Anatomy and White Matter Connections of the Superior Parietal Lobule

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Anatomy and White Matter Connections of the Superior Parietal Lobule

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BACKGROUND: The superior parietal lobule (SPL) is involved in somatosensory and visuospatial integration with additional roles in attention, written language, and working memory. A detailed understanding of the exact location and nature of associated white matter tracts could improve surgical decisions and subsequent postoperative morbidity related to surgery in and around this gyrus.

OBJECTIVE: To characterize the fiber tracts of the SPL based on relationships to other well-known neuroanatomic structures through diffusion spectrum imaging (DSI)-based fiber tracking validated by gross anatomical dissection as ground truth.

METHODS: Neuroimaging data of 10 healthy, adult control subjects was obtained from a publicly accessible database published in Human Connectome Project for subsequent tractographic analyses. White matter tracts were mapped between both cerebral hemispheres, and a lateralization index was calculated based on resultant tract volumes. Post-mortem dissections of 10 cadavers identified the location of major tracts and validated our tractography results based on qualitative visual agreement.

RESULTS: We identified 9 major connections of the SPL: U-fiber, superior longitudinal fasciculus, inferior longitudinal fasciculus, inferior fronto-occipital fasciculus, middle longitudinal fasciculus, extreme capsule, vertical occipital fasciculus, cingulum, and corpus callosum. There was no significant fiber lateralization detected.

CONCLUSION: The SPL is an important region implicated in a variety of tasks involving visuomotor and visuospatial integration. Improved understanding of the fiber bundle anatomy elucidated in this study can provide invaluable information for surgical treatment decisions related to this region.

KEY WORDS: Superior parietal lobule, SPL, DSI, Anatomy, Tractography, White matter

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Advances in neuroimaging demonstrate the relationship between structural connectivity and network function is foundational to practical understanding of brain operation. Research into the superior parietal lobule (SPL) has revealed it to be a functionally diverse region involved in numerous functions, such as visuospatial and visuomotor integration,[1-4] attentional processing,[5-8] memory,[9,10] and language tasks,[11-13] as well as in higher order, multi-regional networks, such as the salience network.[14,15]

Despite such developments in our understanding of the functional assignment and connectivity of the SPL, the precise knowledge of the anatomic relations that underpin these characteristics is still obscure, thus rendering clinical application of contemporary advances a struggling endeavor. Similarly, intraoperative visuomotor and visuospatial mapping is underdeveloped compared to speech and motor mapping which has proved beneficial in neurosurgery, imploring the need for further understanding of the subcortical anatomy that precedes these processes.

In this study, we derive clinically actionable knowledge of the cortical SPL and its major white matter tract associations

ABBREVIATIONS: ExtC, extreme capsule; **IFOF,** inferior fronto-occipital fasciculus; **ILF,** inferior longitudinal fasciculus; **MdLF,** middle longitudinal fasciculus; **SLF,** superior longitudinal fasciculus; **VOF,** vertical occipital fasciculus

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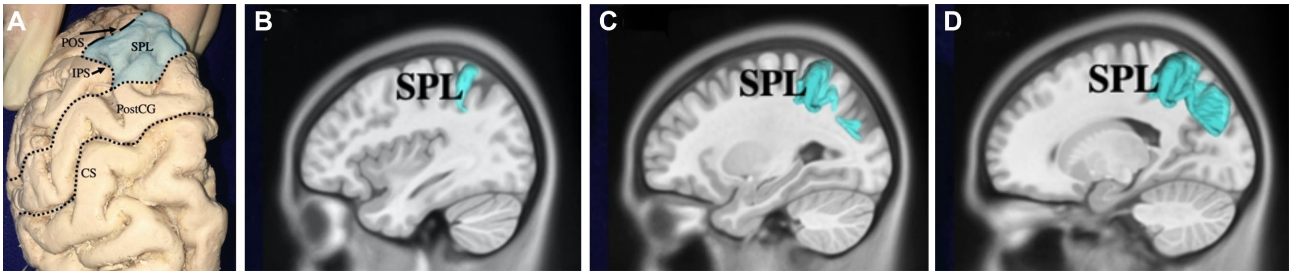

FIGURE 1. *Superficial anatomy and boundaries of the superior parietal lobe (SPL).* **A**, *Anterior limit formed by the posterior boundary of the postcentral gyrus (PostCG). Posterior limit is loosely defined as the parieto-occipital sulcus (POS), drawn differently to show it is not a perfectly discrete boundary. Inferior limit taken at the intraparietal sulcus (IPS). The medial boundary is less rigidly defined at the precuneus and paracentral lobule.* **B-D**, *The definition of region of interest of SPL, from lateral to medial.*

utilizing diffusion spectrum imaging (DSI)-based fiber tractography validated by gross anatomic dissection as ground truth. We propose that a description of the nuanced anatomic associations of the SPL in the broader context of its involvement in various functional networks is essential to the true application of arcane neuroscientific advancement.

METHODS

Defining the Region of Interest

For fiber tracking analysis, the SPL was divided into a single region of interest in which the postcentral gyrus and sensory strip served as the anterior boundary, the parieto-occipital sulcus served as the posterior boundary, the intraparietal sulcus between the SPL and IPL served as the inferior boundary, and the precuneus and paracentral lobule served as the medial boundary (Figure 1).

White Matter Tractography

Publicly available imaging data of 10 healthy, unrelated subjects were obtained from the Human Connectome Project (http://humanconnectome.org, release Q3).[16] The diffusion imaging with corresponding T1-weighted images were analyzed by fiber tracking with methods previously described by our team (**see Text, Supplemental Digital Content** *Methods* for detailed description).[17,18]

Tractographic analyses were completed along the length of the SPL in the anterior-posterior direction before gross anatomic dissection. Resultant tract volumes from major identified white matter bundles were further compared to create a laterality index,[19] with possible asymmetry and cerebral differences investigated by unpaired *t*-tests ($P \leq .05$).

Post-Mortem Dissection

Gross anatomic dissections of white matter tracts connecting with the SPL were utilized as ground truth to validate the tractography results.[17,20] Obtained from our institution's Willed Body Program with approval of the state's anatomical board, 10 healthy subjects were dissected utilizing a modified Klinger technique with careful attention to preserving major white matter bundles as previously elucidated.[17,18,21]

RESULTS

Major Connections

Major connections between SPL and adjacent cortial areas involve multiple types of connecting pathway are elucidated in Table 1, with their tractography as shown in Figure 2. All major tracts were successfully dissected in all 10 specimens demonstrating high concordance between cadaveric and tractography results.

The current study found no significant inter-hemispheric differences in tract volume for the connections studied (Table 2).

As detected in both tractography and gross anatomic dissection, the SPL is structurally connected to distinct cortical regions through an abundance of local, short association white matter bundles, or "U-fibers," as well as via multiple long-range fibers which are described below. Additionally, more detailed descriptions of SPL fiber connections across cortical regions as well as their perceived functional significance are in detailed in the **Text, Supplemental Digital Content** *Results* and *Discussion* sections.

Short Association Fibers (U-Fibers)

Within the SPL, the U-fibers are observed immediately below the cortical surface, which display mainly a U-shaped morphology (Figure 3). In addition to the connections within the SPL itself, U-fibers, which originates on the cortical SPL, also project to other cortical areas including the parietal, frontal, temporal, and occipital lobes via connections with regions such as the middle frontal gyrus, precentral gyrus, and inferior temporal gyrus (Figure 4).

Long-Range Connections

Superior Longitudinal Fasciculus

The SPL is structurally connected to distinct cortical regions via multiple long-range fibers, including superior longitudinal fasciculus (SLF), inferior fronto-occipital fasciculus (IFOF),

