Supplementary Information for 'Node Degree Volatility for Seizure Onset Zone Localization'

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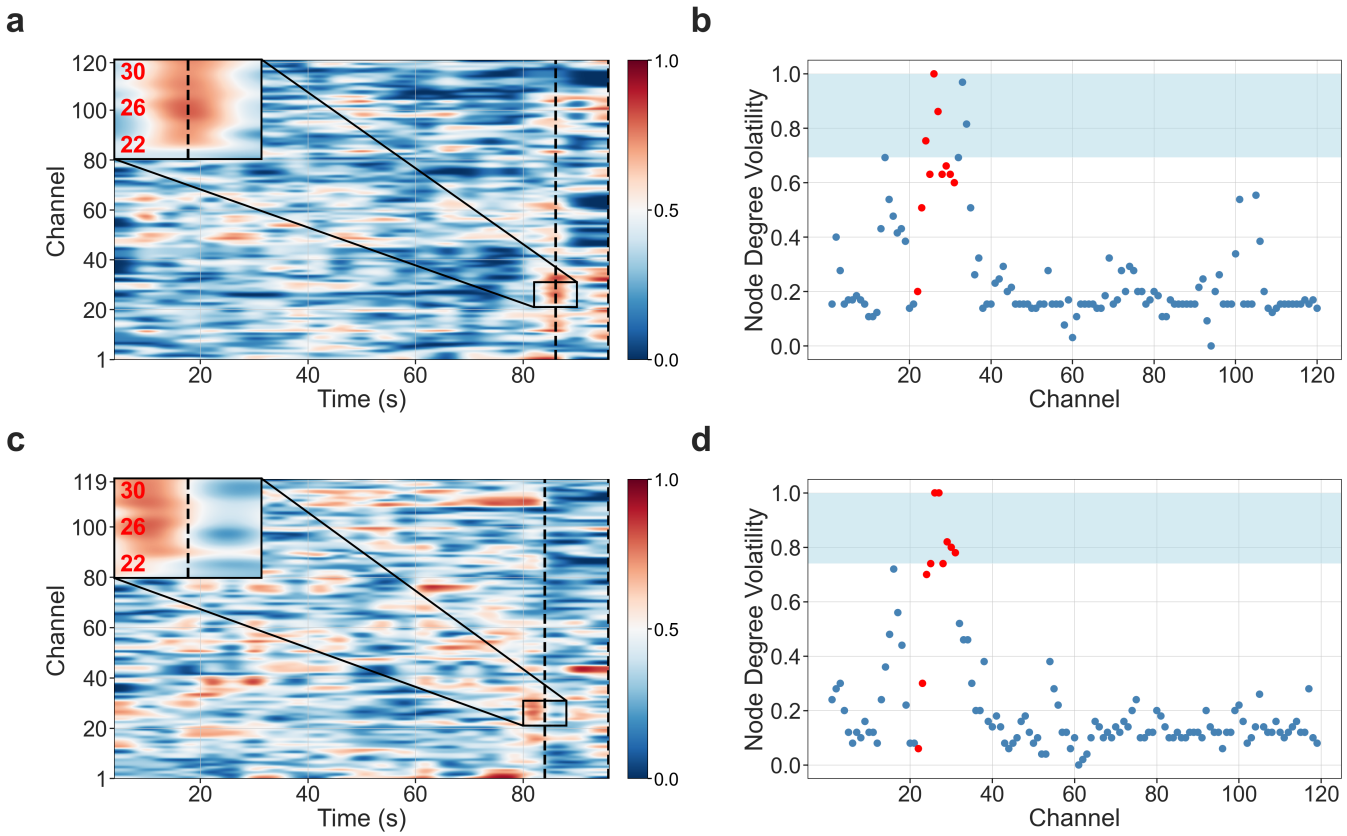
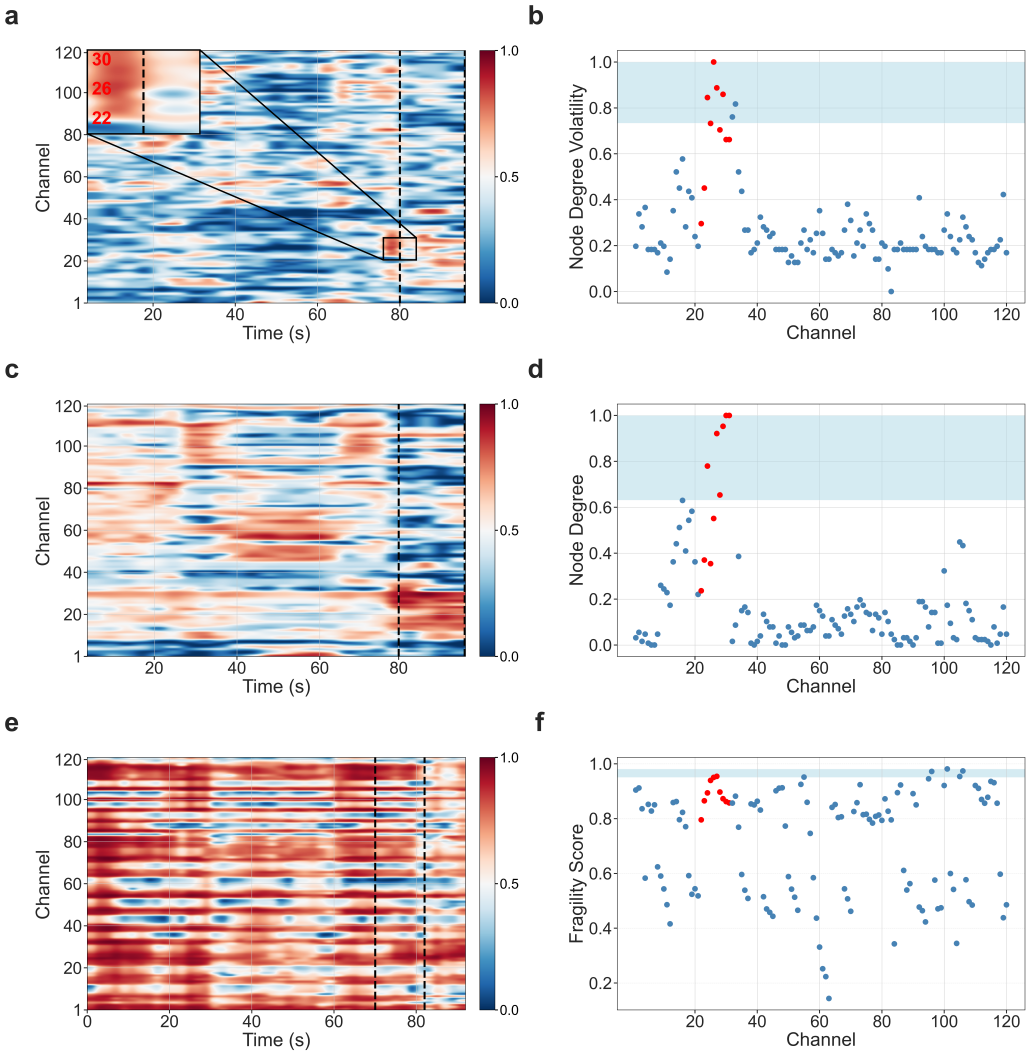
Supplementary Note 1: Node degree volatility and additional SOZ biomarkers for patient 0

