

## research papers

# The Contributions of the Arcuate Fasciculus Segments to Language Processing: Evidence from Brain Tumor Patients

### **Andrey Zyryanov**

National Research University Higher School of Economics,  
Moscow, Russia

### **Valeriya Tolkacheva**

European Masters in Clinical Linguistics +,  
University of Groningen, Netherlands

### **Valeriya Zelenkova**

National Research University Higher School of Economics,  
Moscow, Russia

### **Andrey Zuev**

National Medical and Surgical Center named after  
N. I. Pirogov, Moscow, Russia

### **Svetlana Malyutina**

National Research University Higher School of Economics,  
Moscow, Russia;  
Federal Center for Cerebrovascular Pathology and Stroke,  
Moscow, Russia

### **Nikita Pedyash**

National Medical and Surgical Center named after  
N. I. Pirogov, Moscow, Russia

### **Ekaterina Stupina**

National Research University Higher School of Economics,  
Moscow, Russia

### **Oleg Bronov**

National Medical and Surgical Center named after  
N. I. Pirogov, Moscow, Russia

### **Viktor Karpychev**

National Research University Higher School of Economics,  
Moscow, Russia

### **Dmitry Kopachev**

National Medical Research Center for Neurosurgery  
named after N. N. Burdenko, Moscow, Russia

### **Elizaveta Gordeyeva**

National Research University Higher School of Economics,  
Moscow, Russia

### **Igor Pronin**

National Medical Research Center for Neurosurgery  
named after N. N. Burdenko, Moscow, Russia

### **Valeriya Zhirnova**

National Research University Higher School of Economics,  
Moscow, Russia

### **Olga Dragoy**

National Research University Higher School of Economics,  
Moscow, Russia;  
Federal Center for Cerebrovascular Pathology and Stroke,  
Moscow, Russia

### **Anna Artemova**

National Research University Higher School of Economics,  
Moscow, Russia

**Abstract.** The connectivity between perisylvian language areas is subserved by the three segments of the arcuate fasciculus (AF): the long segment (AFLong), connecting posterior temporal and inferior frontal areas, and anterior and posterior segments (AFant, AFpost), connecting the inferior parietal lobule to inferior frontal and posterior temporal areas, respectively. Damage to the AFLong induces conduction aphasia, which manifests itself in impaired repetition likely due to a deficit in sensorimotor integration in speech. However, systematic investigations of the specific contributions of the three AF segments to language processing are lacking. The current study addressed the roles of these white-matter tracts in language production and comprehension at word and sentence levels. We found that lower volume of the AFLong following neurosurgery was associated with a greater deficit in language repetition, consistent with the tract's role in sensorimotor integration in speech. Furthermore, we found that a postoperative decrease in AFLong volume was associated with lower postoperative sentence comprehension abilities. We did not observe any relation between postoperative decreases of the AFant and AFpost volumes, and language deficits. One plausible explanation is that these tracts are not critical for language processing, while the functions they underlie in healthy speakers demonstrate a greater capacity for reorganization during slow brain tumor growth, as opposed to those carried out by the AFLong.

**Correspondence:** Andrey Zyryanov, [zyryanov.andrew@gmail.com](mailto:zyryanov.andrew@gmail.com), Center for Language and Brain, National Research University Higher School of Economics, 21/4 Staraya Basmannaya str., Office 510, 105066 Moscow, Russia; Valeriya Zelenkova, [vzelenkova@hse.ru](mailto:vzelenkova@hse.ru); Svetlana Malyutina, [smalyutina@hse.ru](mailto:smalyutina@hse.ru); Ekaterina Stupina, [estupina@hse.ru](mailto:estupina@hse.ru); Viktor Karpichev, [vkarpichev@hse.ru](mailto:vkarpichev@hse.ru); Elisaveta Gordeyeva, [egordeyeva@hse.ru](mailto:egordeyeva@hse.ru); Valeriya Zhirnova, [evilyval@gmail.com](mailto:evilyval@gmail.com); Anna Artemova, [tema.ankin@gmail.com](mailto:tema.ankin@gmail.com); Valeriya Tolkacheva, [tolkacheva.valeria@gmail.com](mailto:tolkacheva.valeria@gmail.com); Andrey Zuev, [mosbrain@gmail.com](mailto:mosbrain@gmail.com); Nikita Pedyash, [rusneuro@gmail.com](mailto:rusneuro@gmail.com); Oleg Bronov, [bronovou@pirogov-center.ru](mailto:bronovou@pirogov-center.ru); Dmitriy Kopachev, [dmkopachev@gmail.com](mailto:dmkopachev@gmail.com); Igor Pronin, [pronin@nsi.ru](mailto:pronin@nsi.ru); Olga Dragoy, [odragoy@hse.ru](mailto:odragoy@hse.ru)

**Keywords:** neuroanatomy of language, aphasia, white-matter tracts, diffusion tensor imaging, brain tumor, arcuate fasciculus

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**Acknowledgements.** We thank Anna Laurinavichyute for her suggestions regarding data analysis. The study was supported by the Russian Foundation for Basic Research, Grant No. 18-012-00829.

Received December 25, 2018, accepted March 22, 2019.

## Introduction

Growing evidence is challenging the long-held view on Broca's area as critical for language production. In fact, focal Broca's area damage only causes a transient and rapidly recovering language production deficit (Dronkers, Redfern, & Knight, 2000; Penfield & Roberts, 1959). By contrast, damage to the long segment of the arcuate fasciculus (AFLong), the white-matter tract connecting Broca's area and, more broadly, the inferior frontal gyrus (IFG) and the precentral gyrus, to the posterior temporal language areas, causes a severe and largely irreversible Broca's or conduction aphasia (Catani, Jones, & ffytche, 2005). In the same vein, AFLong damage is associated with the severity of the central symptoms of Broca's and conduction aphasia types — impaired syntactic processing (Caramazza, Berndt, Basili, & Koller, 1981; Schwartz, Saffran, & Marin, 1980; Wilson et al., 2015) and repetition (Sierpowska et al., 2017), respectively. This makes a strong case for the critical role of the frontotemporal connectivity via the AF in language production.

However, questions remain regarding the linguistic contribution of the adjacent frontotemporal pathway via the inferior parietal lobule (IPL; Catani et al., 2005). This pathway comprises the posterior (AFpost) and anterior (AFant) segments of the arcuate fasciculus, connecting

the IPL to the posterior temporal and inferior frontal areas, respectively. The IPL is heavily involved in semantic processing during word production, as suggested by extensive functional neuroimaging and lesion evidence (for a review, see Coslett & Schwartz, 2018). Furthermore, IPL lesions impair comprehension of complex syntactic constructions, which is a central linguistic symptom in patients with semantic aphasia (Dragoy, Akinina, & Dronkers, 2017; Luria, 1969; Newhart et al., 2012). Thus, the strong involvement of the IPL in language processing points to a possible role of its white-matter connectivity to the frontal and temporal language areas via the AFant and AFpost in language processing.