TABLE 1. Major Connectivity of the Superior Parietal Lobule

Target		Connecting pathway	Speculated function
Frontal lobe	Superior frontal gyrus	IFOF	Working memory; visual conceptualization
	Middle frontal gyrus	SLF, IFOF, U-fibers	Semantic cognition; working memory; visual conceptualization
	Precentral gyrus	SLF, U-fibers	Visuomotor integration
	Pars opercularis	SLF, IFOF	Syntactic, phonologic, and semantic processing; verbal memory
	Pars orbitalis	IFOF	Syntactic, phonologic, and semantic processing; emotional perception and memory
	Pars triangularis	IFOF	Syntactic, phonologic, and semantic processing; emotional memory; sensorimotor integration
	Lateral orbitofrontal cortex	IFOF	Decision-making; spatial and sensory processing
Parietal lobe	Inferior parietal lobule	SLF, U-fibers, VOF, ILF	Semantic and phonologic processing; visuospatial processing
	Supramarginal gyrus	SLF, U-fibers,	Visuospatial attention; phonological processing
	Postcentral gyrus	SLF, U-fibers	Somatosensory processing; sensorimotor processing
	Precuneus	IFOF, MdLF, U-fibers, Cingulum, ILF	Visuospatial processing and attention; decision-making; working and episodic memory
	Pericalcarine cortex	SLF, IFOF, VOF, ILF	Visual processing
Temporal lobe	Superior temporal gyrus	IFOF, MdLF, ILF, ExtC	Visuospatial processing; integrative audiovisual processing; attention control
	Middle temporal gyrus	ILF	Semantic processing; verbal memory
	Inferior temporal gyrus	U-fibers, VOF, ILF	Visuospatial processing; phonologic and semantic processing; verbal memory
	Heschl's gyrus	MdLF, ILF	Integrative audiovisual processing; syntax processing
	Fusiform gyrus	VOF, ILF	Highly selective visual processing; visuospatial perception
	Insula	ExtC	Attention control; somatosensory processing; visuospatial awareness; speech motor planning
Occipital lobe	Cuneus	IFOF, U-fibers, VOF, ILF	Visual processing
	Lateral occipital lobe	IFOF, VOF, ILF	Visual processing (object recognition)
	Lingual gyrus	IFOF, VOF, ILF	Lexical memory; visual processing
Limbic lobe	Cingulate gyrus	Cingulum, VOF, ILF	Emotional processing; decision-making; working memory
	Parahippocampal gyrus	ILF	Visuospatial processing; memory encoding and retrieval

SLF, superior longitudinal fasciculus; ILF: inferior longitudinal fasciculus; IFOF, inferior fronto-occipital fasciculus; MdLF, middle longitudinal fasciculus; ExtC, extreme capsule; VOF, vertical occipital fasciculus.

middle longitudinal fasciculus (MdLF), inferior longitudinal fasciculus (ILF), extreme capsule (ExtC), vertical occipital fasciculus (VOF), and cingulum. The SLF projects inferiorly into the parietal lobe before curving 90 degrees anteriorly towards the frontal lobe and bending laterally and inferiorly to other parietal areas (Figure 5). The SLF fiber connectivity and its tractography arising within the SPL overlaps with the U-fibers, which is further validated by gross dissection as shown in Figure 6.

MdLF

MdLF fibers arise from the lateral aspect of the SPL and its fibers course inferiorly and obliquely from the parietal lobe into the white matter of the temporal lobe, lateral to the lateral ventricle. Represented in both gross anatomy dissection and tractography, SLF and MdLF arise from the anterior edge of the SPL, whereas MdLF bends inferior to the SLF after entering the white matter (Figure 7).

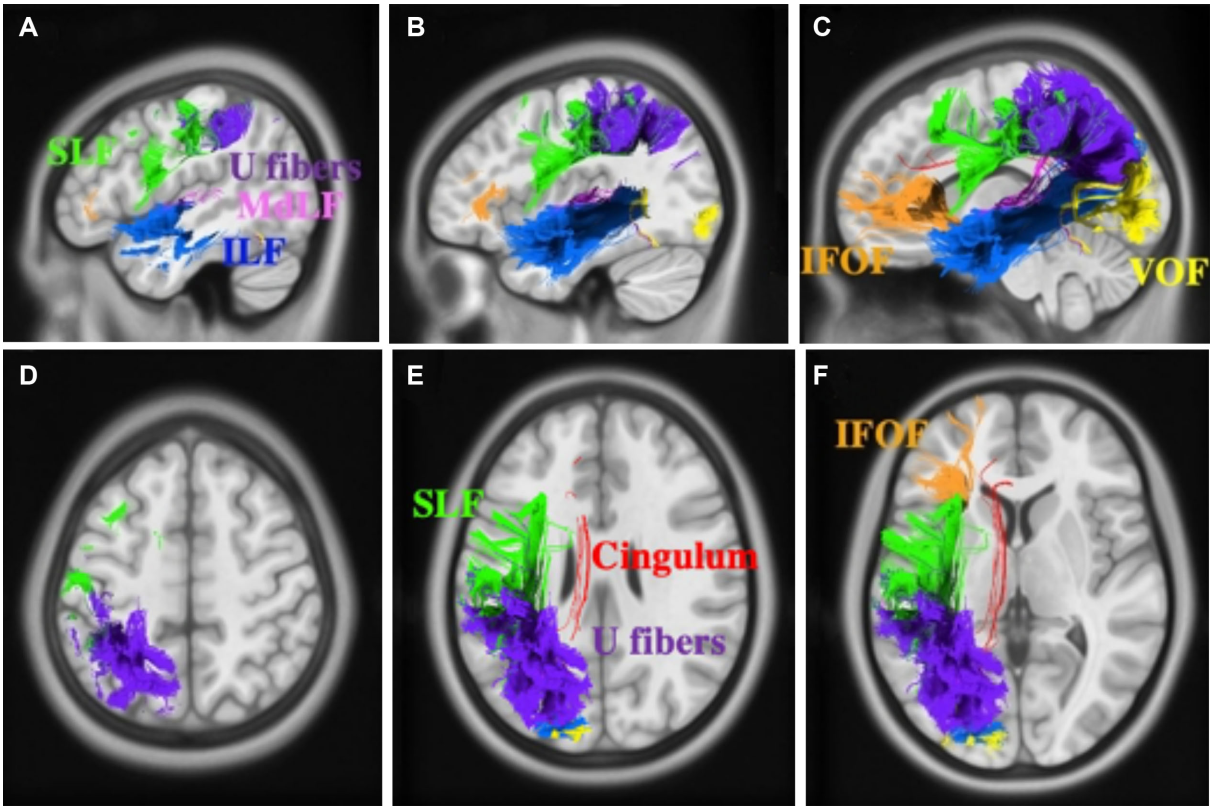

FIGURE 2. *Tractography of association fibers that connect the superior parietal lobule to other cortical areas, including SLF, ILF, MdLF, IFOF, VOF, cingulum, and U-fibers (except the ExtC and corpus callosum).* **A-C**, *Demonstration of the extent of SLF, U-fibers, MdLF, ILF, IFOF, and VOF fiber projections as shown in sagittal sections from lateral-medial.* **D-F**, *Termination of SLF, U-fibers, cingulum, and IFOF fibers as shown in axial sections from the posterior to anterior.*

VOF

The VOF arises from the posterior end of the SLF and is one of the main observable pathways that is involved in SPL connections to its adjacent cortical areas, including the inferior temporal and fusiform gyri of the temporal lobe (giving a "C-shape" morphology), cuneus, lateral occipital lobe, and lingual gyrus of the occipital lobe, and cingulate gyrus, pericalcarine cortex, and inferior parietal lobule of the limbic and parietal lobe respectively (Figures 8 and 9).

ILF

ILF arise from the posterior region of the SPL, and is one of the major association fibers that connects the SPL to the temporal occipital and limbic lobes. For temporal connections, the ILF travels down towards the posterior end of the insula and gives branches that connect the SPL to Heschl's gyrus and fusiform gyrus as well as the superior, middle, and inferior temporal gyri. For the limbic lobe, cingulate and parahippocampal gyri are also observed to be connected to the SPL via ILF fibers (Figures 10 and 11).

IFOF

IFOF arises within the posterior aspect of the SPL, coursing deep to the SLF. The IFOF projects inferiorly into the occipital and posterior temporal lobe, and after curving medially into the extreme and external capsules within the insula, IFOF fibers then inflect superiorly approximately at the point where they meet the central sulcus of the insula. At the superior border of the insula short gyrus, some fibers travel anteriorly to terminate in the superior and middle frontal gyrus, whereas the others deflect laterally to terminate in the lateral orbitofrontal cortex and the inferior frontal gyrus (Figures 12 and 13).

Cingulum

Cingulum arises from the posterior surface of the SPL and enters the subcortical white matter before travelling longitudinally above the corpus callosum. Cingulum is one of the association fibers that is involved in the connection of the SPL with other cortical regions, including the precuneus of the parietal lobe and the cingulate gyrus of the limbic lobe (Figure 14).