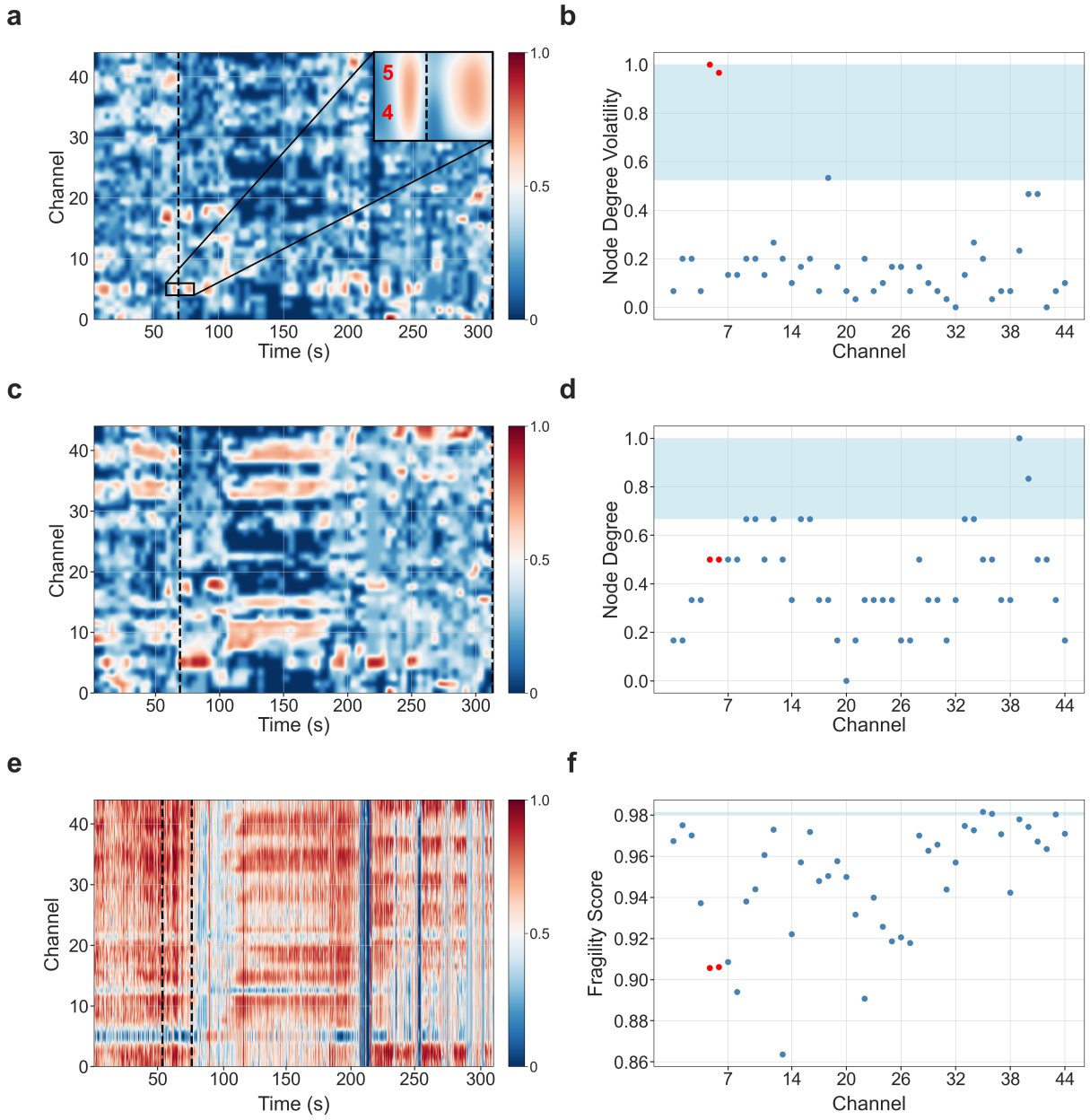


Supplementary Figure 1. Node degree volatility for patient 0 (episode 2 and 3). (a-d). Left panel: Heatmaps illustrate the temporal derivatives of node degree, with black dashed lines indicating a 16-second window centered around seizure onset. Right panel: the top right scatter plot shows abrupt changes in channels 23, 25 and 26 (highlighted in red), which fall within the top 5% of the distribution. For episode 3, the bottom right scatter plot reveals that channels 25, 26, 28, 29, and 30 fall within the 95th percentile, indicating their importance for SOZ identification.