To date, the evidence regarding the roles of the AFant and AFpost in language processing remains inconclusive. For example, Fridriksson, Guo, Fillmore, Holland, and Rorden (2013) reported that lower AFant integrity was associated with lower speech fluency in aphasia. By contrast, Basilakos et al. (2014) found that only damage to the junction between the AFant and the frontal aslant tract, but not to the AFant itself, was a significant predictor of lower speech fluency. However, these inconsistencies may arise for methodological reasons. For example, the use of atlas-based estimations of tract integrity (Basilakos et al., 2014) may overlook great individual variability

**Table 1. Participants' Clinical Information**

Participant ID	Age	Sex	Tumor Histopathology	WHO Grade	Anatomical Location	Normalized Resection Cavity Volume, cm <sup>3</sup>	AF Segments Damaged <sup>1</sup>	Days Between Surgery and Postoperative Language Assessment	Days Between Surgery and Postoperative DTI	Scanner
1	35	female	astrocytoma	3	frontal	24.6	AFlong, AFant	2	2	GE HDxt
2	41	male	oligodendroglioma	3	frontal, parietal	43.0	AFlong, AFant, AFpost	4	1	Siemens Skyra
3	49	male	oligodendroglioma or astrocytoma <sup>2</sup>	2	frontal	12.6	None	4	5	GE HDxt
4	53	female	glioblastoma	4	frontal, temporal, insula	64.6	AFlong, AFant	4	1	Siemens Skyra
5	43	male	astrocytoma	2	frontal	14.0	AFant	4	0	GE HDxt
6	30	female	astrocytoma	2	temporal, insula	23.3	AFant	32	4	GE HDxt
7	26	male	astrocytoma	2	temporal	31.7	AFlong	9	4	GE HDxt
8	27	male	astrocytoma	2	frontal	58.0	AFlong, AFant	5	3	Siemens Skyra
9	30	male	astrocytoma	3	temporal	31.8	AFant	3	1	GE HDxt
10	47	female	oligodendroglioma	3	frontal	50.4	AFant	2	4	GE HDxt
11	38	male	astrocytoma	3	frontal	31.9	AFlong	4	NA	GE HDxt
12	43	male	astrocytoma	3	temporal	48.8	AFlong, AFpost	5	1	Siemens Skyra
13	59	male	astrocytoma	2	frontal	7.7	AFlong, AFant	6	6	GE HDxt
14	21	female	astrocytoma	2	temporal, insula	39.6	AFlong, AFant, AFpost	4	1	Siemens Skyra
15	35	male	astrocytoma	3	frontal	12.0	AFant	2	1	GE HDxt
16	49	female	oligodendroglioma or astrocytoma <sup>2</sup>	3	temporal	19.7	AFlong, AFpost	1	5	GE HDxt
17	31	female	ganglioglioma	1	temporal	28.3	AFlong, AFant	3	24	GE HDxt
18	40	male	astrocytoma	2	frontal	59.0	AFlong, AFant	6	1	Siemens Skyra
19	34	female	astrocytoma	3	temporal, insula	35.9	AFlong, AFant	4	6	GE HDxt
20	30	male	astrocytoma	2	temporal, insula	21.0	AFlong, AFpost	2	7	GE HDxt
21	46	male	astrocytoma	2	temporal	21.9	AFlong	4	5	GE HDxt
22	44	female	glioblastoma	4	temporal, insula	124.6	AFant	5	1	Siemens Skyra
23	53	female	oligodendroglioma or astrocytoma <sup>2</sup>	3	frontal	27.7	None	1	4	GE HDxt
24	63	male	astrocytoma	2	temporal, insula	39.9	AFlong, AFant, AFpost	4	1	Siemens Skyra
25	43	female	oligodendroglioma or astrocytoma <sup>2</sup>	2	frontal	14.5	AFant	4	12	GE HDxt
26	26	male	astrocytoma	2	frontal	12.2	AFlong, AFant	2	5	GE HDxt
27	31	male	astrocytoma	2	temporal	26.3	AFlong, AFant, AFpost	2	21	GE HDxt
28	55	female	astrocytoma	2	temporal	9.5	AFlong, AFant, AFpost	2	1	Siemens Skyra
29	19	male	astrocytoma	3	temporal	40.7	AFlong, AFant, AFpost	6	1	GE HDxt
30	28	male	oligodendroglioma	3	frontal	44.0	AFpost	1	4	GE HDxt
31	33	male	astrocytoma	2	frontal, insula	22.1	AFlong, AFpost	4	4	GE HDxt
32	33	male	astrocytoma	2	temporal, insula	44.5	AFlong, AFant	5	1	GE HDxt
33	25	male	oligodendroglioma	2	frontal	14.8	AFpost	2	1	GE HDxt
34	44	male	astrocytoma	2	temporal, insula	46.6	AFant	2	4	GE HDxt
35	42	male	oligodendroglioma	2	temporal	21.4	AFlong, AFant	3	4	GE HDxt

**Note.** <sup>1</sup> To assess tract damage, a formal criterion was applied: a tract was considered damaged if its postoperative tract volume was lower compared to the preoperative volume.

<sup>2</sup> The final histopathological diagnosis was not available at the time of publication.

**Abbreviations:** AF — arcuate fasciculus; AFlong — long segment of the AF; AFant — anterior segment of the AF; AFpost — posterior segment of the AF; DTI — diffusion-tensor imaging; NA — not available; WHO — World Health Organization.

in white-matter anatomy (Thiebaut de Schotten et al., 2011). Furthermore, since different AF segments are often concurrently damaged, correlating each AF segment with behavioral measures separately (as opposed to fitting a single regression model) may result in spurious positive results precluding inferences about their unique linguistic functions. Finally, with regard to the linguistic function of the AFpost, several studies have reported language comprehension deficits following parietal lobe damage likely involving the AFpost (McCarthy & Warrington, 1984; Newhart et al., 2012). However, direct evidence for the correlations between the AFpost integrity metrics derived from individual diffusion-tensor imaging (DTI) and language processing is still lacking.

To overcome the above limitations and further explore the roles of the three AF segments in language processing, we combined DTI tractography with detailed language assessment in individuals with brain tumors. In contrast to post-stroke aphasia, where a premorbid anatomical baseline is not available, preoperative tract integrity metrics serve as an individual anatomical baseline for postoperative tract measurements. This constrains the factors underlying the variability in tract integrity metrics to those related to focal surgery-induced damage (resection and edema), rather than the premorbid individual variability. Finally, all three tracts were included in statistical models simultaneously. This allows inferences regarding the unique contributions of each AF segment to language processing while controlling for damage to the adjacent segments. For the language assessment, we utilized a series of tests tapping into participants' language production, comprehension and repetition abilities at the word and sentence levels. Given the well-established role of the AFlong in language production, we expected to replicate previous findings and confirm its role in language production and repetition. Additionally, we aimed to explore its potential contribution to language comprehension. Finally, based on evidence attributing the IPL a role in processing complex syntactic constructions, we expected that the AFant and AFpost would mediate an impairment specifically in the sentence-level linguistic tests.

## Method

### Participants

Thirty-five individuals with primary brain tumors in the left hemisphere participated in the study (mean age 39, range 19–63 years). Table 1 presents the participants' clinical information. All participants underwent a craniotomy for tumor removal. All participants were right-handed monolingual native speakers of Russian. The participants were recruited at the National Medical and Surgical Center named after N.I. Pirogov and at the National Medical Research Center for Neurosurgery named after N.N. Burdenko in Moscow. The participants signed an informed consent form before participation.

### Behavioral Assessment

Before and during the first week after surgery, all participants underwent magnetic resonance imaging and language assessment. Pre- and postoperative language assess-

ment was performed using the Russian Aphasia Test (RAT; Ivanova et al., 2016). RAT is a standardized assessment battery tapping into language production and comprehension at different linguistic levels. In the present study, accuracies in the following RAT subtests were analyzed: noun and verb comprehension, noun and verb production, sentence production, sentence comprehension, and pseudoword repetition, which is best suited for the assessment of sensorimotor integration in language production (Sierpowska et al., 2017).