TABLE 2. Lateralization Index (LI) of White Matter Tracts of the Superior Parietal Lobule

	SLF			ILF			IFOF		
Participant	**R**	**L**	**LI**	**R**	**L**	**LI**	**R**	**L**	**LI**
1	6.58	2.17	0.50	4.05	1.41	0.48	3.93	9.04	−0.39
2	24.39	22.15	0.05	116.69	72.83	0.23	146.13	139.86	0.02
3	10.92	13.87	−0.12	70.67	0.00	1.00	0.00	0.00	0.00
4	1.05	1.03	0.01	0.45	2.12	−0.65	7.16	0.00	1.00
5	21.63	8.04	0.46	65.48	0.00	1.00	0.00	0.00	0.00
6	3.98	26.88	−0.74	80.70	19.89	0.60	70.41	41.13	0.26
7	21.63	8.04	0.46	3.61	68.50	−0.90	0.00	0.00	0.00
8	3.98	26.88	−0.74	42.68	1.72	0.92	63.96	9.02	0.75
9	6.58	0.76	0.79	78.85	4.02	0.90	12.23	14.24	−0.08
10	1.17	10.01	−0.79	3.55	27.33	−0.77	13.92	31.78	−0.39
Averages	10.19	11.98	−0.08	46.67	19.78	0.40	31.77	24.51	0.13
P-value		.67			.10			.29	
	Cingulum			**ExtC**			**VOF**		
Participant	**R**	**L**	**LI**	**R**	**L**	**LI**	**R**	**L**	**LI**
1	20.70	54.65	−0.45	17.49	93.50	−0.68	0.32	1.16	−0.57
2	84.05	85.93	−0.01	101.77	43.89	0.40	3.99	2.72	0.19
3	0.00	0.00	0.00	0.00	0.00	0.00	5.78	0.68	0.00
4	109.00	0.00	1.00	0.00	51.67	−1.00	3.57	1.21	0.49
5	58.92	115.00	−0.32	2.84	0.00	1.00	0.90	0.59	0.21
6	0.00	98.50	−1.00	9.63	19.41	−0.34	2.03	0.34	0.71
7	8.15	20.20	−0.43	3.12	3.42	−0.05	0.64	0.24	0.45
8	2.70	5.62	−0.35	23.75	59.92	−0.43	0.59	1.03	−0.27
9	7.37	28.86	−0.59	108.50	24.20	0.64	0.32	0.53	−0.25
10	63.00	165.00	−0.45	26.67	0.00	1.00	0.48	0.79	−0.24
Averages	35.39	57.38	−0.24	29.38	29.60	0.00	1.86	0.93	0.33
P-value		.27			.99			.13	
	MdLF			**U-fibers**			**Corpus callosum**		
Participant	**R**	**L**	**LI**	**R**	**L**	**LI**	**/**		
1	2.25	15.59	−0.75	1.24	0.84	0.19	6.28		
2	34.06	25.76	0.14	8.22	5.24	0.22	77.08		
3	0.00	0.00	0.00	1.15	0.78	0.19	0.00		
4	10.25	0.00	1.00	1.55	1.23	0.12	14.45		
5	6.62	37.58	−0.70	1.91	1.10	0.27	45.29		
6	2.73	2.62	0.02	1.38	1.20	0.07	42.82		
7	52.00	0.00	1.00	1.22	1.21	0.00	0.02		
8	5.64	0.09	0.97	1.22	0.89	0.16	0.06		
9	46.49	3.34	0.87	1.71	0.97	0.28	12.45		
10	38.31	0.00	1.00	0.59	0.80	−0.15	0.00		
Averages	19.84	8.50	0.40	2.02	1.43	0.17	19.84		
P-value		.53			.07		/		

LI was calculated utilizing the formula (Right volume − Light volume)/(Right volume + Left volume). R, right hemisphere; L, left hemisphere.

ExtC

The ExtC arises from the medial surface of the SPL and descends into the white matter immediately. It travels anteriorly and inferiorly to bifurcates at the posterior end of the lentiform nucleus, where the fibers then terminate at the insula and superior temporal gyrus (Figure 15).

Paired Connections

Paired association fibers also arise from the SPL and project through the posterior body of the corpus callosum before terminating in the contralateral parietal lobe (Figure 16). These connections are organized into two distinct bands: an anterior tract connecting the anterior body of each SPL and a posterior tract arising from the inferomedial portion of each SPL (Figure 14).

DISCUSSION

With advances in neuroimaging and multimodal navigation, the ability to identify functional tracts during cranial operations

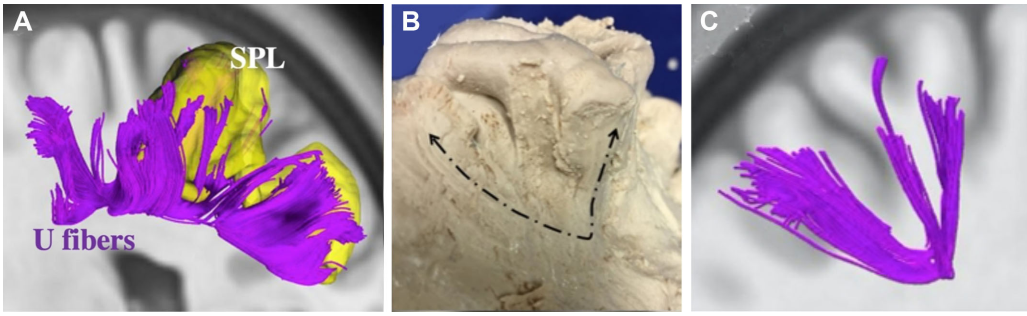

FIGURE 3. *Short association fibers ("U-fibers") located in the parietal lobe. Their distinct U-shaped morphology is illustrated* **A**. *Isolated U-fiber bundle mediating intraparietal connectivity is shown in gross dissection* **B** *and its tractographic counterpart in* **C**.

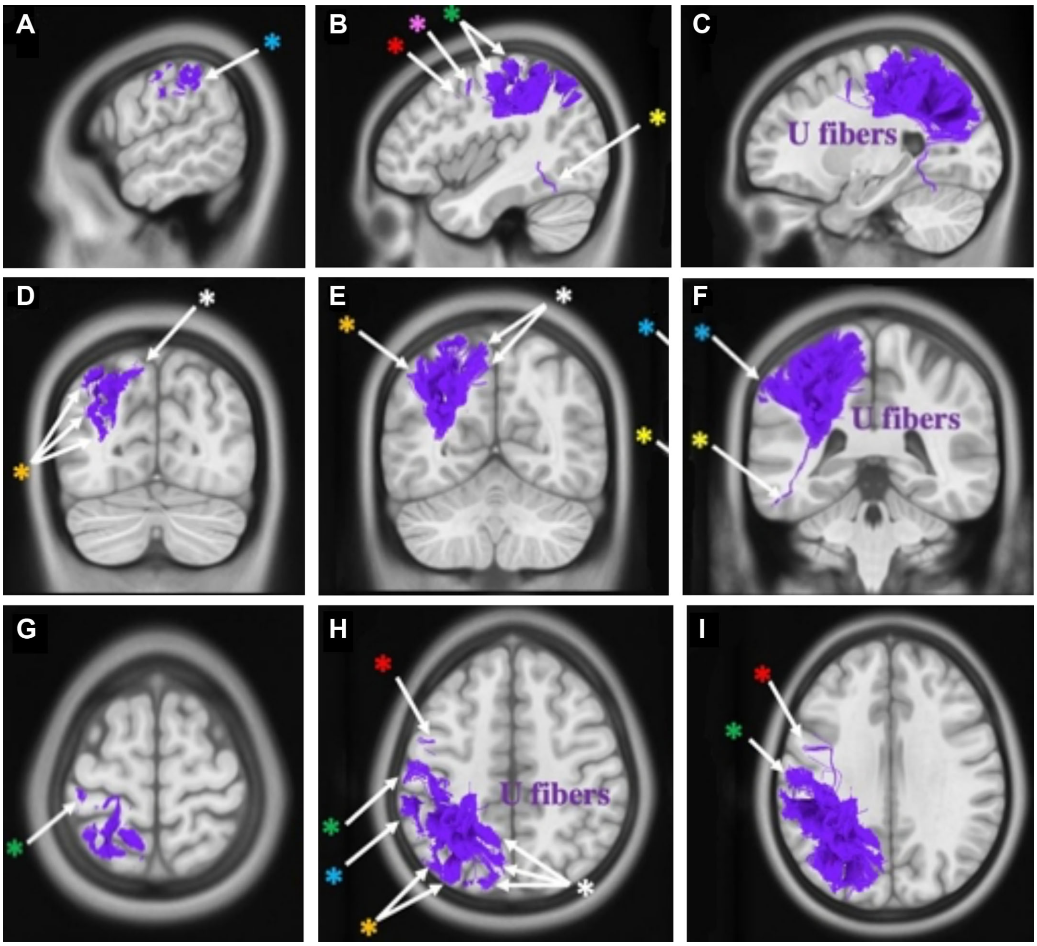

FIGURE 4. *Demonstration of U-fibers located in the superior parietal lobule as seen with tractographic analyses.* **A-C**, *The extent of U-fiber projections is seen with sagittal sections from lateral-medial.* **D-F**, *Termination of the U-fibers in the superior parietal lobule as seen in coronal sections from the posterior-anterior.* **G-I**, *Termination of the U-fibers in the superior parietal lobule as seen in axial sections from the posterior-anterior. U-fibers are shown connecting the SPL to multiple other cortical regions, including the precuneus (white star), the middle frontal gyrus (red star), the inferior parietal lobule (orange star), the precentral gyrus (Pink Star), the postcentral gyrus (green star), the inferior temporal gyrus (yellow star), and then supramarginal gyrus (blue star).*