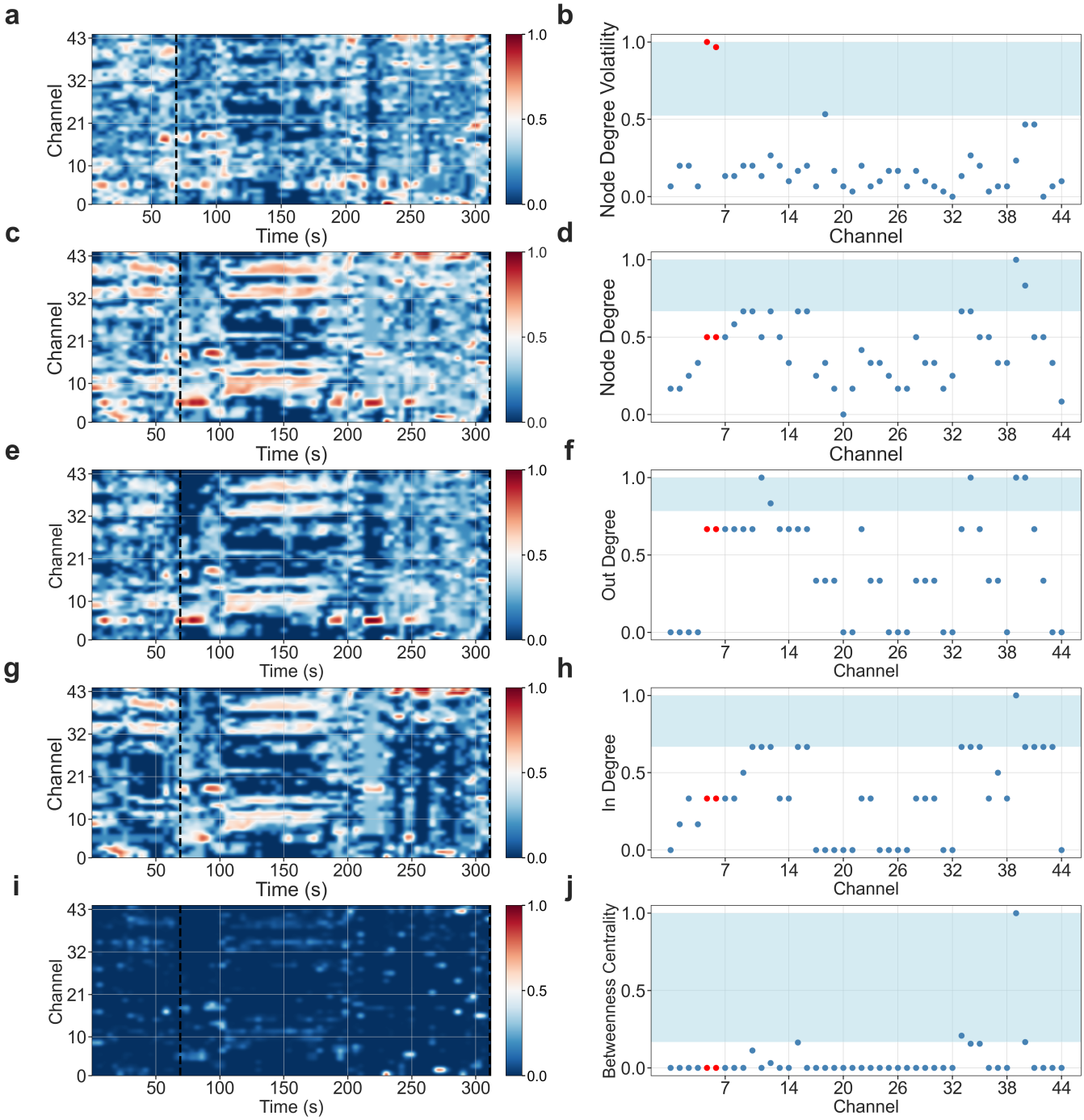


Supplementary Figure 2. Comparison of existing SOZ biomarkers for patient 0 (episode 1). Plots follow the format of Fig. 3: heatmaps (left) show the temporal evolution of each SOZ biomarker, and scatter plots (right) display the maximum metric values within a 16-second window centered on seizure onset. Red circles indicate clinically labeled SOZ channels; blue circles denote non-SOZ channels.