### Magnetic Resonance Imaging

Diffusion-weighted magnetic resonance imaging (DWI) was performed using one of two scanners (Siemens Magnetom Skyra in 9 participants and GE Signa HDxt in 26 participants) with a single-shot echo-planar imaging sequence. Critically, the same scanner was used to acquire pre- and postoperative data in all participants, ensuring consistency between scanning sessions. We used the following acquisition parameters: 64 non-collinear diffusion directions, b-value 1500 s/mm<sup>2</sup>, voxel size 2×2×2 mm (Siemens Magnetom Skyra) or 2.5×2.5×2.5 mm (GE Signa HDxt), number of non-diffusion-weighted images — 1 (Siemens Magnetom Skyra) or 9 (GE Signa HDxt). The sequence was repeated twice with opposite phase-encoding directions: anterior-posterior (AP) and posterior-anterior (PA). In addition, for participants with one non-diffusion-weighted image in each sequence repetition, we acquired two short sequences with opposite phase-encoding directions (AP and PA), which contained three non-diffusion-weighted images. To ensure a consistent processing pipeline across participants, we used four non-diffusion-weighted images (two in the AP and two in the PA direction) in all participants for subsequent artifact correction. DWI data were corrected for eddy-current-induced distortions and subject motion using the 'eddy' function implemented in the FMRIB Software Library (<http://fsl.fmrib.ox.ac.uk/fsl/>). We performed tensor-based tractography using ExploreDTI (<http://www.exploredti.com/>). Streamlines were propagated from all voxels with fractional anisotropy (FA) ≥ .15 with a step size of 1 mm until a streamline reached a voxel with FA below .15 or the angle between two consecutive propagation steps became smaller than 45°.

AF segments were manually reconstructed in TrackVis (<http://www.trackvis.org/>) using three regions of interest (ROIs) placed in the IFG, superior and middle temporal gyri, and the IPL. Each AF segment was reconstructed using two of these ROIs: AFlong — IFG and temporal ROIs, AFant — IFG and IPL ROIs, AFpost — IPL and temporal ROIs. All reconstructions were performed in the participant's native scanning space. We first placed three ROIs strictly according to anatomical landmarks: for the IFG ROI — a sphere covering pars opercularis, pars triangularis and the ventral portion of the precentral gyrus; for the temporal ROI — a sphere covering the posterior thirds of the superior, middle and inferior temporal gyri; and for the IPL ROI — a sphere placed immediately above the temporal ROI extending to the intraparietal sulcus. This particular default ROI placement was utilized to cover the cortical terminations of the AF segments as reported previously for healthy individuals (Catani & Thiebaut de Schotten, 2012).

We then increased the radii of the spheres to ensure that all fibers with trajectories corresponding to those of the AFlong, AFant and AFpost were included in the tracts' reconstructions<sup>1</sup>. The resulting mean (*SD*) sphere radius was 8.04 (.23) for the IFG ROI, 8.00 (0) for the temporal ROI, and 8.09 for the IPL ROI (0.29). After this, exclusion ROIs were used to remove the artifacts, such as fiber loops and fibers belonging to the adjacent tracts. To minimize potential anatomical biases, each reconstruction was then verified by an expert in white-matter anatomy (O. D. or S.M.). Since the reconstruction for each participant was not performed independently by two raters, we do not have data on the inter-rater reliability. The rationale behind using the manual reconstruction approach, as opposed to an automated one, was that it allowed us to take into account individual variability due to pathology-induced tract displacement. This is especially relevant for brain tumor patients, since a tumor gradually displaces white matter in an often unpredictable manner, adding to the premorbid individual variability in white-matter anatomy (Thiebaut de Schotten et al., 2011). The tracts' pre- and postoperative volumes were extracted and, to control for total brain volume, divided by the participant's total brain volume obtained from the brain-extracted native T1-weighted images. We then calculated the difference between post- versus preoperative tract volumes for each of the three AF segments.

A high-resolution postoperative whole-brain T1-weighted (voxel size  $1 \times 1 \times 1$  mm) and, when available, T2- and FLAIR-weighted images were reoriented to the AC-PC plane and co-registered in the SPM12 Matlab toolbox. The resection cavity was manually delineated in ITK-SNAP (Yushkevich et al., 2006) and then normalized using the MR segment-normalize tool in the Clinical Toolbox (Nachev, Coulthard, Jäger, Kennard, & Husain, 2008) for SPM12. A non-enantiomorphic normalization algorithm and a younger T1 template were used. The volumes of the normalized resection cavity masks were extracted to be used as covariates in our statistical analyses.

## Data Analysis

Single-trial accuracy data were analyzed in linear mixed-effects models fitted using the *lme4* package (Bates, Maechler, Bolker, & Walker, 2015) in R (R Core Team, 2017). Fixed effects of our interest were: testing session (post- versus preoperative assessment), and the post- vs. preoperative difference in tract volumes for each AF segment. Word production and comprehension analyses additionally included part of speech as a fixed effect (categorical variable with two levels: nouns and verbs). To account for potential confounds, we also included normalized resection cavity volume, number of days between surgery and postoperative behavioral assessment, and number of days between surgery and postoperative DWI acquisition as covariates. Testing session was treatment-coded with postoperative assessment taken as a baseline. Therefore, the coefficient estimate of each predictor refers to the relation between this predic-

tor and postoperative behavioral performance. The tracts' and resection cavities' volumes were centered and scaled. Random effects were by-participant and by-item random intercepts. Below, we report uncorrected *p*-values and specify which predictors retained their significance at the  $\alpha = .01$  following a Bonferroni correction for the total number of fitted models.

## Results

Mean (*SD*) volume of the AFlong was 13.2 cm<sup>3</sup> (6.0 cm<sup>3</sup>) preoperatively and 11.6 cm<sup>3</sup> (6.5 cm<sup>3</sup>) postoperatively; AFant: 8.0 cm<sup>3</sup> (4.7 cm<sup>3</sup>) preoperatively and 7.1 cm<sup>3</sup> (4.0 cm<sup>3</sup>) postoperatively; AFpost: 9.8 cm<sup>3</sup> (4.3 cm<sup>3</sup>) preoperatively and 9.5 cm<sup>3</sup> (4.6 cm<sup>3</sup>) postoperatively. Postoperatively, 23 participants presented with a decreased AFlong volume, 24 showed a decreased AFant volume, and 12 showed a decreased AFpost volume.

Table 2 summarizes participants' pre- and postoperative behavioral performance.

