SS, can result in visual field defects, impaired visual recognition, and potentially other sensory processing issues. The central sagittal lamina's role in separating signal pathways may be critical in maintaining the functional integrity of the visual and sensory systems.	N/A
15	Gil-Robles *et al.*[14]	Damage to the ILF could lead to deficits in visual recognition, such as difficulty recognizing familiar objects or reading, while damage to the IFOF may cause semantic paraphasia, affecting the ability to name objects or interpret visual symbols correctly.	N/A
16	Wedeen *et al.*[30]	N/A	N/A.
17	Mukherjee *et al.*[23]	Damage to the associated tracts during critical periods of development in children can lead to severe impairments in interhemispheric communication. These deficits are likely to differ from those in adults due to the ongoing development and higher plasticity in children.	The study emphasizes the ongoing development of WM tracts well into childhood, with significant changes in anisotropy and diffusion. This suggests that injuries to the SS in children could have more profound effects due to the incomplete maturation of these tracts. The plasticity observed in children might lead to different compensatory mechanisms compared to adults.
18	Lebel *et al.*[20]	Damage to the SS, including these tracts, during development can lead to deficits in visual processing, cognitive functions, and interhemispheric communication. The timing and severity of these deficits can differ between children and adults due to the different stages of brain maturation.	The study shows that the maturation of WM tracts follows a nonlinear trajectory, with significant changes occurring well into adolescence and even into the twenties. This suggests that injuries sustained during childhood or adolescence could have different outcomes than those in adults, with the potential for both greater recovery and greater vulnerability due to ongoing development.

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Table 2: *(Continued)*

Study ID	Author(s)	Impact of SS damage	Age-related implications
19	Paus *et al.*[25]	Damage to these maturing tracts within the SS during childhood or adolescence could lead to impairments in motor skills, language acquisition, and visual processing. The severity and type of deficits may differ from those observed in adults due to the ongoing development of these pathways.	The study demonstrates significant age-related increases in WM density in these tracts, suggesting that they are still maturing during late childhood and adolescence. This ongoing maturation implies that injuries sustained during this period could have different consequences compared to injuries in adults, potentially leading to greater recovery potential but also heightened vulnerability.
20	Giedd *et al.*[13]	Damage to these maturing tracts during childhood or adolescence could result in long-term deficits in visual processing, language functions, and interhemispheric communication. The outcomes might differ from those in adults due to the ongoing development of these tracts.	The study demonstrates linear increases in WM volume throughout childhood and adolescence, suggesting that injuries sustained during this period could result in different outcomes compared to adults, whose WM tracts are fully matured. This ongoing development also indicates that the brain's plasticity could allow for greater recovery potential in children, although the risk of developmental disruptions remains high.
Study ID	**Author(s)**	**Neuroimaging & intraoperative techniques**	**Follow-up findings**
1	Fernández Coello *et al.*[12]	Preoperative MRI (FLAIR, T2-weighted), intraoperative brain stimulation (2–4 mA), postoperative MRI, and DTI-based tractography.	Postoperative MRI and functional assessments showed no significant deficits, except for a minor left superior quadrantanopia. The patient returned to normal life within 3 months.
2	Rolland *et al.*[27]	Preoperative MRI (T1-weighted, T2-weighted, FLAIR), intraoperative DES (1.5–3 mA), and postoperative MRI within 24 h and at 3-month intervals.	Neuropsychological assessments were performed 5 days after surgery and then at 3 months postoperatively. This included spatial cognition tasks, such as the bell test and line bisection task. All patients recovered within 3 months after surgery, except for 4 patients who had a persistent left superior quadrantanopia.
3	Berro *et al.*[3]	Preoperative MRI (FLAIR, T2-weighted, T1-weighted with contrast), Intraoperative DES (1.5–3.25 mA), Postoperative MRI within 24 h and 3-month follow-up.	At 3 months postoperatively, there were no permanent neurological impairments except for an expected left superior quadrantanopia in 9 out of 17 patients.
4	Robles *et al.*[26]	DTI, FA, SWI, Structural MRI	Follow-up assessments were conducted at approximately 6 months postinjury. Significant decreases in FA were observed in the CC (especially the genu and body), the left corticospinal tract, and superficial frontal and temporal fasciculi. These changes were linked to older age, male sex, and the presence of CMBs.
5	Chan-Seng *et al.*[6]	Preoperative MRI (FLAIR, T2-weighted, T1-weighted with contrast), intraoperative subcortical electrostimulation (1.5–3 mA), and postoperative MRI.	By 3 months postsurgery, all patients recovered to normal neurological function, except for a persistent right superior quadrantanopia in 5 cases. These patients still maintained a high quality of life, with the ability to return to normal social and professional activities. Follow-up periods range from 12 to 48 months, with all patients having a KPS score of 90 or 100 at the most recent follow-up visit. This suggests that the majority of functional recovery was maintained over the long term.
6	Wu *et al.*[31]	DSI using a 3-T MRI scanner, GQI approach for tractography, analyzed in both subject-specific and template-based approaches.	N/A
7	Latini *et al.*[17]	DTI with tractography and FA analysis, WM dissection of 14 postmortem human brains, DTI in 24 healthy volunteers.	N/A