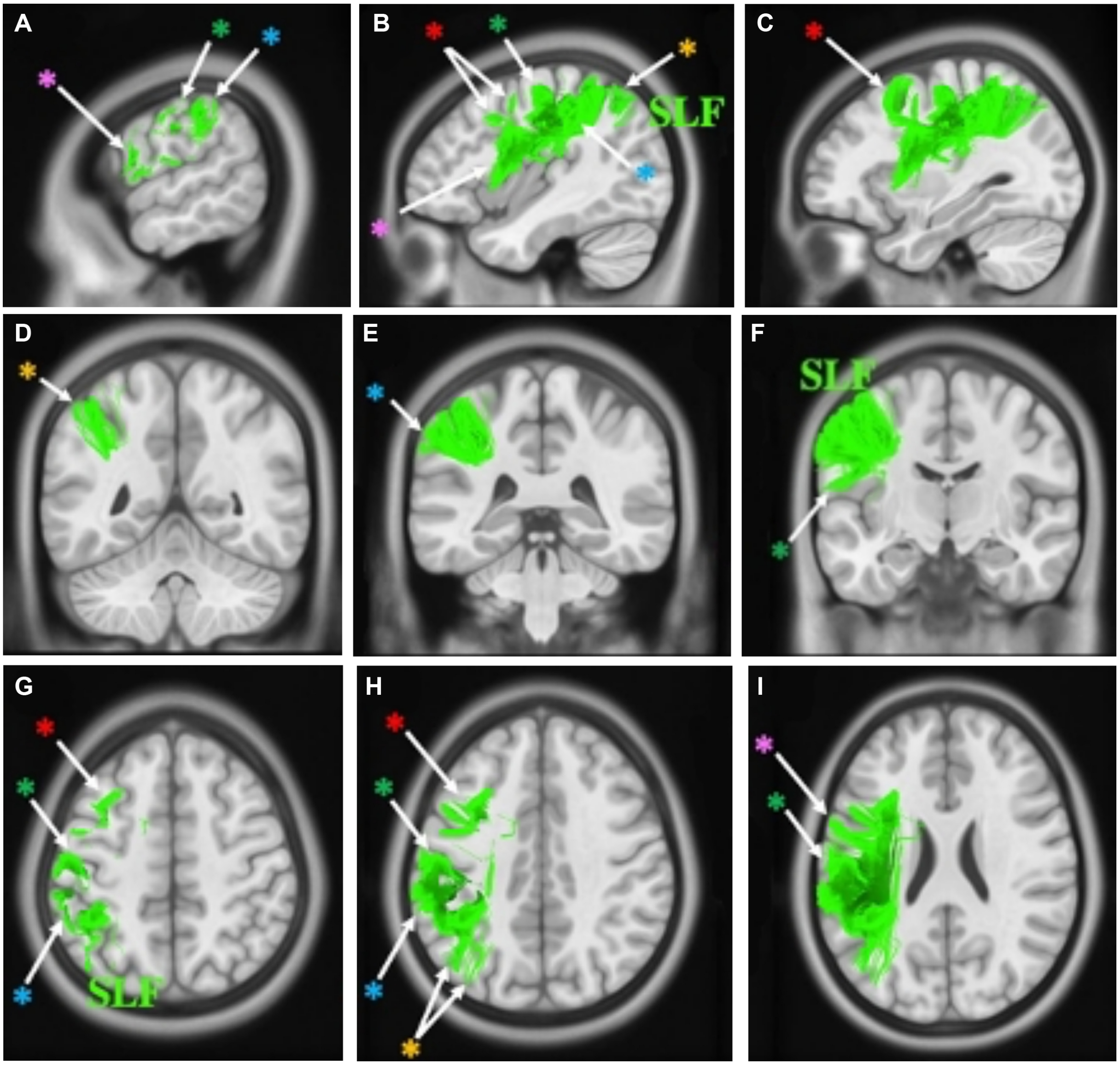

FIGURE 5. *Representation of the SLF fibers, which begin in the superior parietal lobule.* **A-C**, *Demonstration of the extent of SLF fibers, which project between the frontal and parietal lobes as seen in sagittal sections from lateral-medial.* **D-F**, *Termination of SLF fibers in the parietal lobe as seen in coronal sections from the posterior-anterior.* **G-I**, *Termination of U-fibers at the frontal and parietal lobes as seen in axial sections from the posterior-anterior. SLF fibers are shown connecting the SPL to multiple other cortical regions, including the middle frontal gyrus (red star), the inferior parietal lobule (orange star), the precentral gyrus (pink star), the postcentral gyrus (green star), and the supramarginal gyrus (blue star).*

to minimize complications are promising, but still inadequate for effectively understanding and guiding the surgical treatments. Therefore, this study aims to present information that can be readily applied to current surgical techniques and clinical managements to minimize postoperative complications and facilitate patient recovery.

Our study uses diffusion tractography validated by gross anatomic dissection to identify relevant white matter tracts that can be utilized to preserve the cortical networks during cerebral surgery. In this study, we have outlined the underlying subcortical anatomy of the superior parietal lobe, a major part of the cortex involved in multiple white matter pathways, as well as discuss

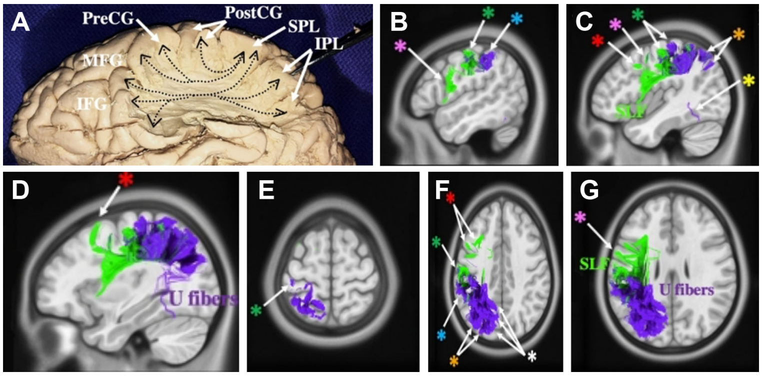

FIGURE 6. *White matter anatomy of the SLF and U-fibers that originate from the superior parietal lobule (SPL).* **A**, *Gross anatomy dissection of white matter fibers.* **B-D**, *Demonstration of the extent of U-fiber and SPL fibers projections as seen in sagittal sections from lateral-medial.* **E-G**, *Termination of U-fibers as seen in axial sections from the posterior-anterior. Association fibers are shown connecting the SPL to multiple other cortical regions, including the precuneus (white star), the middle frontal gyrus (red star), the inferior parietal lobule (orange star), the precentral gyrus (pink star), the postcentral gyrus (green star), the inferior temporal gyrus (yellow star), and the supramarginal gyrus (blue star). SPL: superior parietal lobule; IPL: inferior parietal lobule; MFG: middle frontal gyrus; IFG: inferior frontal gyrus.*

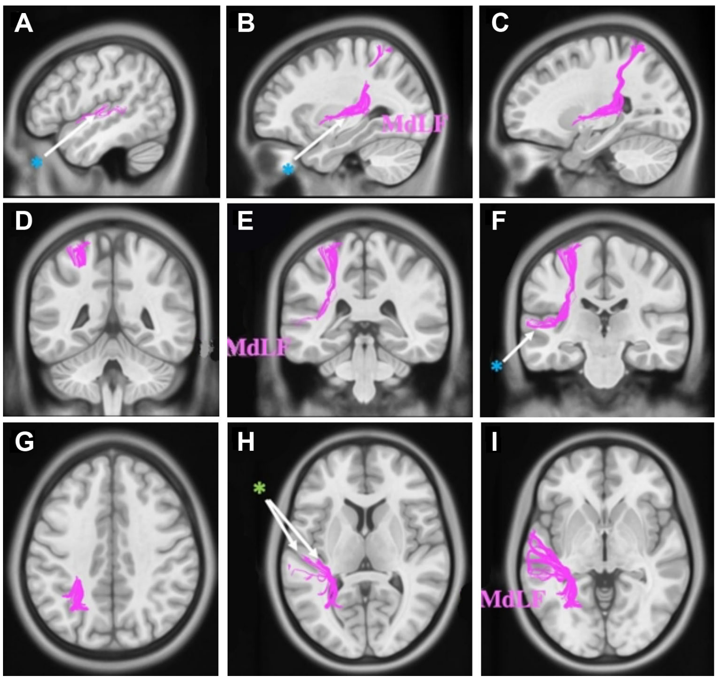

FIGURE 7. *Representation of the MdLF fibers, which originate from the superior parietal lobule as seen with tractographic analyses.* **A-C**, *Demonstration of the extent of MdLF fibers, which project between the temporal and parietal lobes as seen in sagittal sections from lateral-medial.* **D-F**, *Termination of MdLF fibers at the superior temporal gyrus as seen in coronal sections from the posterior-anterior.* **G-I**, *Termination of MdLF fibers at the Heschl's gyrus of the temporal lobe as seen in axial sections from the posterior-anterior. MdLF fibers are shown connecting the SPL to the superior temporal gyrus (blue star) and to Heschl's gyrus (green star).*