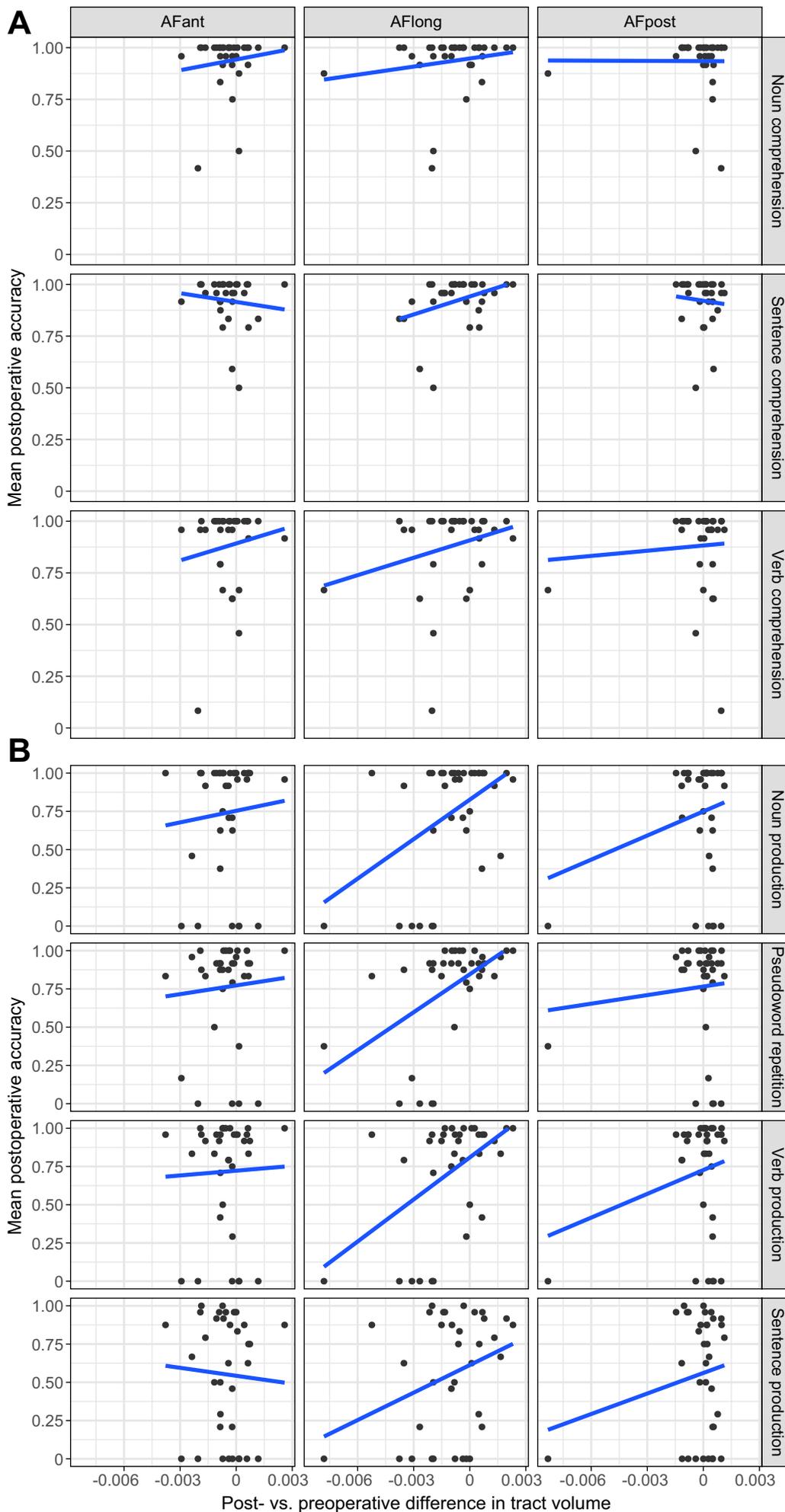
**Table 2.** Participants' Pre- and Postoperative Behavioral Performance

Subtest	Preoperative Score, Mean % ( <i>SD</i> )	Postoperative Score, Mean % ( <i>SD</i> )	Paired T-Test Statistic
Word comprehension (verbs and nouns, mean)	98.0 (2.2)	90.9 (16.6)	$t(33)=2.43$ $p=.020$
Sentence comprehension	97.6 (3.9)	89.9 (19.3)	$t(33)=2.29$ $p=.030$
Word production (verbs and nouns, mean)	95.3 (6.2)	74.3 (34.5)	$t(34)=3.60$ $p=.001$
Sentence production	95.1 (3.4)	74.5 (34.5)	$t(32)=3.33$ $p=.002$

Figure 1 presents the distribution of participants' average postoperative accuracies in each test as a function of post- vs. preoperative tract volume differences.

Three participants were excluded from the comprehension analyses as their single-trial performance data were missing for technical reasons. Table 3 presents the results of linear mixed-effects modelling. Greater resection cavity volume was associated with lower accuracy in all the analyzed tests (for model estimates, see Table 3). However, only the effect of resection cavity volume on sentence comprehension retained significance following a Bonferroni correction. We found that a postoperative decrease in AFlong volume was associated with lower postoperative accuracy in word comprehension,  $\beta = 1.08$ ,  $SE = .47$ ,  $z = 2.29$ ,  $p = .02$ ,  $OR = 2.96$ , 95% CI [1.17, 7.48], sentence comprehension,  $\beta = 1.42$ ,  $SE = .41$ ,  $z = 3.45$ ,  $p = .0006$ ,  $OR = 4.15$ , 95% CI [1.85, 9.31], and pseudoword repetition,  $\beta = 1.15$ ,  $SE = .37$ ,  $z = 3.14$ ,  $p = .002$ ,  $OR = 3.15$ , 95% CI [1.54, 6.45]. Postoperative decrease in AFlong volume was not associated with postoperative word and sentence production performance in our cohort. Preservation of both the AFant and AFpost volumes postoperatively was associated with lower postop-

<sup>1</sup> In two participants, the AFpost had a large fork-shaped parietal projection. Therefore, one sphere ROI in the parietal lobe could not completely cover the parietal projections of both the AFant and AFpost. In these two participants, we used two spherical ROIs in the parietal lobe to encompass the AFant and AFpost parietal projections separately.



**Figure 1.** Scatter plots showing the distribution of participants' average postoperative accuracies in each behavioral test as a function of postoperative volume changes in each segment of the arcuate fasciculus A) for language comprehension subtests and B) for language production subtests. AFlong — the long segment of the arcuate fasciculus; AFant — the anterior segment of the arcuate fasciculus, AFpost — the posterior segment of the arcuate fasciculus.

**Table 3. Results of Linear Mixed-Effects Modelling**

Predictors	Word Comprehension			Sentence Comprehension			Pseudoword Repetition			Word Production			Sentence Production		
	Odds Ratios	CI	p	Odds Ratios	CI	p	Odds Ratios	CI	p	Odds Ratios	CI	p	Odds Ratios	CI	p
(Intercept)	19.00	8.44–42.75	<.001**	26.14	11.15–61.31	<.001**	7.91	3.63–17.20	<.001**	5.84	2.37–14.39	<.001**	1.30	0.58–2.90	.519
Testing session (pre-operative)	7.38	4.64–11.73	<.001**	4.22	2.28–7.82	<.001**	4.81	3.35–6.89	<.001**	14.38	10.50–19.70	<.001**	8.94	6.57–12.18	<.001**
Part of speech (nouns vs. verbs)	1.52	1.26–1.82	<.001**	NA	NA	NA	NA	NA	NA	1.07	0.95–1.22	.265	NA	NA	NA
AFlong	2.96	1.17–7.48	.022	4.15	1.85–9.31	.001**	3.15	1.54–6.45	.002**	2.27	0.94–5.50	.069	1.22	0.56–2.66	.622
AFant	0.65	0.29–1.45	.292	0.45	0.23–0.89	.022	0.85	0.46–1.57	.608	0.91	0.44–1.91	.804	0.80	0.41–1.53	.492
AFpost	0.60	0.28–1.30	.196	0.22	0.07–0.72	.013	0.64	0.33–1.25	.195	1.02	0.44–2.33	.970	1.14	0.54–2.40	.732
Time from surgery to postoperative DTI	1.07	0.96–1.19	.218	1.05	0.96–1.15	.305	0.99	0.90–1.09	.831	1.02	0.91–1.15	.694	1.03	0.93–1.14	.600
Resection cavity volume	0.56	0.34–0.92	.023	0.57	0.39–0.85	.006**	0.60	0.37–0.97	.036	0.51	0.28–0.92	.024	0.53	0.31–0.89	.018
Time from surgery to postoperative language assessment	0.96	0.87–1.07	.508	0.95	0.87–1.04	.291	0.96	0.87–1.05	.356	0.99	0.88–1.11	.877	0.99	0.89–1.10	.805
<b>Random Effects</b>															
$\sigma^2$	3.29			3.29			3.29			3.29			3.29		
$\tau_{00}$	1.59 <sub>ID</sub>			0.62 <sub>ID</sub>			1.54 <sub>ID</sub>			2.63 <sub>ID</sub>			2.12 <sub>ID</sub>		
	0.03 <sub>Item</sub>			0.70 <sub>Item</sub>			0.40 <sub>Item</sub>			0.36 <sub>Item</sub>			0.18 <sub>Item</sub>		
ICC	0.33			0.29			0.37			0.48			0.41		
N	31 <sub>ID</sub>			31 <sub>ID</sub>			34 <sub>ID</sub>			34 <sub>ID</sub>			34 <sub>ID</sub>		
	24 <sub>Item</sub>			24 <sub>Item</sub>			24 <sub>Item</sub>			24 <sub>Item</sub>			24 <sub>Item</sub>		
Observations	2855			1388			1632			3264			1632		
Marginal R <sup>2</sup> / Conditional R <sup>2</sup>	.303 / .533			.288 / .492			.244 / .524			.320 / .644			.236 / .551		

**Note.** Predictors significant at  $\alpha = .05$  significance level are highlighted in bold. Predictors that retained their significance following the Bonferroni correction for the total number of models (that is, significant at the  $\alpha = .01$  level) are labeled with \*\*.