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Table 2: *(Continued)*

Study ID	Author(s)	Neuroimaging & intraoperative techniques	Follow-up findings
8	Herbet *et al.*[15]	Intraoperative DES during awake brain surgery, preoperative and postoperative neuropsychological assessments, MRI (FLAIR, T1-weighted).	All patients underwent a neuropsychological assessment 5 days after surgery, where they scored above the cutoff in both the naming task (DO80) and the PPTT, which assesses nonverbal semantic processing. The patients maintained their performance levels at the 3-month follow-up, indicating no significant long-term impairments in either verbal or nonverbal semantic cognition.
9	Chen *et al.*[7]	DTI with tractography, AFQ, statistical analysis using Random Forest classifier, and neuropsychological assessments including MMSE and MoCA.	N/A
10	Duffau *et al.*[9]	MRI, DTI, intraoperative cortical and subcortical mapping	All 17 patients experienced transient semantic paraphasias immediately after surgery. At the 3-month follow-up, all patients had recovered completely from the transient semantic disturbances, and they were able to return to normal social and professional activities.
11	Duffau *et al.*[10]	Preoperative MRI (T1-weighted, T2-weighted, FLAIR), intraoperative subcortical electrical stimulation, postoperative MRI	All 115 patients experienced a transient reduction in language performance immediately after surgery, including speech initiation difficulties, naming disorders, and disturbances in semantic fluency. By 3 months, all patients except two had returned to their baseline language function or had improved beyond their preoperative status. normal social and professional life.
12	Maldonado *et al.*[22]	Preoperative MRI, intraoperative direct cortical and subcortical stimulation mapping under awake conditions	Transient language disorders, such as articulatory, phonological, or naming disturbances, were observed in 8 out of 11 patients immediately after surgery. No semantic disorders were noted. By the end of the follow-up period (30 months on average), 7 patients were completely asymptomatic. The remaining 4 patients had mild symptoms that did not interfere with their social or professional lives, including difficulties with writing and calculation, attention and memory problems, and slight hemianopia.
13	Eichert *et al.*[11]	DW-MRI, Probabilistic Tractography	N/A
14	Hosoya *et al.*[16]	MRI, including DWI and IVIM imaging	N/A
15	Gil-Robles *et al.*[14]	Preoperative DTI Tractography, Intraoperative Corticosubcortical Electrostimulation Mapping	Day 3 Postoperative: Patients showed severe language disturbances, including visual paraphasias and severe reading impairments. 1-Month Follow-Up: There was a near-complete recovery of naming ability, though reading and symbol recognition remained impaired. 3-Month Follow-Up: Symbol recognition completely recovered, and reading skills showed significant improvement. 6-Month Follow-Up: Complete recovery of reading skills was observed by 6 months post-surgery.
16	Wedeen *et al.*[30]	DSI, Tractography	N/A
17	Mukherjee *et al.*[23]	DTI	N/A

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Table 2: *(Continued)*

Study ID	Author(s)	Neuroimaging & intraoperative techniques	Follow-up findings
18	Lebel *et al.*[20]	DTI	N/A
19	Paus *et al.*[25]	MRI	N/A
20	Giedd *et al.*[13]	Longitudinal MRI, Anatomical MRI	Longitudinal Data: Linear increases in WM across ages 4–22 years. Cortical gray matter showed nonlinear changes with region-specific patterns: preadolescent increases followed by postadolescent decreases in the frontal and parietal lobes, while the temporal lobe peaked later at around age 16. The occipital lobe continued to increase throughout adolescence. Sex Differences: There are differences in the timing of peak gray matter volume between males and females, with females generally reaching peak gray matter volume earlier than males.
Study ID	**Author(s)**	**Key findings**	**Clinical implications**
1	Fernández Coello *et al.*[12]	The study demonstrated that the right ILF plays a crucial role in visual recognition, specifically contributing to visual hemiagnosia when disrupted.	Highlights the importance of preserving the ILF during surgical interventions to prevent visual recognition deficits, particularly in older adults at risk for cognitive decline.
2	Rolland *et al.*[27]	Functional mapping revealed complex connectivity within the right IPL, emphasizing the need for careful surgical planning to avoid deficits.	Highlights the importance of comprehensive mapping during surgery to preserve cognitive and sensory functions, especially in elderly patients.
3	Berro *et al.*[3]	The study provided a detailed functional map of the right SS, highlighting its complex, multilayered architecture and emphasizing the importance of preserving key tracts during surgery to avoid permanent deficits.	Comprehensive functional mapping is crucial during surgery in the right SS, especially in elderly patients, to prevent irreversible damage to critical pathways that could significantly impact daily living and cognitive function.
4	Robles *et al.*[26]	The study found significant age-related WM degradation, particularly in older adults, with the greatest FA reductions observed in the CC, ILF, and superficial frontal fasciculi. These findings suggest that age, sex, and CMB presence are critical predictors of post-TBI cognitive decline.	The study highlights the need for targeted interventions in older adults with TBI to prevent or mitigate WM degradation, particularly in high-risk tracts like the CC and ILF, to preserve cognitive function and reduce the risk of long-term neurodegenerative outcomes.
5	Chan-Seng *et al.*[6]	The study demonstrated that using awake brain mapping allows for extensive resection of gliomas within the SS while preserving critical functions, particularly those related to language and vision. Most patients experienced transient postoperative deficits but generally recovered with rehabilitation, although some permanent visual deficits (quadrantanopia) were noted.	Highlights the importance of preserving SS tracts during surgery to avoid significant language and visual deficits. In elderly patients, this is particularly important due to the compounded effects of age-related WM degeneration.
6	Wu *et al.*[31]	The study revealed that the IFOF is a complex, multi-component tract with significant inter-subject variability. Five distinct subcomponents were identified, each associated with specific cortical and subcortical regions, suggesting a multi-functional role of the IFOF in the human brain.	The findings provide a detailed anatomical map of the IFOF, highlighting its importance in visual, spatial, and language functions. The study underscores the need for preserving this tract during neurosurgical procedures, especially in older patients, to maintain cognitive and sensory functions.