Supplementary Note 2: Node degree volatility and additional SOZ biomarkers for patient 14

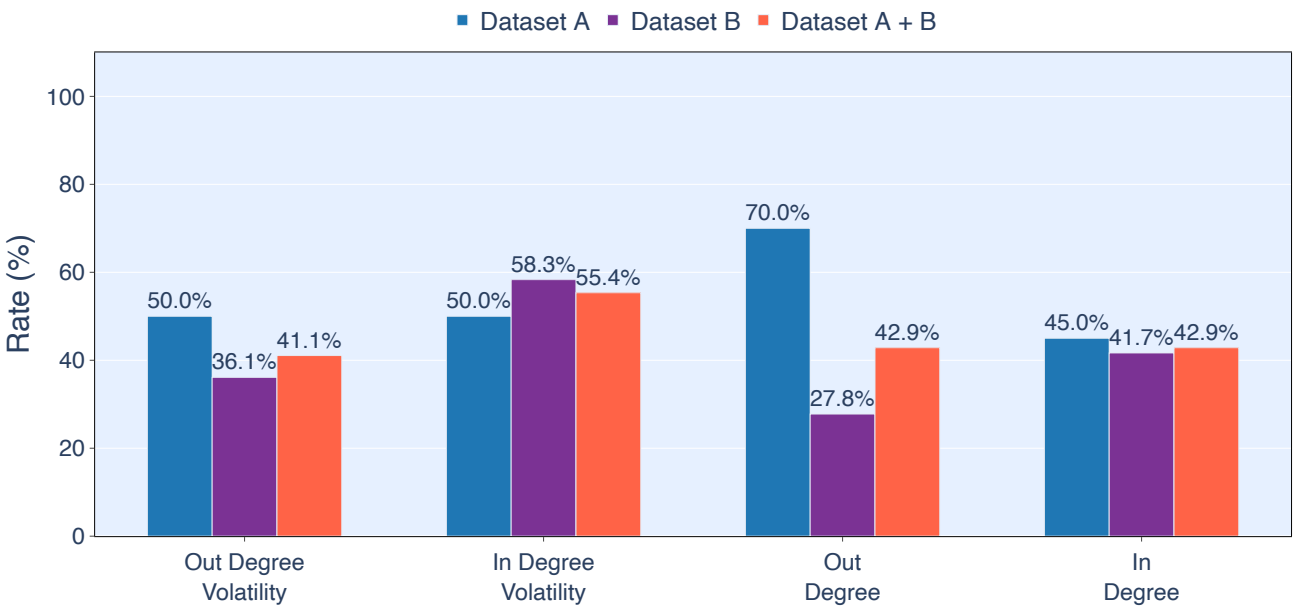


Supplementary Figure 3. Comparison of seizure SOZ biomarkers for patient 14 (Engel Class I). Plots follow the format of Fig. 3. Red circles indicate clinically labeled SOZ channels; blue circles denote non-SOZ channels. (a-b) Node degree volatility. The normalized volatility metric identifies the SOZ channels (4 and 5) within the top 5 % of the distribution. (c-d) Static node degree. Median node degree calculated over the ictal epoch fails to isolate the SOZ channels, which fall below the top 5 % threshold. (e-f) Neural fragility. The fragility metric does not identify the clinically labeled SOZ channels (4 and 5), which appear among dynamically stable nodes.