**Abbreviations:** AFlong — difference in post- vs. preoperative volumes of the long segment of the arcuate fasciculus; AFant — difference in post- vs. preoperative volumes of the anterior segment of the arcuate fasciculus, AFpost — difference in post- vs. preoperative volumes of the posterior segment of the arcuate fasciculus; CI — confidence interval; ICC — intraclass correlation coefficient; NA — not applicable. ID and Item labels indicate random effects parameters that are related to the by-participant and by-item random intercepts, respectively.

erative sentence comprehension accuracy, AFant,  $\beta = -.80$ ,  $SE = .35$ ,  $z = -2.28$ ,  $p = .02$ ,  $OR = .45$ , 95% CI [.23, .89]; AFpost,  $\beta = -1.50$ ,  $SE = .60$ ,  $z = -2.50$ ,  $p = .01$ ,  $OR = .22$ , 95% CI [.07, .72]. These effects did not retain significance following a Bonferroni correction. All other effects of decreased volumes of the AF segments on postoperative performance were non-significant.

To validate these findings and address several methodological concerns, we performed a supplementary analysis on a subset of participants. First of all, visual inspection of the data in Figure 1 revealed an apparent outlier data point in AFpost volume. Secondly, combining data from two different scanning protocols could have biased our model estimates since different voxel sizes in the two protocols could have impacted the variances of the tract volumes. To address whether these factors affected model estimates, we excluded the participant represented by the outlier data point ( $n = 1$ ) and the participants scanned using Siemens Magnetom Skyra ( $n = 9$ ) from the sample, and reanalyzed the resulting subset of participants ( $n = 25$ ). Appendix A presents the results of this analysis. The relations between lower postoperative volumes of the AFant and the AFpost and sentence comprehension became non-significant (AFant:  $p = .18$ ; AFpost:  $p = .05$ ). Otherwise, inferences regarding AF segments remained unchanged compared to our main analysis, suggesting that the outlier point and combined DTI data from the two different MRI protocols did not affect the results obtained in the main analysis. No other control for outliers was applied, as linear mixed-effects models have generally low sensitivity to outliers (Gelman & Hill, 2007).

## Discussion

The current study addressed the effects of surgery-induced damage to the three AF segments on language production, comprehension and repetition. First of all, we aimed to reproduce previous findings showing the relation between AFlong integrity and language production and repetition abilities (Catani et al., 2005; Sierpowska et al., 2017). In addition, we sought to explore the linguistic contributions of the IPL connectivity with the frontal and temporal language areas via the AFant and AFpost, respectively. Based on the data attributing the IPL a role in comprehension of syntactic constructions, we expected to observe a relation between the AFand and AFpost and sentence-level linguistic performance.

In line with previous studies (Catani et al., 2005; Sierpowska et al., 2017), we found that lower volume of the AFlong following left-hemisphere surgery was associated with lower postoperative performance in pseudoword repetition. However, our analysis revealed only a borderline-significant trend for lower word production accuracy postoperatively in participants with lower postoperative AFlong volume, and no effect of the AFlong postoperative volume changes on sentence production performance. Only larger resection cavity volume was associated with lower word and sentence production performance postoperatively. However, this result did not retain significance after applying a Bonferroni correction. A potential explanation for these partially negative results lies in the abundance of transient tissue pathology, such as edema, at the acute

postoperative stage (first days and weeks after surgery). It is plausible that the transient tissue pathology was the most salient factor mediating postoperative language production performance in our cohort, whereas permanent damage to specific anatomical structures only made a relatively small contribution to language production performance. This warrants further research addressing the relation between the integrity of AF segments and language impairment in patients at the subacute and chronic stages after surgery.

Notably, we observed a relation between the lower postoperative volume of the AFlong and postoperative impairment in sentence comprehension and word comprehension (the latter did not retain significance following a Bonferroni correction). These findings are consistent with the previously reported relation between AFlong integrity and sentence comprehension in patients with primary progressive aphasia (Wilson et al., 2015). This is also in line with studies showing agrammatic comprehension in patients with Broca's aphasia (Caramazza et al., 1981; Schwartz et al., 1980), and studies showing that the posterior temporal areas corresponding to the AFlong projections are involved not only in phonological but also lexical-semantic processing (for a review, see Hickok & Poeppel, 2007). These data suggest that AFlong function might be non-uniform; instead, its contributions to language production and comprehension might be differentially subserved by its layers that connect functionally distinct subcomponents of posterior temporal and inferior frontal lobes. Thus, further studies are needed to address the mechanism driving the manifestations of AFlong damage in production and comprehension modalities.

In contrast to the AFlong, postoperative decreases in the volumes of the AFant and AFpost did not affect language production or repetition performance in our cohort. Unexpectedly, we found that the preservation of the AFant and AFpost volumes postoperatively was associated with lower postoperative sentence comprehension abilities. However, these correlations did not retain significance following a Bonferroni correction, and were not reproduced in a supplementary analysis using data from a subset of participants. Furthermore, no correlations between the AFant and AFpost volumes and word comprehension were observed.

The negative results regarding the role of the AFant in language production are consistent with Basilakos and colleagues' (2014) results. Furthermore, the absence of a correlation between AFant volume and word production in the current study suggests that the correlation between the AFant and speech fluency reported by Fridriksson et al. (2013) might be mediated by the deficits in processing stages beyond word retrieval (such as executive functions, which are heavily involved in speech fluency tests). An alternative explanation reconciling the discrepancy between our and Fridriksson and colleagues' (2013) findings lies in the different pathophysiological mechanisms underlying stroke- (Fridriksson et al., 2013) versus surgery-induced language impairments. In contrast to stroke, relatively slow brain tumor growth induces a functional reorganization of the language network (Duffau, 2005). Therefore, acute surgery-induced lesions act upon a preoperatively reorganized language network. As a consequence, the relation between AFant and AFpost damage and language deficits in stroke patients, but not in brain tumor patients,

likely reflects the tracts' greater capacity for functional reorganization over the course of tumor growth.

The negative results may have also been driven by several methodological limitations of the current study. First, although the language assessment used in our study was well-suited to measure the overall severity of language impairment at a given linguistic level, it did not specifically tap into deficits at isolated processing stages, such as deficits in phonological or semantic processing, or articulatory planning. Therefore, it is plausible that our assessment may have lacked sensitivity to detect the relations between the AFant and AFpost and their contributions to these specific processing stages. Secondly, AFpost volume decreased postoperatively only in a relatively small number of participants (12 out of 35). Therefore, our patient cohort may have lacked the anatomical variability in the AFpost needed to establish the relation between its volume and language performance. Finally, the relatively high incidence of concurrent damage to two or more AF segments in our cohort (in 19 out of 35 participants) also presents a potential confound. Namely, this may have precluded us from revealing the specific contributions of each segment to the word- and sentence-level language deficits. The combined analysis of the data acquired with two different DWI protocols and an overall small number of participants are also limitations in our analysis. However, we believe that these factors are negligible, given that a subsequent analysis performed on a subset of participants ( $n=25$ ), all scanned using an identical DWI protocol, yielded analogous results.