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Table 2: *(Continued)*

Study ID	Author(s)	Key findings	Clinical implications
7	Latini *et al.*[17]	The study identified three constant subcomponents of the ILF, each associated with distinct functional roles. The ILF plays a crucial role in integrating visual information with higher cognitive functions such as memory and emotion, with significant lateralization to the right hemisphere.	The detailed segmentation of the ILF provides critical insights for neurosurgeons, emphasizing the need to preserve this tract during surgery to avoid significant visual and cognitive deficits, particularly in older patients who may already be experiencing age-related cognitive decline.
8	Herbet *et al.*[15]	The study provides direct evidence of the involvement of the right IFOF in nonverbal semantic cognition, suggesting that this tract plays a critical role in the bilateral network supporting nonverbal semantic processing.	The findings highlight the need for careful surgical planning to preserve the right IFOF, especially in older patients who may already experience age-related declines in semantic cognition, to prevent further impairment of nonverbal communication and visual-semantic processing.
9	Chen *et al.*[7]	The study demonstrated that microstructural disruption in the right IFOF and ILF is a significant predictor of cognitive impairment in WMH patients, with changes in MD and AD being particularly indicative of cognitive decline.	The findings suggest that MD and AD metrics of the IFOF and ILF could serve as early imaging markers for predicting cognitive impairment in patients with WMH, especially in older adults. Early intervention may mitigate the progression of dementia.
10	Duffau *et al.*[9]	Identified a ventral stream linking temporal and frontal regions, critical for semantic processing, involving the inferior fronto-occipital fasciculus	Highlights the need for careful surgical planning to avoid permanent language deficits, emphasizing the role of the inferior fronto-occipital fasciculus in preserving semantic processing
11	Duffau *et al.*[10]	The study identified five major language pathways that are crucial to preserve during surgery to avoid permanent language deficits. Intraoperative subcortical stimulation mapping significantly reduces the risk of postoperative language deficits and allows for more extensive tumor resection.	Emphasizes the importance of intraoperative subcortical mapping for the safe resection of gliomas in language areas. In elderly patients, this technique is particularly important to minimize the risk of permanent deficits due to age-related decline in neural plasticity.
12	Maldonado *et al.*[22]	The study concluded that the left SLF, particularly its connections under the SMG, is crucial for phonological processing and articulatory rehearsal but does not play a significant role in semantic processing.	The findings suggest that surgical preservation of the SLF during glioma resection is vital for maintaining phonological and articulatory functions. In elderly patients, where neural plasticity may be reduced, careful mapping and preservation of this tract are even more critical to prevent speech-related deficits.
13	Eichert *et al.*[11]	The human AF shows significant left lateralization and expansion compared to macaques, indicating its unique role in supporting advanced language functions. The study provides insights into the evolutionary adaptations that have enabled complex language processing in humans.	The findings enhance our understanding of the neural basis for language, with implications for diagnosing and treating language disorders. The expansion and lateralization of the AF suggest targets for intervention in language-related cognitive decline, particularly in aging populations.
14	Hosoya *et al.*[16]	The study identified six distinct WM layers around the trigone, with the central sagittal lamina being proposed as a new anatomical structure. This discovery has implications for understanding the complex organization of WM in the brain and its role in visual and sensory processing.	The findings highlight the importance of detailed MRI analysis in diagnosing and treating conditions that affect the WM layers around the trigone. In elderly patients, preserving these structures during neurosurgical interventions is critical to prevent further decline in cognitive and sensory functions.

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Table 2: *(Continued)*

Study ID	Author(s)	Key findings	Clinical implications
15	Gil-Robles *et al.*[14]	The study demonstrated a double dissociation between visual recognition and picture naming, suggesting the existence of two distinct visual language routes in the left dominant hemisphere. The ILF was found to mediate visual recognition, while the IFOF was implicated in semantic processing and naming.	These findings have significant implications for the selection of tasks during awake mapping surgeries and for the rehabilitation of language functions postsurgery. The distinction between the roles of the ILF and IFOF is crucial for preserving specific cognitive functions during tumor resection in the BPTC.
16	Wedeen *et al.*[30]	The study revealed that the brain's fiber pathways form a coherent, grid-like structure that is conserved across species. This grid structure supports the brain's functional organization and may underlie its ability to adapt and reorganize throughout life.	The findings suggest that interventions aimed at preserving or restoring the integrity of this grid structure could be beneficial in treating neurodegenerative diseases and cognitive decline. Understanding this geometric organization could also inform surgical approaches to avoid disrupting critical pathways.
17	Mukherjee *et al.*[23]	The study found that water diffusion and anisotropy in WM tracts follow a stereotypical time course, with significant developmental changes occurring within the first decade of life. The maturation of these tracts is crucial for proper cognitive and sensory functions, with delayed or altered development potentially leading to long-term deficits.	The findings highlight the importance of early detection and intervention in cases of WM injury in children. The ongoing development of WM tracts means that injuries sustained during childhood may have different outcomes compared to adults, with the potential for greater recovery due to higher plasticity. However, the severity of deficits might also be greater due to the critical role of these tracts in ongoing cognitive and sensory development.
18	Lebel *et al.*[20]	The study found that the maturation of WM tracts, including those in the SS, continues throughout adolescence, with some tracts reaching 90% of their maximum FA only in the late teens or early twenties. This extended maturation period indicates a prolonged vulnerability to injury during development.	The findings underscore the importance of age-specific approaches to diagnosing and treating WM injuries. The ongoing development of these tracts in children and adolescents suggests that their recovery potential might differ significantly from that of adults, requiring tailored therapeutic strategies.
19	Paus *et al.*[25]	The study found significant age-related increases in WM density within the internal capsule and AF, with more pronounced changes in the left hemisphere, potentially reflecting its role in language processing. The findings underscore the importance of these pathways in the development of motor and cognitive functions.	These findings highlight the need for age-specific considerations in the diagnosis and treatment of WM injuries. The ongoing maturation of these tracts in children and adolescents suggests that interventions may need to be tailored to the developmental stage to optimize recovery and minimize long-term deficits.
20	Giedd *et al.*[13]	The study confirmed that WM volume increases steadily throughout childhood and adolescence, with specific tracts, including those within the SS, showing significant developmental changes. The findings suggest that the brain continues to develop well into adolescence, influencing how injuries to these areas might manifest and recover.	These findings highlight the importance of age-specific approaches to diagnosing and treating WM injuries, particularly in the SS. The ongoing development of these tracts in children and adolescents suggests that their recovery potential might differ significantly from that of adults, necessitating tailored therapeutic strategies to optimize outcomes.