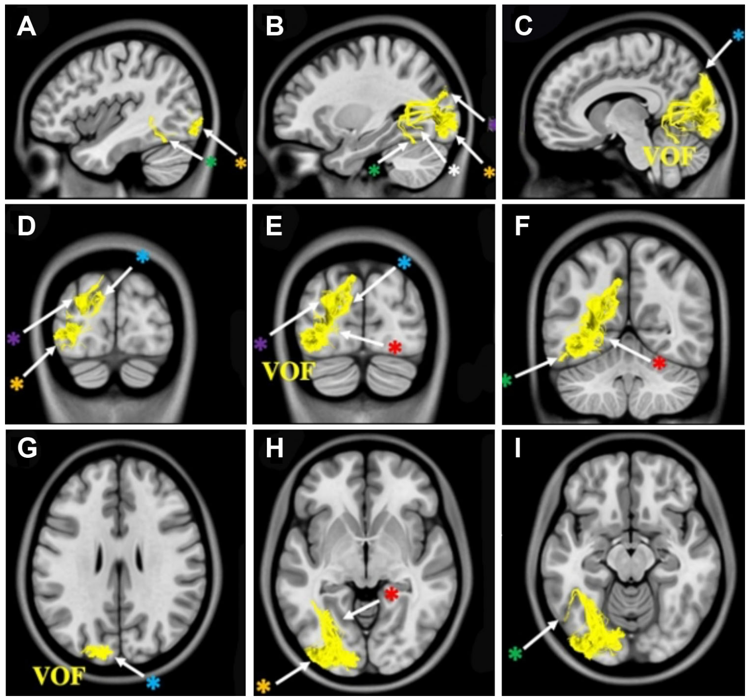

FIGURE 8. *Tractographic representation of the VOF fibers, which originate from the superior parietal lobule.* **A-C**, *Demonstration of the extent of VOF projections between frontal and occipital lobes as seen in sagittal sections from lateral-medial.* **D-F**, *Termination of VOF fibers at the pericalcarine cortex and precuneus of the occipital and parietal lobes as seen in coronal sections from posterior-anterior.* **G-I**, *Termination of VOF fibers at the frontal and occipital lobes as seen in axial sections from the posterior-anterior. The VOF is shown connecting the SPL to multiple other cortical regions, including the cuneus (blue star), the inferior temporal gyrus (green star), the lateral occipital cortex (orange star), the lingual gyrus and pericalcarine cortex (red star), the inferior parietal lobule (purple star), the fusiform gyrus (white star).*

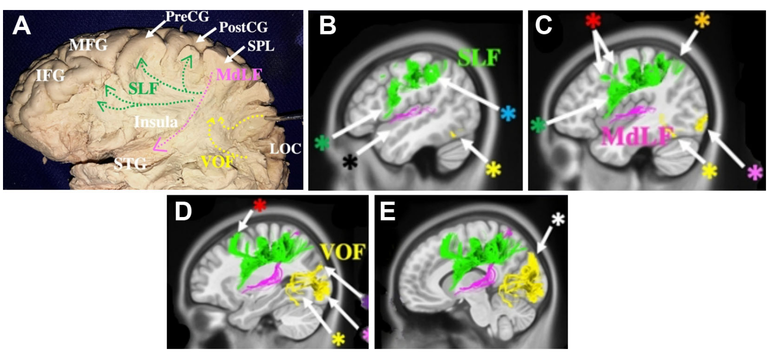

FIGURE 9. *White matter anatomy of the SLF, MdLF, and VOF that originate from the superior parietal lobule (SPL).* **A**, *Gross anatomy dissection of white matter fibers, including the SLF, MdLF, and VOF.* **B-E**, *Demonstration of the extent of SLF, MdLF, and VOF projections as seen in sagittal sections from lateral-medial. The VOF can be seen connecting the SPL to multiple other cortical regions, including: the inferior temporal gyrus (yellow star), the lateral occipital cortex (pink star), the inferior parietal lobule (purple star), the cuneus (white star), the middle frontal gyrus (red star), the inferior parietal lobule (orange star), the precentral gyrus (green star), the supramarginal gyrus (blue star), and the superior temporal gyrus (black star). PreCG: precentral gyrus; PostCG: postcentral gyrus; SPL: superior parietal lobule; MFG: middle frontal gyrus; IFG: inferior frontal gyrus; STG: superior temporal gyrus; LOC: lateral occipital cortex.*

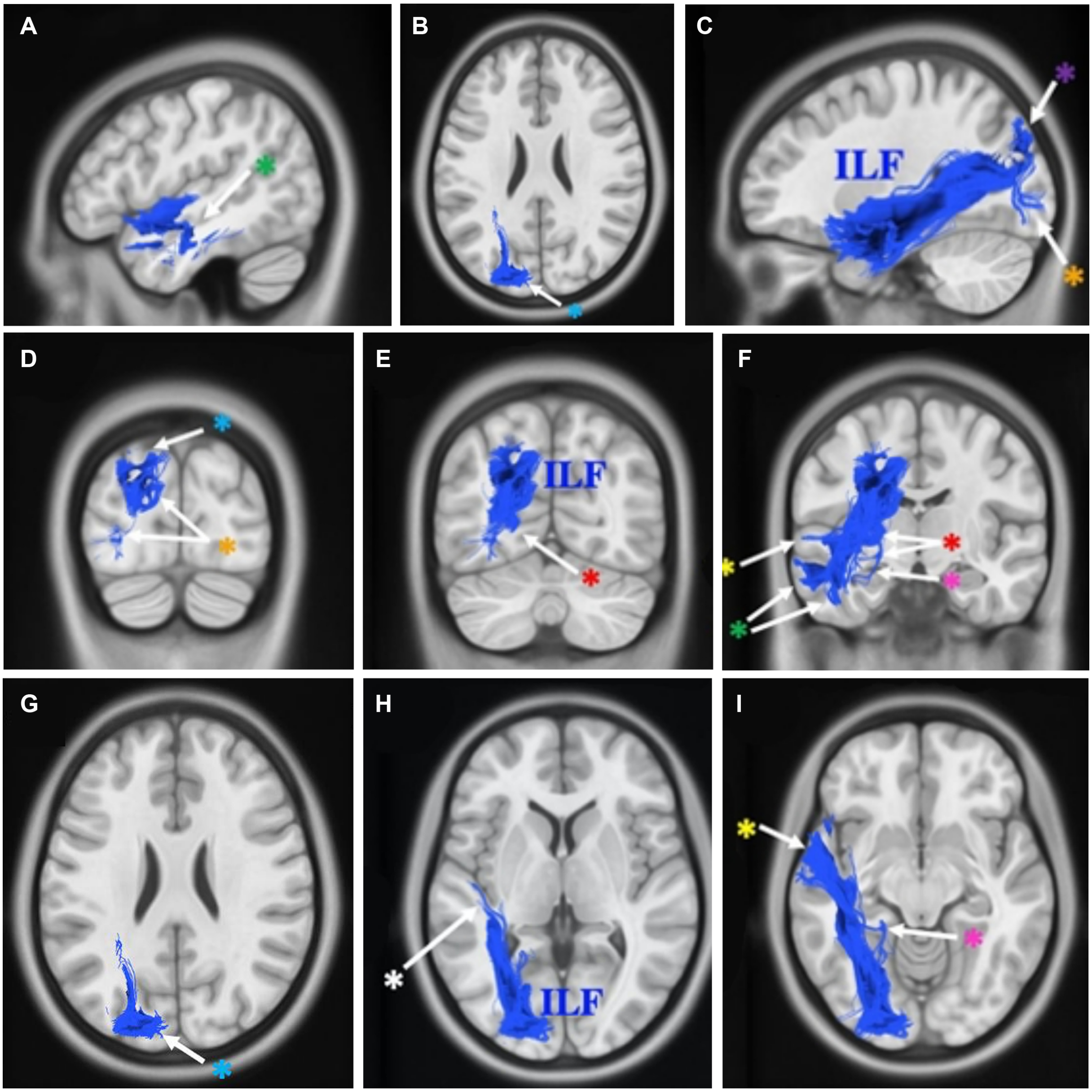

FIGURE 10. *Representation of the ILF fibers, which originate from the superior parietal lobule as seen with tractographic analyses.* **A-C**, *Demonstration of the extent of ILF projections between the temporal and parietal lobes as seen in sagittal sections from lateral-medial.* **D-F**, *Termination of the ILF fibers at the superior temporal gyrus as seen in coronal sections from the posterior-anterior.* **G-I**, *Termination of ILF fibers at the Heschl's gyrus of the temporal lobe as seen in axial sections from posterior-anterior. The ILF fibers are shown connecting the SPL to multiple other cortical regions, including the cuneus (blue star), the middle and inferior temporal gyri (green star), the superior temporal gyrus (yellow star), Heschl's gyrus (white star), and the lateral occipital cortex (orange star).*

its functional significance. From functional magnetic resonance imaging studies, we understand that the SPL facilitates the performance of high-cognitive neurological tasks, specifically regarding visuomotor and visuospatial skills as well as attention, memory, and language.