To conclude, the current data partially replicated earlier findings regarding the role of the AFlong in language production, and confirmed previous evidence showing that the AFlong is involved in sentence comprehension. Our results suggest that the AFlong has a complex function extending beyond language production, and stress the importance of studying the mechanisms driving production and comprehension deficits caused by AFlong damage. Finally, studies utilizing evidence from patients at the chronic stage after stroke and surgery are needed to pinpoint the roles of the AFant and AFpost in language processing and investigate their functional reorganization after focal brain damage.

## References

- Basilakos, A., Fillmore, P.T., Rorden, C., Guo, D., Bonilha, L., & Fridriksson, J. (2014). Regional white matter damage predicts speech fluency in chronic post-stroke aphasia. *Frontiers in Human Neuroscience*, 8, 845. doi:10.3389/fnhum.2014.00845
- Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, 1(1), 1–48. Retrieved from <https://www.jstatsoft.org/v067/i01> doi:10.18637/jss.v067.i01
- Caramazza, A., Berndt, R.S., Basili, A.G., & Koller, J.J. (1981). Syntactic processing deficits in aphasia. *Cortex*, 17(3), 333–347. doi:10.1016/S0010-9452(81)80021-4
- Catani, M., Jones, D.K., & ffytche, D.H. (2005). Perisylvian language networks of the human brain. *Annals of Neurology*, 57(1), 8–16. doi:10.1002/ana.20319
- Catani, M., & de Schotten, M.T. (2012). *Atlas of human brain connections*. Oxford, UK: Oxford University Press.
- Coslett, H.B., & Schwartz, M.F. (2018). The parietal lobe and language. *Handbook of Clinical Neurology*, 151, 365–375. doi:10.1016/B978-0-444-63622-5.00018-8
- Dragoy, O., Akinina, Y., & Dronkers, N. (2017). Toward a functional neuroanatomy of semantic aphasia: A history and ten new cases. *Cortex*, 97, 164–182. doi:10.1016/j.cortex.2016.09.012
- Dronkers, N.F., Redfern, B.B., & Knight, R.T. (2000). The neural architecture of language disorders. In M.S. Gazzaniga (Ed.), *The new cognitive neurosciences* (pp. 949–958). Cambridge: The MIT Press.
- Duffau, H. (2005). Lessons from brain mapping in surgery for low-grade glioma: Insights into associations between tumour and brain plasticity. *The Lancet. Neurology*, 4(8), 476–486. doi:10.1016/S1474-4422(05)70140-X
- Fridriksson, J., Guo, D., Fillmore, P., Holland, A., & Rorden, C. (2013). Damage to the anterior arcuate fasciculus predicts non-fluent speech production in aphasia. *Brain*, 136(Pt 11), 3451–3460. doi:10.1093/brain/awt267
- Gelman, A., & Hill, J. (2006). *Data analysis using regression and multilevel/hierarchical models*. Cambridge: Cambridge University Press. doi:10.1017/CBO9780511790942
- Hickok, G., & Poeppel, D. (2007). The cortical organization of speech processing. *Nature Reviews. Neuroscience*, 8(5), 393–402. doi:10.1038/nrn2113
- Ivanova, M., Dragoy, O., Akinina, J., Soloukhina, O., Iskra, E., Khudyakova, M., & Akhutin, T. (2016). AutoRAT at your fingertips: Introducing the new Russian Aphasia Test on a tablet. *Frontiers in Psychology*, 116. doi:10.3389/conf.fpsyg.2016.68.00116
- McCarthy, R., & Warrington, E.K. (1984). A two-route model of speech production. Evidence from aphasia. *Brain*, 107(Pt 2), 463–485. doi:10.1093/brain/107.2.463
- Nachev, P., Coulthard, E., Jager, H.R., Kennard, C., & Husain, M. (2008). Enantiomorphic normalization of focally lesioned brains. *Neuroimage*, 39(3), 1215–1226. doi:10.1016/j.neuroimage.2007.10.002
- Newhart, M., Trupe, L.A., Gomez, Y., Cloutman, L., Molitoris, J.J., Davis, C., Leigh, R., Gottesman, R.F., Race, D., & Hillis, A.E. (2012). Asyntactic comprehension, working memory, and acute ischemia in Broca's area versus angular gyrus. *Cortex*, 48(10), 1288–1297. doi:10.1016/j.cortex.2011.09.009
- Penfield, W., & Roberts, L. (1959). *Speech and brain mechanisms*. Princeton, NJ: Princeton University Press.
- R Core Team (2017). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from <https://www.R-project.org>
- Schwartz, M.F., Saffran, E.M., & Marin, O.S. (1980). The word order problem in agrammatism: I. Comprehension. *Brain and Language*, 10(2), 249–262. doi:10.1016/0093-934X(80)90055-3
- Sierpowska, J., Gabarros, A., Fernandez-Coello, A., Camins, A., Castaner, S., Juncadella, M., Moris, J., & Rodriguez-Fornells, A. (2017). Words are not enough: Nonword repetition as an indicator of arcuate fasciculus integrity during brain tumor resection. *Journal of Neurosurgery*, 126(2), 435–445. doi:10.3171/2016.2.JNS151592
- Thiebaut de Schotten, M., ffytche, D.H., Bizzi, A., Dell'Acqua, F., Allin, M., Walshe, M., Murray, R., Williams, S.C., Murphy, D.G.M., & Catani, M. (2011). Atlasing location, asymmetry and inter-subject variability of white matter tracts in the human brain with MR diffusion tractography. *Neuroimage*, 54(1), 49–59. doi:10.1016/j.neuroimage.2010.07.055
- Wilson, S.M., Galantucci, S., Tartaglia, M.C., Rising, K., Patterson, D.K., Henry, M.L., Ogar, J.M., DeLeon, J., Miller, B.L., & Gorno-Tempini, M.L. (2011). Syntactic processing depends on dorsal language tracts. *Neuron*, 72(2), 397–403. doi:10.1016/j.neuron.2011.09.014
- Yushkevich, P.A., Piven, J., Hazlett, H.C., Smith, R.G., Ho, S., Gee, J.C., & Gerig, G. (2006). User-guided 3D active contour segmentation of anatomical structures: significantly improved efficiency and reliability. *Neuroimage*, 31(3), 1116–1128. doi:10.1016/j.neuroimage.2006.01.015

## Appendix A. Results from Participants Scanned Using GE Signa HDxt

Table A1. Results of Linear Mixed-Effects Modelling of the Data from Participants Scanned Using GE Signa HDxt, Excluding One Participant Represented by the Outlier Data Point (see Figure 1)