MRI: Magnetic resonance imaging, FLAIR: Fluid-attenuated inversion recovery, IPL: Inferior parietal lobule, OR: Optic radiation, AF: Arcuate fasciculus, DTI: Diffusion tensor imaging, CMBs: Cerebral microbleeds, WM: White matter, TBI: Traumatic brain injury, SS: Sagittal stratum, FA: Fractional anisotropy, SWI: Susceptibility-weighted imaging, DWI: Diffusion-weighted imaging, WHO: World Health Organization, DSI: Diffusion spectrum imaging, OCD: Obsessive-compulsive disorder, PPTT: Pyramids and palm trees test, MD: Mean diffusivity, AD: Axial diffusivity, KPS: Karnofsky performance scale, GQI: Generalized Q-sampling imaging, WMH: White matter hyperintensities, AFQ: Automated fiber quantification, MCI: Mild cognitive impairment, MMSE: Mini-mental state examination, MoCA: Montreal cognitive assessment, DLPFC: dorsolateral prefrontal cortex, IFC: Inferior frontal cortex, STS: Superior temporal sulcus, SMG: Supramarginal gyrus, DW-MRI: Diffusion-weighted magnetic resonance imaging, DES: Direct electrical stimulation, IVIM: Intravoxel incoherent motion, BPTC: Basal posterotemporal cortex, CC: Corpus callosum, CB: Cingulum bundle, FX: Fornix, AC: Anterior commissure

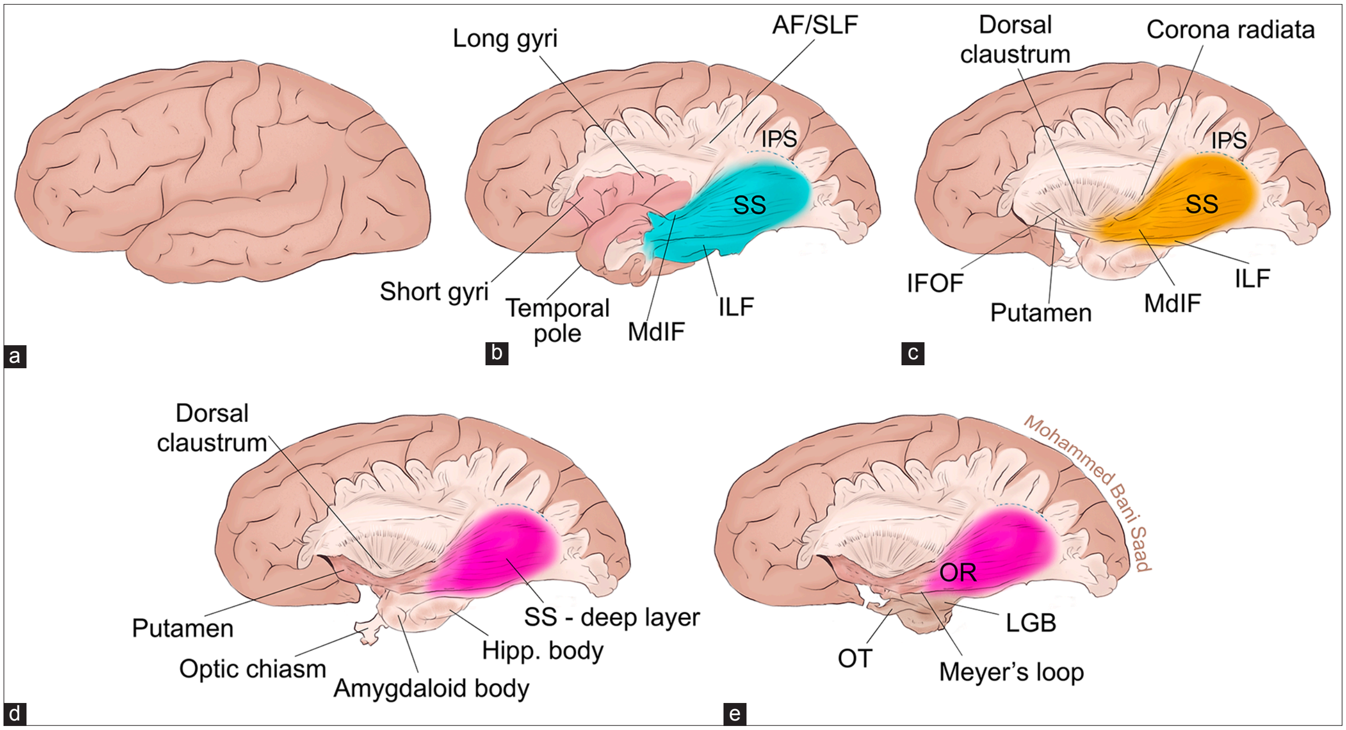

Figure 1: Illustrative representation of the SS and associated white matter tracts in the brain. (a) Lateral view of the brain surface for anatomical orientation. (b) Visualization of the sagittal stratum and its connections with the inferior longitudinal fasciculus and middle longitudinal fasciculus. The angular fasciculus and intraparietal sulcus are shown in relation to the SS.(c) Detailed view showing the SS in relation to the corona radiata, dorsal claustrum, and ILF. (d) The deep layer of the SS and its relationship to the dorsal claustrum, amygdaloid body, and hippocampal body. (e) Illustration of the optic radiation, including Meyer's loop and its connectivity with the SS. AF/SLF: Arcuate fasciculus / Superior longitudinal fasciculus, Hipp. Body: Hippocampal body, IFOF stands for Inferior fronto-occipital fasciculus, ILF: Inferior longitudinal fasciculus, IPS: Intraparietal sulcus, LGB: Lateral geniculate body, MdLF: Middle longitudinal fasciculus, OT: Optic tract, OR: Optic radiation, SS: Sagittal stratum