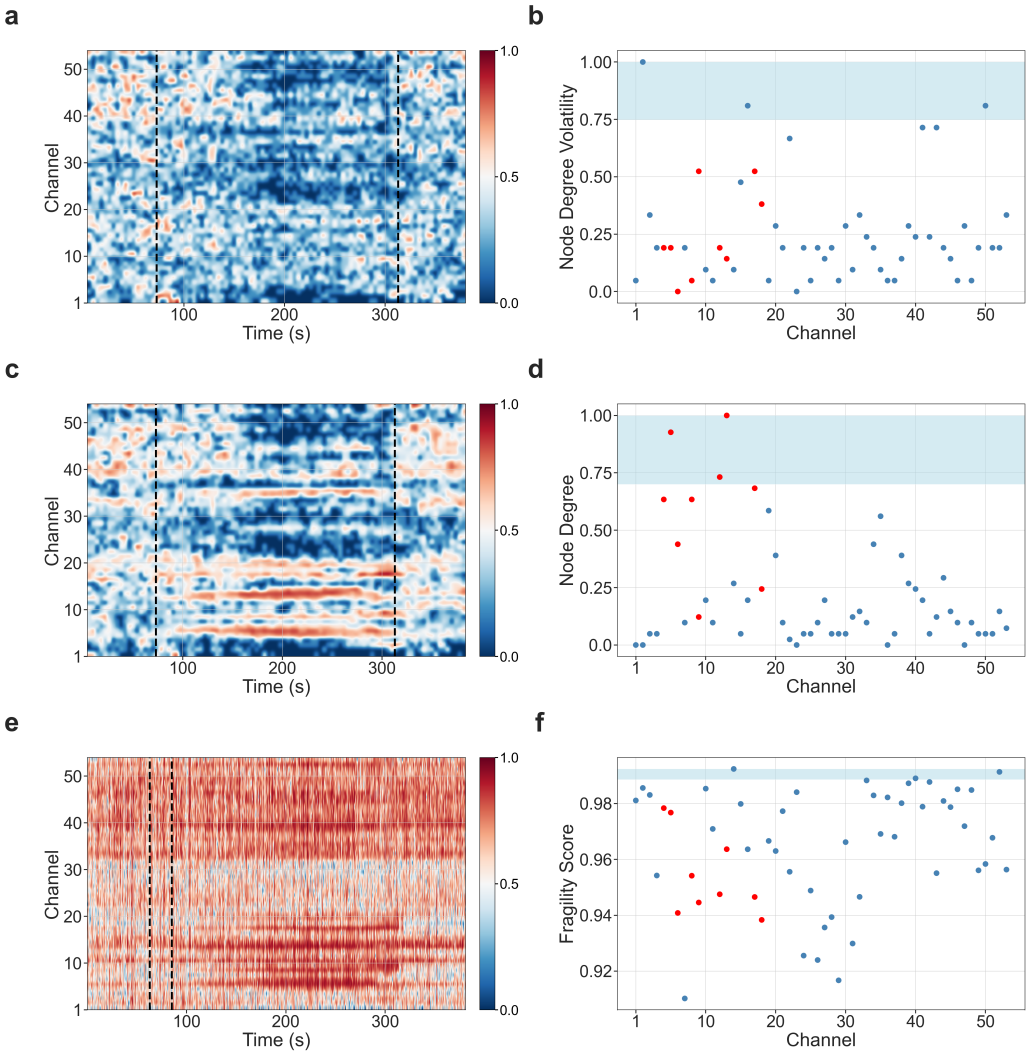
Supplementary Figure 4. Failure of other static graph metrics (in-degree, out-degree, and betweenness centrality) (patient 14, Engel class I). (left column): The graph metrics are computed over the duration of the recording. The ictal epoch, as identified by the surgeon, is demarcated with black dashed lines, from approximately 69 seconds to 313 seconds. (right column): The median graph metrics are calculated over the ictal epoch. Channels 4 and 5, which were labeled by the surgeon as seizure onset zone channels and indicated by red circles, both fall below the top 5% of data, indicated by the dark blue shaded region, suggesting that static graph metrics are not effective biomarkers for this patient's seizure onset zone.

Supplementary Note 3: Overall sensitivity outcomes: directed network metrics.



Supplementary Figure 5. Comparative sensitivity of directed network metrics for SOZ localization in Engel class I patients. This figure complements Fig. 4 in the main text. Node degree volatility, defined as the rate of change of the total node degree (the sum of in-degree and out-degree) over time, consistently outperformed both in-degree and out-degree volatility, as well as their static counterparts.

Supplementary Note 4: Node degree volatility and additional SOZ biomarkers for patient 9 with an unsuccessful surgical outcome.



Supplementary Figure 6. Comparison of SOZ biomarkers for patient 9 (Engel class II) with an unsuccessful surgical outcome. Plots correspond to Fig. 5 in the main text. Red circles indicate clinically labeled SOZ channels; blue circles denote non-SOZ channels. (a-b) Node degree volatility. The normalized volatility metric does not identify the clinically labeled SOZ channels within the top 5 % of the distribution (shaded blue). (c-d) Static node degree. Median node degree calculated over the ictal epoch produces a hypothesized false-positive identification, assigning top 5 % values to hypothesized non-epileptogenic channels. (e-f) Neural fragility. The fragility metric does not identify the clinically labeled SOZ channels. Yet, it yields a broader set of high-ranking nodes near the 5 % threshold, resulting in reduced interpretability and overall performance compared with node degree volatility.