The Superior Parietal Lobule and Visuomotor and Visuospatial Skills

Visual information is processed in two streams, including the ventral and dorsal streams, where visual information is processed

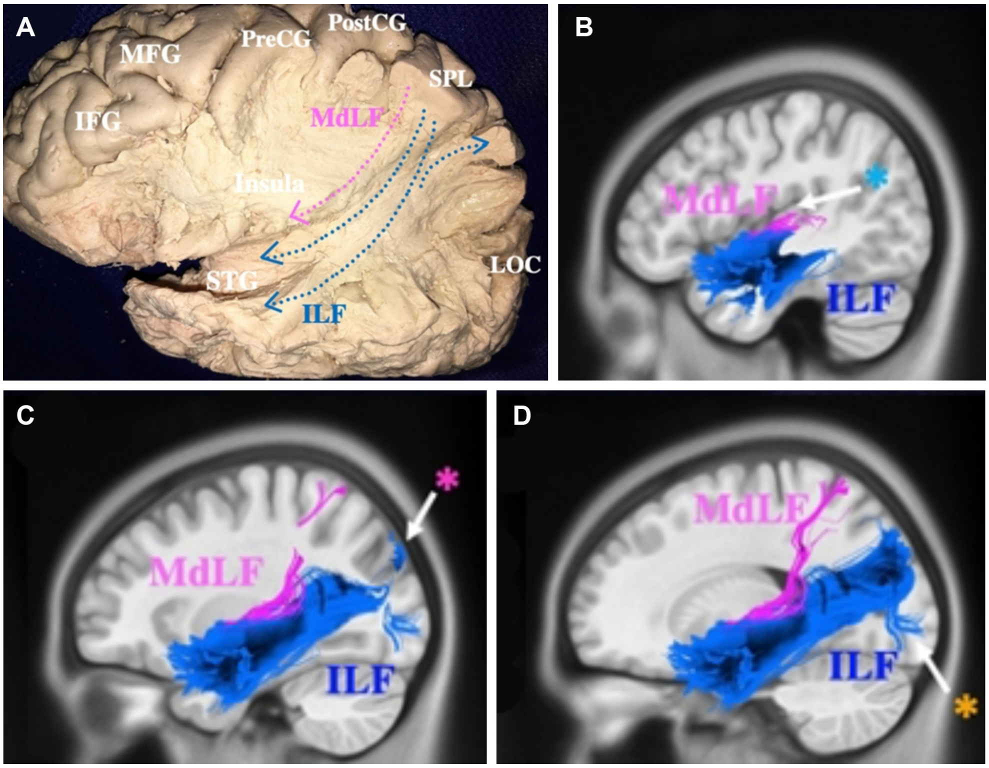

FIGURE 11. *White matter anatomy of the MdLF and ILF that originate from the superior parietal lobule (SPL).* **A**, *Gross anatomy dissection of white matter fibers, including the MdLF and ILF.* **B-D**, *Demonstration of the extent of MdLF and ILF fibers projections as seen in sagittal sections from lateral-medial. The MdLF can be seen connecting the SPL to the superior temporal gyrus (blue star). The ILF fibers can be seen connecting the SPL to the inferior parietal lobule (pink star) and the lateral occipital cortex (orange star). PreCG: precentral gyrus; PostCG: postcentral gyrus; SPL: superior parietal lobule; MFG: middle frontal gyrus; IFG: inferior frontal gyrus; STG: superior temporal gyrus; LOC: lateral occipital cortex.*

for visual perception and action control correspondingly.[22,23] Based on the anatomy and function of the dorsal stream, it is further presented as the dorso-dorsal and ventro-dorsal streams, where SPL and inferior parietal lobule are two of the termination sites respectively.[22] Damage to the dorso-dorsal stream results in optic ataxia, which is known to be a deficit in vision-related motor control.[22,24] Concordantly, as a termination site of the dorso-dorsal stream, the SPL is critical in spatially and kinesthetically dependent motor functions, with implications in defective visually guided reaching,[2,25] ideomotor apraxia,[26] and ideational apraxia.[3]

Given that the SPL is thought to have its functional role in space perception,[22] its abnormality could result in visual-spatial processing impairments, as seen with underdeveloped SPL grey matter in patients with Williams Syndrome.[27] Several studies have also demonstrated regional based SPL functional activation during visuomotor and visuospatial tasks.[10,28] Given the understanding of these functional roles, some have proposed that the SPL serves as a hub between visual input processing centers and subsequent motor output as well as further possible roles in motor learning.[29,30]

The Superior Parietal Lobule and Attention, Memory, and Language

The SPL has been implicated in the shifting of attention in a number of studies.[5,31] Bilateral activation of the SPL can be seen during tasks requiring attention shifts between visual targets[32] as well as in spatial-related attention shifts.[33] Interestingly, it has been proposed that the SPL may have a more specific, transient role in the act of shifting between attentive states rather than maintaining any one specific attentive state.[34]

The SPL also plays a role in working memory.[10,35] Meta-analytic data on functional studies support the role of the superior parietal cortex in executive functions and cognitive tasks, which specifically facilitate the manipulation of items obtained from working memory.[9] SPL lesions are associated with deficits in manipulation and rearrangement of information