Predictors	Word Comprehension			Sentence Comprehension			Pseudoword Repetition			Word Production			Sentence Production		
	Odds Ratios	CI	p	Odds Ratios	CI	p	Odds Ratios	CI	p	Odds Ratios	CI	p	Odds Ratios	CI	p
(intercept)	16.01	5.60–45.75	<b>&lt;.001**</b>	25.73	7.85–84.37	<b>&lt;.001**</b>	7.59	2.61–22.05	<b>&lt;.001**</b>	4.04	1.54–10.62	<b>.005**</b>	0.66	0.25–1.72	.396
Testing session (pre-operative)	5.53	2.96–10.33	<b>&lt;.001**</b>	4.95	1.92–12.76	<b>.001**</b>	4.03	2.46–6.58	<b>&lt;.001**</b>	7.24	4.96–10.56	<b>&lt;.001**</b>	5.08	3.58–7.21	<b>&lt;.001**</b>
Part of speech (nouns vs. verbs)	1.42	1.10–1.84	<b>.007**</b>	NA	NA	NA	NA	NA	NA	0.96	0.82–1.13	.610	NA	NA	NA
AFlong	2.43	0.84–7.01	.101	4.05	1.40–11.74	<b>.010</b>	4.53	1.84–11.16	<b>.001**</b>	3.01	1.25–7.23	<b>.014</b>	1.84	0.79–4.28	.155
AFant	0.97	0.42–2.28	.952	0.54	0.21–1.34	.183	1.33	0.62–2.84	.458	1.63	0.85–3.13	.144	1.31	0.69–2.49	.410
AFpost	0.34	0.07–1.60	.172	0.20	0.04–1.03	.054	0.26	0.06–1.21	.086	0.70	0.18–2.72	.602	2.55	0.66–9.91	.177
Time from surgery to postoperative DTI	1.06	0.96–1.18	.238	1.02	0.93–1.12	.629	0.98	0.90–1.07	.653	1.01	0.92–1.10	.854	1.03	0.95–1.13	.463
Resection cavity volume	0.30	0.11–0.81	<b>.018</b>	0.24	0.08–0.75	<b>.014</b>	0.46	0.18–1.23	.122	0.19	0.07–0.48	<b>&lt;.001**</b>	0.22	0.09–0.55	<b>.001**</b>
Time from surgery to postoperative language assessment	0.99	0.89–1.09	.778	0.95	0.86–1.04	.267	0.98	0.90–1.07	.637	1.00	0.92–1.10	.929	0.98	0.89–1.07	.613
Random Effects															
$\sigma^2$	3.29			3.29			3.29			3.29			3.29		
$\tau_{00}$	0.01 <sub>Item</sub>			0.65 <sub>Item</sub>			1.11 <sub>ID</sub>			1.27 <sub>ID</sub>			1.32 <sub>ID</sub>		
	1.11 <sub>ID</sub>			0.51 <sub>ID</sub>			0.47 <sub>Item</sub>			0.43 <sub>Item</sub>			0.20 <sub>Item</sub>		
ICC	0.25			0.26			0.32			0.34			0.32		
N	22 <sub>ID</sub>			22 <sub>ID</sub>			24 <sub>ID</sub>			24 <sub>ID</sub>			24 <sub>ID</sub>		
	24 <sub>Item</sub>			24 <sub>Item</sub>			24 <sub>Item</sub>			24 <sub>Item</sub>			24 <sub>Item</sub>		
Observations	1991			980			1152			2304			1152		
Marginal R <sup>2</sup> / Conditional R <sup>2</sup>	.309 / .485			.311 / .491			.290 / .520			.331 / .559			.248 / .486		

Note. Predictors significant at  $\alpha = .05$  significance level are highlighted in bold. Predictors that retained their significance following the Bonferroni correction for the total number of models (that is, significant at the  $\alpha = .01$  level) are labeled with \*\*.

Abbreviations: AFlong — difference in post- vs. preoperative volumes of the long segment of the arcuate fasciculus; AFant — difference in post- vs. preoperative volumes of the anterior segment of the arcuate fasciculus, AFpost — difference in post- vs. preoperative volumes of the posterior segment of the arcuate fasciculus; CI — confidence interval; ICC — intraclass correlation coefficient; NA — not applicable. ID and Item labels indicate random effects parameters that are related to the by-participant and by-item random intercepts, respectively.

**■ экспериментальные сообщения ■**

# Роли отдельных сегментов дугообразного пучка в обеспечении речевой обработки у пациентов с опухолями головного мозга

**Андрей Сергеевич Зырянов**

Национальный исследовательский университет  
«Высшая школа экономики», Москва, Россия

**Валерия Андреевна Толкачёва**

Европейская магистратура по клинической  
лингвистике +, Университет Гронингена, Нидерланды

**Валерия Игоревна Зеленкова**

Национальный исследовательский университет  
«Высшая школа экономики», Москва, Россия

**Андрей Александрович Зуев**

Национальный медико-хирургический центр  
им. Н. И. Пирогова, Москва, Россия

**Светлана Александровна**

**Малютина**

Национальный исследовательский университет  
«Высшая школа экономики», Москва, Россия;  
Федеральный центр цереброваскулярной патологии  
и инсульта, Москва, Россия

**Никита Витальевич Педяш**

Национальный медико-хирургический центр  
им. Н. И. Пирогова, Москва, Россия

**Екатерина Алексеевна Ступина**

Национальный исследовательский университет  
«Высшая школа экономики», Москва, Россия

**Олег Юрьевич Броннов**

Национальный медико-хирургический центр  
им. Н. И. Пирогова, Москва, Россия

**Виктор Викторович Карпычев**

Национальный исследовательский университет  
«Высшая школа экономики», Москва, Россия

**Дмитрий Николаевич Копачёв**

Национальный медицинский исследовательский  
центр нейрохирургии им. академика Н. Н. Бурденко,  
Москва, Россия

**Елизавета Александровна Гордеева**

Национальный исследовательский университет  
«Высшая школа экономики», Москва, Россия

**Игорь Николаевич Пронин**

Национальный медицинский исследовательский  
центр нейрохирургии им. академика Н. Н. Бурденко,  
Москва, Россия

**Валерия Александровна Жирнова**

Национальный исследовательский университет  
«Высшая школа экономики», Москва, Россия

**Ольга Викторовна Драгой**

Национальный исследовательский университет  
«Высшая школа экономики», Москва, Россия;  
Федеральный центр цереброваскулярной патологии  
и инсульта, Москва, Россия

**Анна Игоревна Артёмова**

Национальный исследовательский университет  
«Высшая школа экономики», Москва, Россия

**Аннотация.** Функциональная связанность перисильвиевых представительств речи обеспечивается системой ассоциативных трактов, соединяющих задние отделы височной доли и нижнюю лобную извилину (длинный сегмент дугообразного пучка, далее — ДП), а также каждую из этих областей с нижней теменной долькой (задний и передний сегменты ДП соответственно). Поражение длинного сегмента ДП вызывает проводниковую афазия, центральной манифестацией которой является нарушение повторения речи вследствие дефицита сенсомоторной интеграции в речевой модальности. Однако отсутствуют систематические исследования того, какие аспекты речевой обработки обеспечивают тракты, связывающие нижнюю теменную дольку с лобными и височными представлениями речи. Данная работа направлена на выявление роли каждого из трех сегментов ДП в понимании, порождении и повторении речи на различных лингвистических уровнях. Мы обнаружили, что уменьшение объема длинного сегмента ДП в результате резекции опухоли головного мозга связано с нарушениями при повторении речи, что соотносится с ролью данного тракта в сенсомоторной интеграции в речевой модальности. Кроме того, послеоперационное уменьшение объема длинного сегмента ДП было связано с нарушениями при понимании предложений. Мы не обнаружили связи между изменениями объемов переднего и заднего сегментов ДП и речевыми нарушениями. Данный результат может объясняться тем, что передний и задний сегменты ДП не являются критическими для речевой обработки, а функции, которые они обеспечивают в норме, могут быть подвержены большей реорганизации в ходе постепенного роста опухоли мозга — в отличие от длинного сегмента.