While the inferior longitudinal fasciculus (ILF) has been related to the integration of visual recognition and memory, different functions laterally remain relatively less known. The left ILF is more concerned with proper name retrieval, especially face-name association, and lexical access, interconnecting the occipital and temporal regions essential for visual recognition and word retrieval. The right ILF, on the other hand, is more involved in face recognition and visual working memory processing. It makes a large contribution to cross-hemispheric processing in individuals with both right- and left-handers or those who have atypical language lateralization. In addition, the right ILF may also subserve nonverbal semantic processing and emotion recognition via projections to the temporal lobe—and thus is crucially placed in integrating visual stimuli with emotional context.[4]

The IFOF is essential in linking visual stimuli to conceptual knowledge and has lateralized functions playing a crucial role in verbal and nonverbal semantic cognition. On the left, IFOF subserves language comprehension and visual-language integration via semantic processing, while on the right, it contributes significantly to nonverbal tasks—mostly in the realm of visual-semantic processing, such as facial expression interpretation and object recognition. Damage to the left IFOF has been associated with language deficits, and in particular with difficulties in linking visual input to semantic meaning. In contrast, damage to the right IFOF can affect the meaning given to visual stimuli and nonverbal cues, including facial expressions, underlining its role in nonverbal semantic cognition.[2]

The superior longitudinal fasciculus (SLF) and the AF play important roles in interconnecting language-related areas and supporting a number of other higher cognitive functions; their roles also significantly lateralize. The left SLF is especially concerned with language processing—particularly in connecting receptive and expressive language areas—and plays a crucial role in spatial working memory and coordinating complex cognitive functions related to language and attention. On the other hand, the right SLF is part of the interplay between occipito-temporal regions and prefrontal areas that take part in social cognition, emotional

Table 3: Functional lateralization of the sagittal stratum components.

Anatomical layer (sagittal stratum components)	Left (Lt)	Right (Rt)
ORs[24]	• Transmits visual information from the lateral geniculate nucleus to the visual cortex. • Processes visual field information, specifically the right visual field.	• Processes visual field information, specifically the left visual field. • Critical for integrating visual input from the contralateral visual field.
Inferior longitudinal fasciculus (ILF)[25]	• Central role in proper name retrieval, particularly in face-name association and lexical access. • Connects occipital and temporal regions, essential for visual recognition and word retrieval.	• Involved in face recognition and the processing of visual memory. • Plays a crucial role in cross-hemispheric processing, particularly in atypical language lateralization (e.g., left-handers). • May contribute to nonverbal semantic processing and emotional recognition through its connections to the temporal lobe.
Inferior fronto-occipital fasciculus (IFOF)[26]	• Essential for semantic processing, particularly linking visual stimuli with conceptual knowledge. • Supports language comprehension and visual-language integration.	• Involved in visual-semantic processing, crucial for interpreting visual stimuli in nonverbal tasks. • Plays a significant role in nonverbal semantic cognition, including the interpretation of facial expressions and object recognition.
Superior longitudinal fasciculus (SLF)[26,27]	• Critical for connecting receptive and expressive language areas. • Connects the posterior temporoparietal area to the frontal areas, often terminating in the precentral gyrus (motor areas). • Involved in spatial working memory and coordination of complex cognitive functions related to language and attention.	• Plays a role in connecting occipito-temporal regions with prefrontal areas. • Involved in social cognition, emotional regulation, and face processing, with alterations linked to social anxiety disorder.
AF[21]	• Primary role in language processing, including phonological processing, language comprehension, and verbal memory. • Higher FA and number of streamlines, correlating with better language-related cognitive performance in children.	- Involved in nonverbal cognitive functions. • Some individuals demonstrate rightward lateralization, which is associated with different cognitive abilities but is generally less effective in language tasks compared to the left AF.
Thalamocortical Radiations[30]	• Critical for executive functions, including attention, cognitive efficiency, and problem-solving. • Alterations in microstructure are associated with deficits in mental flexibility, inhibition, and shifting, particularly in children with TLE. • The integrity of the left thalamocortical pathway is closely linked to cognitive outcomes, with damage or underdevelopment potentially leading to significant functional impairments.	• Similarly involved in executive functions, particularly those related to attention and cognitive efficiency. • Alterations in the microstructure of the right thalamocortical fibers are associated with deficits in executive function, especially in children with epilepsy. • The right thalamocortical pathway is important for integrating sensory information and maintaining cognitive flexibility.

OR: Optic radiations, AF: Arcuate fasciculus, FA: Fractional anisotropy, TLE: temporal lobe epilepsy

regulation, and face processing. The right SLF has lately been implicated in social anxiety disorder, thus showing its involvement in emotional and social processing.[2,29] Similarly, language processing primarily involves the left AF, including phonological processing, language comprehension, and verbal memory. Although some nonverbal cognitive functions are interested in the right AF, generally, it has worse performance in language tasks compared to the left AF. Therefore, damage to these tracts can cause language and social cognition deficits, whose specific impairments are based on the side of the damage.[18]

The thalamocortical radiations are critically involved in executive functions, including attention, cognitive efficiency, and problem-solving. It has been proven that there is a high correlation between the left thalamocortical pathway integrity and good cognitive outcomes. Thalamocortical radiations may also intervene healthily in mental flexibility, inhibition, and shifting. Along with the left thalamocortical pathway, an executive function is also supported by the right thalamocortical pathway, particularly the aspects of attention and cognitive efficiency. WM microstructure changes in the right thalamocortical fibers have been reported as related to executive dysfunction, mainly in children affected by epilepsy. This position emphasizes its integral role in the global process of sensorial integration and maintenance of "cognitive flexibility."[19]

Surgical considerations and outcomes

The SS, with its associated WM tracts, is involved in maintaining a wide range of cognitive, sensory, and motor functions. Surgical interventions for SS, mainly gliomas and other brain lesions, need adequate preplanning and intraoperative strategies to reduce postoperative deficits. The current discourse synthesizes findings from multiple studies and then points out the surgical considerations and outcomes related to interventions close to the SS.