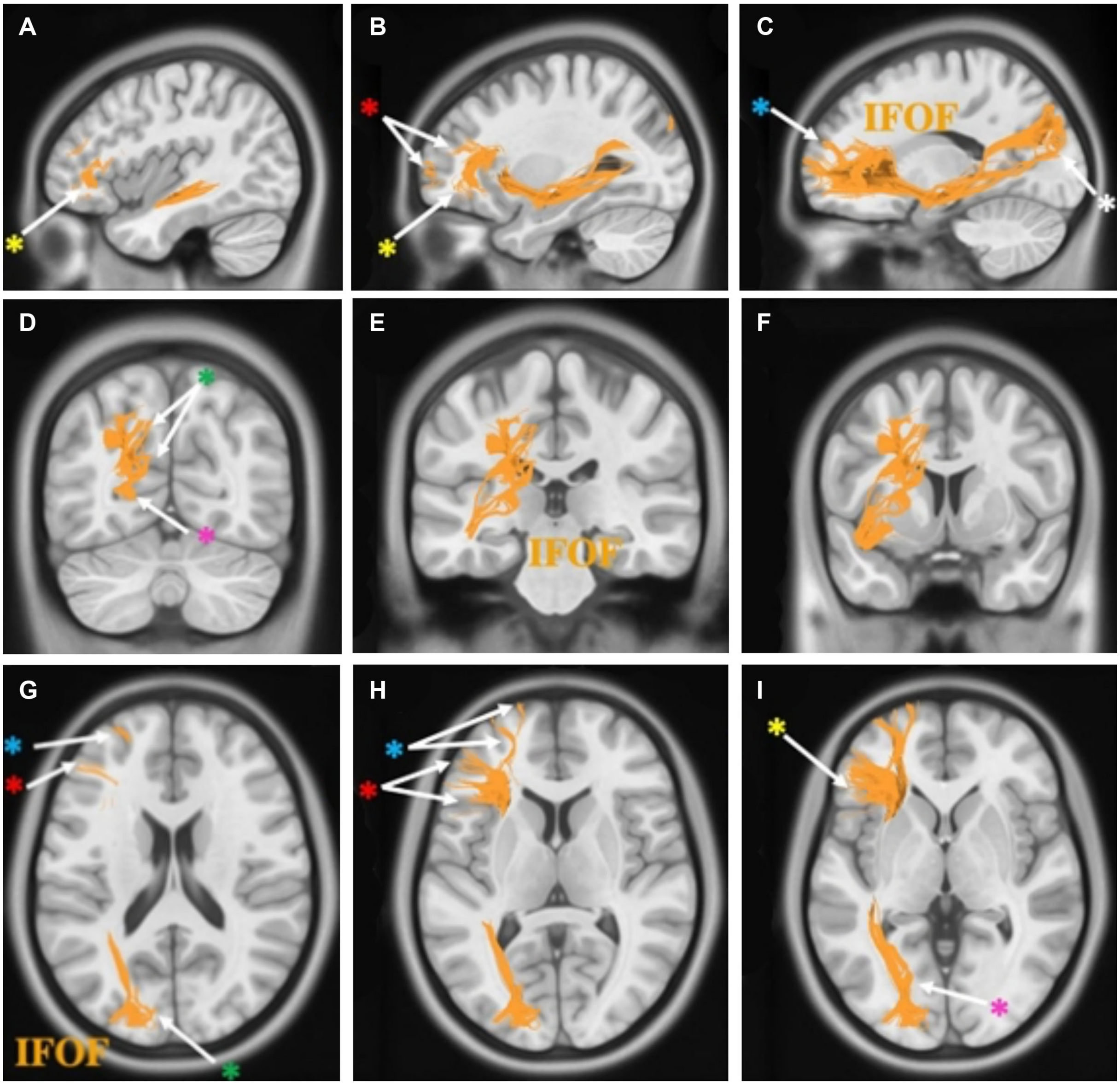

FIGURE 12. *White matter anatomy of IFOF, which can be seen originating from the superior parietal lobule.* **A-C**, *Demonstration of the extent of IFOF projections between frontal and occipital lobes as seen in sagittal sections from lateral-medial.* **D-F**, *Termination of IFOF fibers at the pericalcarine cortex and precuneus of the occipital and parietal lobes as seen in coronal sections from the posterior-anterior.* **G-I**, *Termination of IFOF fibers at the frontal and occipital lobes as seen in axial sections from the posterior-anterior. The IFOF fibers can be seen connecting the SPL to the lateral occipital lobe (white star), the precuneus (green star), the middle frontal gyrus (red star), the inferior frontal gyrus (yellow star), the pericalcarine cortex (pink star), and the superior frontal gyrus (blue star).*

in the working memory for both auditory-verbal and visual-spatial stimuli, but not simple retention and retrieval of information in working memory.[10] Other lesion and stroke studies suggest additional roles of the SPL in the executive rearrangement of working memory information,[10] sequential memory required for sequence writing,[36] and in organization of spatial and kinesthetic information within working memory.[37,38]

SPL is responsible for higher-level cognitive functioning given that its functional connectivity offers modifications and interactions between the SPL and various language and motor areas during the course of writing. The left rostral SPL has

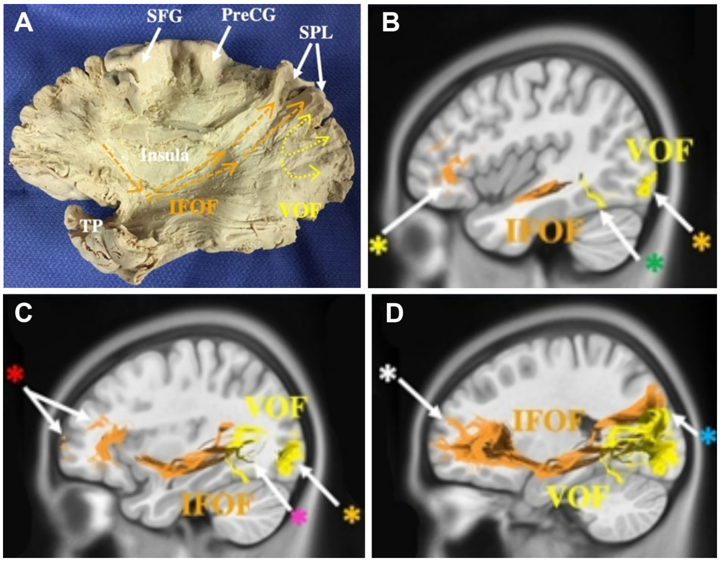

FIGURE 13. *White matter anatomy of the IFOF and VOF that originate from the superior parietal lobule (SPL).* **A**, *Gross anatomy dissection of white matter fibers, including the IFOF and VOF.* **B-D**, *Demonstration of the extent of IFOF and VOF projections as seen in sagittal sections from lateral-medial. The IFOF (orange) can be seen connecting the SPL to multiple other cortical regions, including the middle frontal gyrus (red star), the inferior frontal gyrus (yellow star), and the superior frontal gyrus (white star). The VOF fibers (yellow) can be seen connecting the SPL to the lateral occipital cortex. The VOF connects the SPL to the inferior temporal gyrus (green star) and the fusiform gyrus (pink star). The association fibers connects the SPL to inferior parietal lobule (blue star). PreCG: precentral gyrus; SPL: superior parietal lobule; SFG: superior frontal gyrus; TP: temporal pole.*

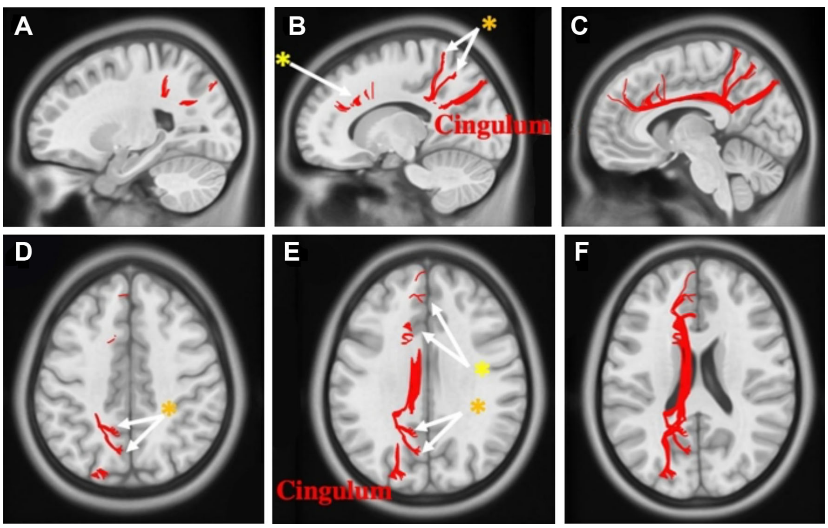

FIGURE 14. *White matter anatomy of the cingulum demonstrating its origin from the superior parietal lobule.* **A-C**, *Demonstration of the extent of cingulum projections between the frontal and parietal lobes as seen in sagittal sections from lateral-medial.* **D-F**, *Termination of cingulum fibers at the frontal and parietal lobes as seen in axial sections from the posterior-anterior. The cingulum is shown connecting the SPL to the cingulate gyrus (yellow star) and the precuneus (orange star).*