Supplementary Note 5: Node degree volatility metrics overview

Supplementary Table 1 provides a comprehensive summary of the performance of the node degree volatility metric evaluated on a per-patient basis from Dataset A. The analysis includes 27 seizure episodes, comprising 20 from patients with Engel class I outcomes and 7 from patients with Engel class II and IV outcomes. Sensitivity and specificity values derived from this dataset are visualized in the main text. Sensitivity metrics are reflected by the dark blue bars on the left side of the histograms in Fig. 4, while specificity is shown in the corresponding bars in Fig. 6.

Supplementary Table 1. Statistics for node degree volatility (Dataset A). Method validation across patient outcomes. The positive group includes Engel Class I patients, while the negative group includes Engel Class II and IV patients. For a positive case, the method is considered successful if at least one surgeon-marked node falls within the top 5% of the node degree volatility distribution. For a negative case, the method is successful if no surgeon-marked nodes fall within the top 5%. When considering both positive and negative groups together, the method achieves an overall accuracy of 77.8%.

Diagnostic Accuracy and Error Rate Analysis					
Accuracy	**Precision (PPV)**	**Sensitivity (TPR)**	**Specificity (TNR)**	**False Positive Rate**	**False Negative Rate**
77.8% (21/27)	89% (16/18)	80% (16/20)	71.4% (5/7)	28.6% (2/7)	20% (4/20)

Supplementary Table 2. Statistics for node degree volatility (Dataset B). Validation of the method across Engel Class I (positive group) and Engel Class II and IV (negative group) patients. The evaluation criterion is identical to that used in Supplementary Table 1.

Diagnostic Accuracy and Error Rate Analysis					
Accuracy	**Precision (PPV)**	**Sensitivity (TPR)**	**Specificity (TNR)**	**False Positive Rate**	**False Negative Rate**
70.9% (39/55)	81.3% (26/32)	72.2% (26/36)	68.4% (13/19)	31.6% (6/19)	27.8% (10/36)

Supplementary Table 3. Statistics for node degree volatility from the combined Datasets A and B.

Diagnostic Accuracy and Error Rate Analysis					
Accuracy	**Precision (PPV)**	**Sensitivity (TPR)**	**Specificity (TNR)**	**False Positive Rate**	**False Negative Rate**
73.2% (60/82)	84.0% (42/50)	75% (42/56)	69.2% (18/26)	30.8% (8/26)	25.0% (14/56)

Supplementary Note 6: Patient Demographics

Supplementary Table 4 provides an overview of patient demographics in Dataset A. All patient data was collected from the OpenNeuro repository (Epilepsy iEEG Multicenter Dataset (ds003029)) with the exception of patient 0, whose three distinct seizure episodes were provided by Emory University. Dataset ID labels correspond to the clinical summary provided in the repository.

Patient ID	Dataset ID	Gender	Age at Surgery	Clinical Center	Engel Score
0 (ep. 1)	N/A	F	30	Emory	1
0 (ep. 2)	N/A	F	30	Emory	1
0 (ep. 3)	N/A	F	30	Emory	1
1	pt1	F	30	NIH	1
2	pt2	F	28	NIH	1
6	pt8	M	25	NIH	1
8	pt11	M	31	NIH	1
10	pt13	M	27	NIH	1
12	pt15	F	59	NIH	1
13	pt16	F	52	NIH	1
14	pt17	M	13	NIH	1
16	ummc002	M	17	UMMC	1
17	ummc003	M	31	UMMC	1
18	ummc004	M	38	UMMC	1
19	ummc005	M	47	UMMC	1
20	ummc006	M	36	UMMC	1
22	ummc008	M	49	UMMC	1
23	ummc009	M	36	UMMC	1
28	jh105	NG	NG	JHH	1
96	umf001	F	37	UMF	1
4	pt6	M	33	NIH	2
7	pt10	F	44	NIH	2
9	pt12	F	43	NIH	2
11	pt14	F	49	NIH	4
24	jh101	NG	NG	JHH	4
26	jh103	NG	NG	JHH	4
30	jh108	NG	NG	JHH	4