Intraoperative DES has already become a "gold standard" for awake brain surgery aimed at the resection of the tumors situated in close relations with the critical SS tracts with the goal of preserving relevant functions. The case description by Fernández Coello *et al*. (2013)[12] presents this approach implemented in a 41-year-old male patient with a low-grade glioma located in the right basal temporo-occipital region. Preoperative magnetic resonance imaging (MRI) and intraoperative DES enabled a careful mapping of the right ILF such that it was spared, and only a mild left superior quadrantanopia occurred, which resolved within 3 months and contributed to the severe deterioration of visual recognition functions. Rolland *et al*. (2018)[27] conducted a series of awake surgeries on 14 patients with right inferior parietal lobule gliomas. They revealed the complex SS connectivity, mainly the preservation of multiple tracts, including the superior longitudinal fasciculus and the inferior frontal-occipital fasciculus. Most patients recovered within 3 months, but four had persistent left superior quadrantanopia, which shows the importance of accurate functional mapping in order to avoid permanent sensory and cognitive deficits.

Laterality of the affected SS tracts has a significant bearing on the type of functional deficits observed postoperatively. Chan-Seng *et al*. (2014)[6] studied the surgical outcomes of gliomas that involved the left SS of the brain with a concentration on problems that overcome the preservation of language and visual functions. Their results showed that intraoperative stimulation of IFOF could cause semantic paraphasia and that disruption of OR resulted in visual field deficits, mainly quadrantanopia. Despite these risks, the majority of these patients reverted to normal neurological function within 3 months, with few long-term impairments, thus suggesting that effective mapping and surgical techniques can mitigate the impact of left-sided resections. In contrast, Berro *et al*. (2021)[3] focused on right-sided resections, which are usually associated with nonverbal semantic cognition and visual-spatial processing. As previously described, in 17 patients with diffuse low-grade gliomas, although with nine developing left superior quadrantanopia, there was no long-term cognitive deficit. This indicates the divergence in functional risks associated with right- and left-sided surgeries and the need to preserve tracts such as the ILF and IFOF and also to preserve functions involving visual-space and nonverbal cognitive function.

Age is thus an essential consideration in surgical planning because age-related WM degeneration can exaggerate the effects of SS damage. Robles *et al*. (2022)[26] recorded the effects of traumatic brain injury (TBI) on WM tracts, including SS, across a rather wide span of ages. This study demonstrated significant reductions of fractional anisotropy (FA) values in major tracts such as ILF and corpus callosum, with a preferential focus on the same in cases where cerebral microbleeds were present in older patients. The findings thus suggest that, probably due to preexisting WM degradation, older patients are more at risk for cognitive decline after SS surgery and certainly warrant more cautious surgical strategies among this age group. Latini *et al*. (2017)[17] took it further by making efforts to explain the challenges of doing procedures on the elderly through a study on the segmentation and connectivity of the ILF. Their worry revealed that the age erosion of the ILF led it to have detection on the visual and memory functions, which the surgery further affected. This tract is particularly important in older patients for the prevention of accelerated cognitive decline and quality of life preservation.

Long-term recovery and rehabilitation

Overall, long-term functional recovery after SS surgery is quite good if the critical tracts are preserved. Duffau *et al*. (2005, 2008)[9,10] did detailed studies on language function recoveries after glioma resection in the dominant hemisphere. Their studies showed that patients, even if they developed language deficits such as aphasia or semantic paraphasia in the immediate postoperative period, recovered to their baseline or better in 3–6 months. Recovery is supported by plasticity and intraoperative subcortical mapping of the brain, whereby tumors can be safely resected. In contrast, the essential language pathways in the brain are preserved, and the methodology is okay with regard to the preservation of structures like the AF and IFOF. Wu *et al*. (2016)[31] extended this research to various subcomponents of the IFOF using DSI and tractography. This study showed that the IFOF is a multi-component tract involved in both visual-spatial and language functions. The authors, therefore, emphasize the need for detailed preoperative imaging and intraoperative mapping to identify and preserve these subcomponents during surgery to achieve optimal long-term recovery with the smallest possible degree of functional deficit.

Neuroimaging and surgical planning

Advanced neuroimaging modalities form an intrinsic part of surgical planning and execution of procedures at the SS. Hosoya *et al*. (1998)[16] assessed, in a cross-sectional study by MRI, the anatomy of WM layers surrounding the trigone of the lateral ventricle, including the SS. Their findings showcase the importance of careful MRI analysis in the identification of distinct WM layers participating during both visual and sensory processing. It is a complex organization of the tapetum and internal SS; understanding the details of these layers is important for neurosurgeons seeking to retain as much sensory function as possible during surgery, particularly in older patients where WM integrity is already compromised. Eichert *et al*. (2019)[11] provided further insight into the neuroanatomical underpinnings of the SS through a comparative study involving humans and macaques with diffusion-weighted MRI and probabilistic tractography. It showed rectilinear, grid-like WM tract organization, including that of the SS and SLF, which underpins the functional integrity and adaptability of the brain with significant implications for the preservation of cognitive function within surgical intervention. Such disruptions to this grid structure may have important implications, particularly in patients undergoing resection of tumors near these critical pathways.

Preservation of the critical SS pathways during surgery is very important for minimizing functional deficits and ensuring a high quality of life after surgery. According to the accumulated literature, advanced neuroimaging techniques support methods of intraoperative mapping and require sophisticated knowledge of the complex connectivity within the SS to guide surgical decisions. Neurosurgeons should make continuous, unremitting attempts to use the latest techniques and strategies to tide over such challenges, as our understanding of the SS and the associated tracts is ever evolving.

Although SS surgeries carry critical cognitive and sensory risks, the evidence shows that they can be avoided with careful surgical planning, consideration of the patient’s condition, and utilization of advanced intraoperative methods. Future research should further elucidate the long-term outcomes of SS surgeries, particularly age-related differences and possible neural recovery in various populations.