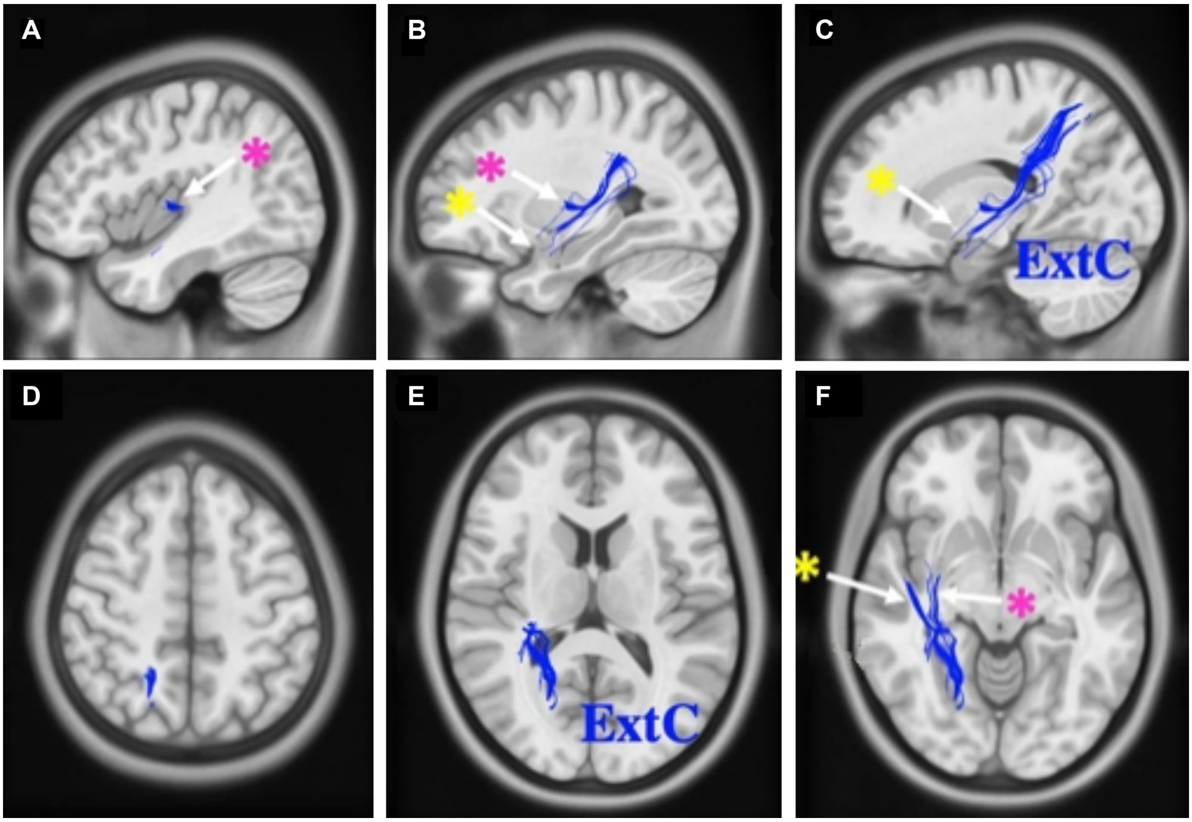

FIGURE 15. *Tractographic representation of the ExtC, which originates from the superior parietal lobule.* **A-C**, *Demonstration of the extent of ExtC projections between the temporal and parietal lobes as seen in sagittal sections from lateral-medial.* **D-F**, *Termination of the ExtC at the superior temporal gyrus and insula of the temporal lobes as seen in axial sections from the posterior-anterior. The cingulum is shown connecting the SPL to the superior temporal gyrus (yellow star) and the insula (pink star).*

been proposed as a major cortical hub between the motor and language networks of the brain[13] and has been thought to be essential for writing because of its role in sensorimotor linguistic integration, which is also supported by lesion studies.[2,11] The rostral part of the SPL, known as area PE, is a major cortical hub between the motor and language brain and is flexible in interacting with multiple cortical areas that are involved in reading, verbal retrieval, and subvocal articulation of speech.[39]

Future Directions

Although tractography provides vivid, qualitative anatomical descriptions of brain networks, quantitative analyses should be viewed cautiously because of individual differences. Still, based on this current project, a thorough understanding of the on-passage tracts surrounding the SPL can create a surgical plane in which surgeons navigate to minimize unnecessary neurologic deficit by preserving relevant white matter tracts.[40] For instance, we demonstrate the SLF (II) originates in the posterolateral parietal cortex within the angular gyrus and travels lateral to the SPL to the intraparietal sulcus before terminating in the dorsolateral prefrontal cortex. Therefore, intraoperative knowledge of the intraparietal sulcus as a lateral boundary surrounding an SPL lesion can be applied to create a safe surgical corridor that preserves the SLF (II) tract to limit postoperative visuospatial deficits.[19]

CONCLUSION

The SPL is an important region implicated in a variety of tasks, including language processing, writing, working memory, attention, and visuospatial and visuomotor integration. The corresponding cerebral networks related to these functions involve a complex series of white matter tracts described in this study. Improved understanding of the SPL white matter connectivity and implementation of perioperative tractography in multimodal navigation of white matter lesions are invaluable additions to the neurosurgical armamentarium.

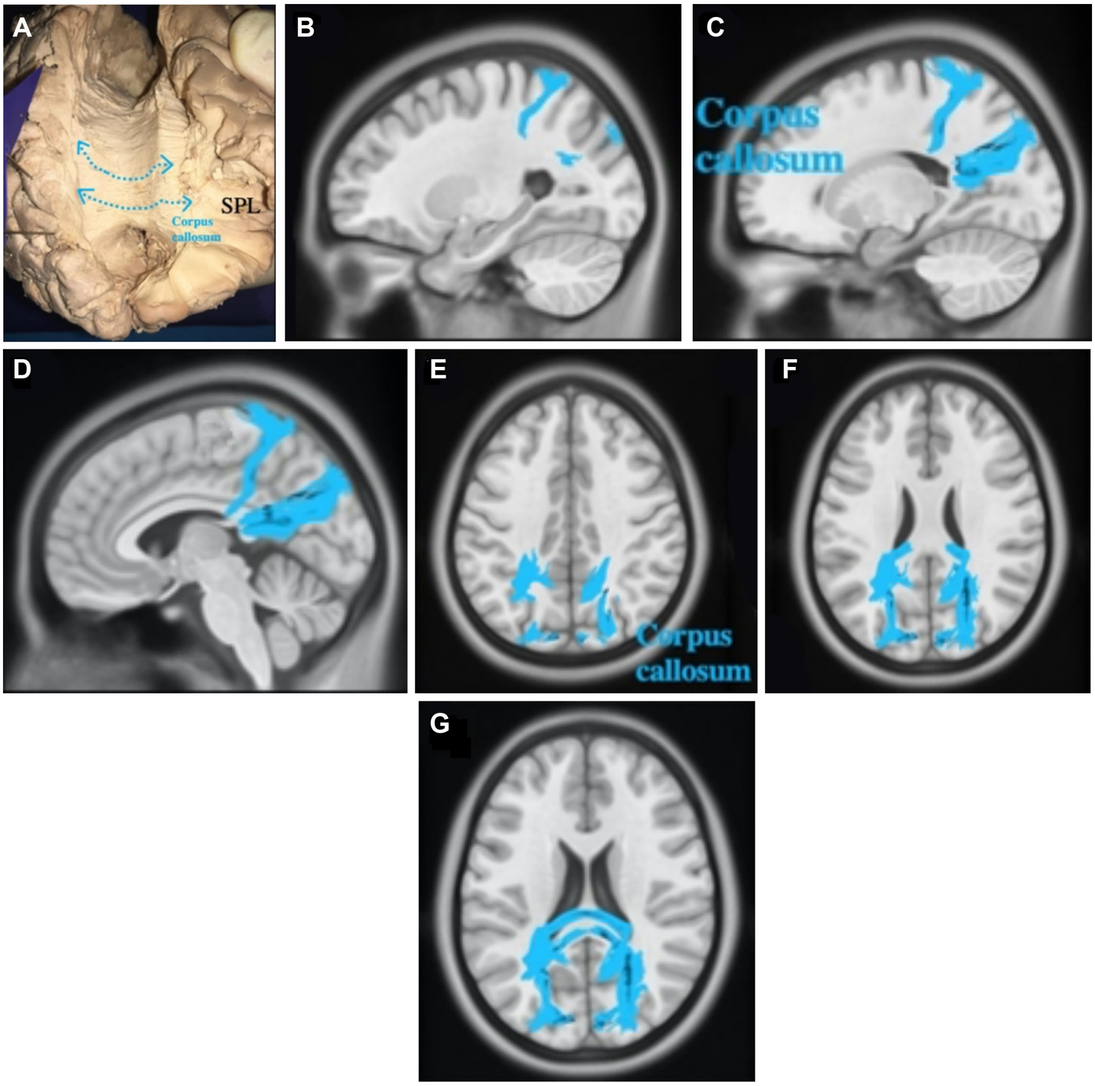

FIGURE 16. A, *A gross anatomy dissection of corpus callosum that connects the superior parietal lobule from the opposite hemisphere.* B-D, *Sagittal sections from lateral to medial demonstrating the corpus callosum, which arises from the superior parietal lobule and projects between the left and right hemispheres.* E-G, *Coronal sections from the posterior to anterior highlighting the termination of corpus callosum. SPL: superior parietal lobule.*

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Supplemental Digital Content. Text. Anatomy and white matter connections of the superior parietal lobule. In this supplemental material, we provide additional information on the specifics of our network-based analysis and tractography as well as elucidate the unique cortical connections in and around the superior parietal lobule with further discussion on their functions.

COMMENT

The authors present an interesting anatomical study of the SPL and its connections using a combination of MR tractography and postmortem dissections. They identified multiple important connections between the SPL and different structures including short U-fibers, superior longitudinal fasciculus, inferior longitudinal fasciculus, inferior fronto-occipital fasciculus, middle longitudinal fasciculus, extreme capsule, vertical occipital fasciculus, cingulum, and the corpus callosum. This offers clinically significant intraoperative knowledge that can contribute to safer outcomes by guiding surgeons through safer surgical corridors between fiber tracts as opposed to disruption of these pathways. The authors note a distinct organization of the paired fibers from the SPL projecting to the posterior corpus callosum before they terminate in the contralateral parietal lobe. It would be interesting to know if these crossing fibers have any intra-callosal crossing between the two bands, and whether there are contributions between the anterior SPL and the contralateral posterior SPL. Knowledge of this may further enlighten our understanding of the extensive local SPL circuitry as well as its connectivity with the contralateral hemisphere. We congratulate the authors for this fine work.

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