Supplementary Table 4. Patient demographics in Dataset A. Emory: Emory University School of Medicine; NIH: National Institute of Health; UMMC: University of Maryland Medical Center; JHH: Johns Hopkins Hospital

Supplementary Table 5 Overview of patient demographics in Dataset B.

Patient ID	Dataset ID	Gender	Age at Surgery	Engel Score
sub-HUP064	sub-HUP064	M	21	1D
sub-HUP065	sub-HUP065	M	36	1B
sub-HUP070	sub-HUP070	M	33	1B
sub-HUP074	sub-HUP074	F	25	1C
sub-HUP082	sub-HUP082	F	56	1A
sub-HUP087	sub-HUP087	M	24	1D
sub-HUP088	sub-HUP088	F	35	1D
sub-HUP089	sub-HUP089	M	29	1B
sub-HUP094	sub-HUP094	F	48	1B
sub-HUP097	sub-HUP097	F	39	1D
sub-HUP105	sub-HUP105	M	39	1A
sub-HUP106	sub-HUP106	F	45	1B
sub-HUP107	sub-HUP107	M	36	1A
sub-HUP111	sub-HUP111	F	40	1B
sub-HUP116	sub-HUP116	F	59	1A
sub-HUP117	sub-HUP117	M	39	1A
sub-HUP123	sub-HUP123	M	36	1A
sub-HUP126	sub-HUP126	F	26	1A
sub-HUP130	sub-HUP130	F	46	1B
sub-HUP134	sub-HUP134	M	32	1B
sub-HUP139	sub-HUP139	M	20	1A
sub-HUP140	sub-HUP140	F	47	1B
sub-HUP141	sub-HUP141	M	30	1C
sub-HUP142	sub-HUP142	M	30	1D
sub-HUP144	sub-HUP144	M	31	1D
sub-HUP146	sub-HUP146	M	16	1A
sub-HUP148	sub-HUP148	M	23	1A
sub-HUP150	sub-HUP150	M	17	1B
sub-HUP157	sub-HUP157	M	25	1B
sub-HUP160	sub-HUP160	F	45	1A
sub-HUP163	sub-HUP163	F	42	1D
sub-HUP164	sub-HUP164	F	34	1D
sub-HUP173	sub-HUP173	F	24	1A
sub-HUP177	sub-HUP177	F	42	1A
sub-HUP180	sub-HUP180	F	28	1A
sub-HUP185	sub-HUP185	M	38	1A
sub-HUP080	sub-HUP080	F	41	2C
sub-HUP086	sub-HUP086	F	25	2A
sub-HUP135	sub-HUP135	M	37	2A
sub-HUP151	sub-HUP151	M	33	2A
sub-HUP171	sub-HUP171	M	50	2A
sub-HUP172	sub-HUP172	F	28	2A

Patient ID	Dataset ID	Gender	Age at Surgery	Engel Score
sub-HUP187	sub-HUP187	M	25	2A
sub-HUP060	sub-HUP060	F	42	3A
sub-HUP112	sub-HUP112	F	21	3A
sub-HUP114	sub-HUP114	F	43	3A
sub-HUP133	sub-HUP133	F	52	3A
sub-HUP162	sub-HUP162	F	35	3A
sub-HUP166	sub-HUP166	M	26	3A
sub-HUP179	sub-HUP179	F	20	3A
sub-HUP181	sub-HUP181	F	31	3A
sub-HUP188	sub-HUP188	F	24	3A
sub-HUP190	sub-HUP190	M	25	3A
sub-HUP075	sub-HUP075	F	57	4A
sub-HUP138	sub-HUP138	M	38	4A

Supplementary Table 5. Patient demographics in Dataset B. All data was collected from the Hospital of the University of Pennsylvania (HUP).