Age-related implications of SS damage

There are important age-related implications for the damage to the SS, especially because aging alone tends to result in the natural degeneration of WM tracts. This degeneration might contribute to the impact of damage in the SS on cognitive and sensory outcomes and may mitigate any outcome advantage observed in older compared with younger subjects.

Little wonder that, in aging, WM structural integrity is generally lowered for key tracts within the SS: ILF and IFOF. It has been demonstrated that this age-related degradation is most rigid in ILF and IFOF—the core pathways related to visual recognition, memory integration, and semantic processing. The natural decline in these tracts’ integrity contributes to an increased vulnerability to cognitive impairments, such as memory deficits and difficulties in visual processing, particularly in tasks that require the integration of visual stimuli with semantic knowledge. For instance, Robles *et al*. (2022)[26] reported that older adults with TBI had dramatic WM loss in the corpus callosum and superficial frontal and temporal fasciculi, locations belonging to or connecting to the SS. Their findings concluded that age is an important predictor of post-TBI cognitive decline in people alongside the presence of cerebral microbleeds. This probably puts older adults at a greater risk of suffering more severe cognitive impairments following SS damage, likely because of the combined effects of aging and reduced plasticity of the aging brain.

Moreover, diminished neural plasticity in elderly patients reduces the chances of recovery from SS damage. The fact that young individuals have a less plastic brain compared to older ones also implies that some compensation/re-organization after injury does occur in the higher-plasticity brain. In contrast, similar damage in the elderly is more likely to result in permanent deficits because of the lesser plasticity of the brain. This impact is best viewed concerning surgical interventions associated with the SS because patients are more likely to have long-term cognitive and sensory deficits if critical WM tracts are damaged during surgical procedures.

Additionally, age-related changes have an impact on neurosurgical outcomes through changes to WM. For instance, studies like those by Chan-Seng *et al*. (2014)[6] and Berro *et al*. (2021)[3] provide evidence that the surgical planning and mapping during the surgeons’ glioma resection in elderly patients were actually suggested for the preservation of key SS tracts. In this regard, the compounding effects of natural WM degeneration and surgical trauma worsen cognitive and visual impairments; thus, damage should be minimized during surgery to these tracts.

In summary, aging processes are a prominent modifier of SS damage outcome, with older individuals more likely to present with cognitive and sensory impairments from both naturally occurring degeneration and decreased neural plasticity. This underlies the importance of age-related considerations in the diagnosis, treatment, and surgical management of pathologies concerning SS.

Synthesis of key findings

This review has indicated disruption to the SS and its cluster WM tracts in a variety of higher-order cognitive and sensory functions. Anatomically, the SS itself proved to be a complex and multilayered structure. Highly lateralized, these tracts have specific functional roles dependent upon their hemispheric location. Functionally, these could result in huge SS damages to the process of vision, comprehension of language, and even cognitive functions, with the degree and nature frequently modulated by the affected tract and its lateralization. These findings have important ramifications for surgical interventions, in which awake brain mapping is used to aid in preserving critical functions and minimizing long-term deficits, especially in older subjects.

In conclusion, this review provides an in-depth understanding of the anatomical and functional importance of the SS and, therefore, the need for careful surgical planning with consideration of age-related changes to optimize the benefit for patients.

DISCUSSION

Within neurosurgical interventions, the SS holds a special place because approximately 60% of all brain tumors, including gliomas, reside in eloquent regions where the integrity of the surrounding WM tracts needs to be maximally preserved to prevent significant postoperative deficits.[24] The SS connects the brain to various WM tracts important for the integration of sensory inputs that underpin higher-order cognitive processes. The complexity of connectivity within the SS itself, including tracts such as the IFOF, OR, and SLF, underlies this structure's critical role in maintaining normal brain function. Damage to the SS resulting from disease or surgical intervention can result in profound deficits, particularly against a backdrop of age-related changes. This discussion synthesizes findings from an extensive body of literature reviewed for SS damage functional outcomes as related to aspects of laterality, challenges of aging, and the critical inclusion of advanced surgical techniques.

Functional results of SS damage are importantly lateralized so that specific patterns of impairment have been associated with the damage of the left or right hemisphere. In reviewing the studies, this paper has shown that SS damage on the left side is often associated with major deficits in language and visual processing. For example, Chan-Seng *et al.* (2014)[6] reported that lesions in the left IFOF give rise to semantic paraphasia, generating a severe disruption of language processing and production. This can create particular problems for patients scheduled for resections of gliomas in the dominant left hemisphere, where even slight perturbations of the IFOF may promote chronic linguistic deficits. Similarly, lesions of the left OR entail visual field deficits, such as quadrantanopia, which compromises the processing of visual information emanating from the contralateral visual field. This lateralized processing of visual information underlies coherent visual perception, and damage to the OR could have important consequences for the ability of a patient to move about freely and interact with their environment.[1]

In contrast, right-sided damage will more likely involve nonverbal cognition and aspects of visual-spatial processing. Berro *et al.* (2021)[3] showed that right-sided resections at this level of the ILF usually result in deficits in visual recognition memory, especially for tasks integrating visual stimuli with emotional or spatial context. This puts a premium on the preservation of the right ILF during surgery for the preservation of these higher-order cognitive functions. The right SLF connects occipitotemporal regions with prefrontal areas and is crucial for social cognition and emotional regulation; damage to this tract has been implicated in disorders as diverse as social anxiety disorder, therefore also underscoring the essence of these meticulous surgical plannings when operating in these areas.

Another critical component of the SS includes the thalamocortical radiations interconnecting the thalamus with the cerebral cortex. These tracts play a critically important role in executive functions for attention, cognitive efficiency, and problem-solving. Law *et al.* (2018)[18] emphasized the preservation of such connections, particularly in pediatric temporal lobe epilepsy patients, where interruptions to the thalamocortical pathways may result in important cognitive deficits. Their findings underline the need for highly accurate surgical techniques that will cause minimal damage to these tracts, especially in younger patients in whom the possibility for long-term cognitive impact is very high.