**Контактная информация:** Андрей Сергеевич Зырянов, [zyryanov.andrew@gmail.com](mailto:zyryanov.andrew@gmail.com), 105066, Москва, ул. Старая Басманная 21/4, стр. 1, офис 510, Центр языка и мозга, Национальный исследовательский университет «Высшая школа экономики»; Валерия Игоревна Зеленкова, [vzelenkova@hse.ru](mailto:vzelenkova@hse.ru); Светлана Александровна Малюткина, [smalyutina@hse.ru](mailto:smalyutina@hse.ru); Екатерина Алексеевна Ступина, [estupina@hse.ru](mailto:estupina@hse.ru); Виктор Викторович Карпычев, [vkarpuchev@hse.ru](mailto:vkarpuchev@hse.ru); Елизавета Александровна Гордеева, [eagordeyeva@hse.ru](mailto:eagordeyeva@hse.ru); Валерия Александровна Жирнова, [evilyval@gmail.com](mailto:evilyval@gmail.com); Анна Игоревна Артёмова, [tema.ankin@gmail.com](mailto:tema.ankin@gmail.com); Валерия Андреевна Толкачёва, [tolkacheva.valeria@gmail.com](mailto:tolkacheva.valeria@gmail.com); Андрей Александрович Зуев, [mosbrain@gmail.com](mailto:mosbrain@gmail.com); Никита Витальевич Педяш, [rusneuro@gmail.com](mailto:rusneuro@gmail.com); Олег Юрьевич Броннов, [bronovou@pirogov-center.ru](mailto:bronovou@pirogov-center.ru); Дмитрий Николаевич Копачёв, [dmkopachev@gmail.com](mailto:dmkopachev@gmail.com); Игорь Николаевич Пронин, [pronin@nsi.ru](mailto:pronin@nsi.ru); Ольга Викторовна Драгой, [odragoy@hse.ru](mailto:odragoy@hse.ru)

**Ключевые слова:** нейроанатомия речи, афазия, длинные ассоциативные тракты, диффузионно-тензорная томография, глиома, дугообразный пучок

**Благодарности.** Мы выражаем благодарность Анне Лауринавичюте за помощь с анализом данных. Исследование выполнено при поддержке Российского фонда фундаментальных исследований, грант № 18-012-00829.

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Статья поступила в редакцию 25 декабря 2018 г. Принята в печать 22 марта 2019 г.

## Литература

- Basilakos A., Fillmore P. T., Rorden C., Guo D., Bonilha L., Fridriksson J.* Regional white matter damage predicts speech fluency in chronic post-stroke aphasia // *Frontiers in Human Neuroscience*. 2014. Vol. 8. P. 845. doi:10.3389/fnhum.2014.00845
- Bates D., Mächler M., Bolker B., Walker S.* Fitting linear mixed-effects models using lme4 // *Journal of Statistical Software*. 2015. Vol. 1. No. 1. P. 1–48. URL: <https://www.jstatsoft.org/v067/i01> doi:10.18637/jss.v067.i01
- Caramazza A., Berndt R. S., Basili A. G., Koller J. J.* Syntactic processing deficits in aphasia // *Cortex*. 1981. Vol. 17. No. 3. P. 333–347. doi:10.1016/S0010-9452(81)80021-4
- Catani M., Jones D. K., ffytche D. H.* Perisylvian language networks of the human brain // *Annals of Neurology*. 2005. Vol. 57. No. 1. P. 8–16. doi:10.1002/ana.20319
- Catani M., de Schotten M. T.* Atlas of human brain connections. Oxford, UK: Oxford University Press, 2012.
- Coslett H. B., Schwartz M. F.* The parietal lobe and language // *Handbook of Clinical Neurology*. 2018. Vol. 151. P. 365–375. doi:10.1016/B978-0-444-63622-5.00018-8
- Dragoy O., Akinina Y., Dronkers N.* Toward a functional neuroanatomy of semantic aphasia: A history and ten new cases // *Cortex*. 2017. Vol. 97. P. 164–182. doi:10.1016/j.cortex.2016.09.012
- Dronkers N. F., Redfern B. B., & Knight R. T.* The neural architecture of language disorders // *The new cognitive neurosciences / M. S. Gazzaniga (Ed.)*. Cambridge: The MIT Press, 2000. P. 949–958.
- Duffau H.* Lessons from brain mapping in surgery for low-grade glioma: Insights into associations between tumour and brain plasticity // *The Lancet. Neurology*. 2005. Vol. 4. No. 8. P. 476–486. doi:10.1016/S1474-4422(05)70140-X
- Fridriksson J., Guo D., Fillmore P., Holland A., Rorden C.* Damage to the anterior arcuate fasciculus predicts non-fluent speech production in aphasia // *Brain*. 2013. Vol. 136. No. Pt 11. P. 3451–3460. doi:10.1093/brain/awt267
- Gelman A., Hill J.* Data analysis using regression and multilevel/hierarchical models. Cambridge: Cambridge University Press, 2006. doi:10.1017/CBO9780511790942
- Hickok G., Poeppel D.* The cortical organization of speech processing // *Nature Reviews. Neuroscience*. 2007. Vol. 8. No. 5. P. 393–402. doi:10.1038/nrn2113

Ivanova M., Dragoy O., Akinina J., Soloukhina O., Iskra E., Khudyakova M., Akhutina T. AutoRAT at your fingertips: Introducing the new Russian Aphasia Test on a tablet // *Frontiers in Psychology*. 2016. No. 116. doi:10.3389/conf.fpsyg.2016.68.00116

McCarthy R., Warrington E. K. A two-route model of speech production. Evidence from aphasia // *Brain*. 1984. Vol. 107 ( Pt 2). P. 463–485. doi:10.1093/brain/107.2.463

Nachev P., Coulthard E., Jager H. R., Kennard C., Husain M. Enantiomorphic normalization of focally lesioned brains // *Neuroimage*. 2008. Vol. 39. No. 3. P. 1215–1226. doi:10.1016/j.neuroimage.2007.10.002

Newhart M., Trupe L. A., Gomez Y., Cloutman L., Molitoris J. J., Davis C., Leigh R., Gottesman R. F., Race D., Hillis A. E. Asyntactic comprehension, working memory, and acute ischemia in Broca's area versus angular gyrus // *Cortex*. 2012. Vol. 48. No. 10. P. 1288–1297. doi:10.1016/j.cortex.2011.09.009

Penfield W., Roberts L. *Speech and brain mechanisms*. Princeton, NJ: Princeton University Press, 1959.

R Core Team. *A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing, 2017. URL: <https://www.R-project.org>

Schwartz M. F., Saffran E. M., Marin O. S. The word order problem in agrammatism: I. Comprehension // *Brain and Language*. 1980. Vol. 10. No. 2. P. 249–262. doi:10.1016/0093-934X(80)90055-3

Sierpowska J., Gabarros A., Fernandez-Coello A., Camins A., Castaner S., Juncadella M., Moris J., Rodriguez-Fornells A. Words are not enough: Nonword repetition as an indicator of arcuate fasciculus integrity during brain tumor resection // *Journal of Neurosurgery*. 2017. Vol. 126. No. 2. P. 435–445. doi:10.3171/2016.2.JNS151592

Thiebaut de Schotten M., ffytche D. H., Bizzi A., Dell'Acqua F., Allin M., Walshe M., Murray R., Williams S. C., Murphy D. G. M., Catani M. Atlasing location, asymmetry and inter-subject variability of white matter tracts in the human brain with MR diffusion tractography // *Neuroimage*. 2011. Vol. 54. No. 1. P. 49–59. doi:10.1016/j.neuroimage.2010.07.055

Wilson S. M., Galantucci S., Tartaglia M. C., Rising K., Patterson D. K., Henry M. L., Ogar J. M., DeLeon J., Miller B. L., Gorno-Tempini M. L. Syntactic processing depends on dorsal language tracts // *Neuron*. 2011. Vol. 72. No. 2. P. 397–403. doi:10.1016/j.neuron.2011.09.014

Yushkevich P. A., Piven J., Hazlett H. C., Smith R. G., Ho S., Gee J. C., Gerig G. User-guided 3D active contour segmentation of anatomical structures: significantly improved efficiency and reliability // *Neuroimage*. 2006. Vol. 31. No. 3. P. 1116–1128. doi:10.1016/j.neuroimage.2006.01.015