One of the major confounding variables within SS damage management is aging, whose degenerating process with age significantly worsens surgical- and disease-related disruptions in WM tracts. Robles *et al.* (2022)[26] provided very compelling evidence that older individuals are more at risk of late-onset cognitive decline after SS surgery, more so in the presence of pre-existing conditions like cerebral microbleeds. Their findings included a significant decline in FA in important tracts, like the ILF and the corpus callosum, indicating patients are at an increased risk for postoperative cognitive impairment. This places a sharp focus on the imperative need for surgical age-specific strategies that account for reduced plasticity and enhanced vulnerability of the maturing brain. Latini *et al.* (2017)[17] extended the investigation into how SS damage affects older patients with a study on the segmentation of the ILF and its connectivity in aging. Their results evidenced that age-related degradation may well contribute to dramatic failures of visual and memory functions worsened by surgical interventions in the ILF. This tract is of essence to be preserved in older adults to prevent an accelerated cognitive decline and impairment of quality of life. The results further support the surgical strategies that are compared to the possible vulnerabilities of the old aging brain.

Besides these structural concerns, neural plasticity is reduced in older adults, which complicates the recovery from damage to the SS. Because neural plasticity is higher in the young, the damage can often be compensated for by changing the organization of brain networks. A similar amount of damage may result in more permanent deficits in older adults because their aging brain lacks such adaptability. This is especially evident in visual and memory functions, where any recovery is limited by age-related degradation of WM. Additive effects of aging and SS damage call for older patients to follow a more cautious surgical approach.

Recent research into the cerebral WM myelination process has greatly improved knowledge of how age, gender, and cognitive functions are intertwined in brain development at crucial white-matter pathways, such as the SS. Myelination is one critical process that enables efficient neural transmission that significantly changes across the lifespan and thus impacts cognitive ability and the overall functional integrity of the brain. As Buyanova and Arsalidou (2021)[5] convincingly argue in their competitive review, the decline in myelination with age, especially of the IFOF and SLF, reduces the threshold for older adults to acknowledge cognitive impairments due to SS injuries. Most recently, it also brought attention to sex/gender variations in WM development, which may further modulate cognitive outcomes subsequent to SS injury. In particular, this differential rate and extent of myelination may introduce variations within male and female brains in terms of response to damage, thereby indicating possible gender-specific therapeutic strategies on the one hand for clinical diagnosis and surgical interventions on the other. Putting all these findings together into the general context of SS research points out that individual variability in myelination is a factor that should be controlled when trying to quantify the overall impact of SS damage. Such an approach could provide more individualized strategies for the management and mitigation of SS injury effects, particularly in aging populations in whom WM integrity is already somewhat compromised.

Preservation of SS tracts at surgery is important to reduce postoperative deficits and to have good long-term outcomes. Progress in neuroimaging and intraoperative mapping has dramatically enhanced a neurosurgeon's possibility to recognize and spare critical pathways during brain surgery. Wu *et al*. (2016)[31] reported that diffusion tensor imaging (DTI) and tractography displayed SS tracts, for example, the IFOF, in detail, thus providing surgeons with information to avoid these critical areas in its resection. The utility of the technique has been greatest in surgeries for gliomas, where the potential for mapping and preserving language and visual pathways may make a great deal of difference in postoperative quality of life. Awake brain surgery has become a gold standard in preserving function during SS surgeries due to DES on its own during procedures. This approach was demonstrated to be effective in keeping one's abilities in visual recognition and spatial processing by Fernández Coello *et al*. (2013)[12] and, more recently, by Rolland *et al*. (2018).[27] These findings underline the importance of real-time functional mapping in preserving the critical SS pathways and reducing the risk of permanent deficits. Extensive research on language function recovery after glioma resection in the dominant hemisphere by Duffau *et al*. (2005, 2008)[9,10] showed that even in patients with an initial deficit, such as aphasia or semantic paraphasia, most recovered to baseline or better within 3–6 months. It is promoted by the plasticity of the brain and intraoperative subcortical mapping, which enables safe tumor resection that does the least damage to essential language pathways, including the AF and IFOF. These results underline the fact that surgical preservation of the critical tracts is basic in sustaining long-lasting functional recovery.

The findings of the current study provide further support for the need for more research into the functional implications of SS damage and the refining of surgical techniques. With the evolving knowledge of the SS and its associated tracts, the need for further research persists into the long-term outcomes of SS surgeries, particularly in different age groups. Future studies should be more focused on the potential for neural recovery in older people and on developing interventions that can enhance this recovery, possibly mitigating the effects of WM degradation with age. On a clinical level, these results point out the need for surgical planning. Some forms of advanced neuroimaging and intraoperative mapping should be standard in SS surgeries to preserve the most critical pathways and thereby avoid deficits in the patient following the surgery.

In that sense, it is of great necessity that during surgery, the SS and all of its tracts be preserved to minimize possible functional impairments, ensuring a high quality of life for the patients. The results support further findings and clinical applications that underscore the necessity of a nuanced approach to SS in neurological function, with a proportional value of surgical methods for tailoring approaches according to the challenges that WM changes appear to pose throughout the aging process.

CONCLUSION

In conclusion, the SS plays a crucial role in integrating sensory, cognitive, and motor functions, making its preservation essential during neurosurgical procedures, particularly in older adults who may already have compromised WM integrity. Advances in neuroimaging and intraoperative techniques, such as DTI and DES, have significantly reduced the risks associated with SS damage. Ongoing research and the refinement of surgical approaches are vital to minimize the impact of SS injury further, ultimately aiming to improve patient outcomes and quality of life following surgery.

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Ethical approval

Institutional Review Board approval is not required.

Declaration of patient consent

Patient's consent not required as there are no patients in this study.

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Conflicts of interest

There are no conflicts of interest.

Use of artificial intelligence (AI)-assisted technology for manuscript preparation

The authors confirm that there was no use of artificial intelligence (AI)-assisted technology for assisting in the writing or editing of the manuscript and no images were manipulated using AI.

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