# Supplementary Material for 'Interictal Scale-Free Neural Dynamics Identify Epileptogenic Cortex'

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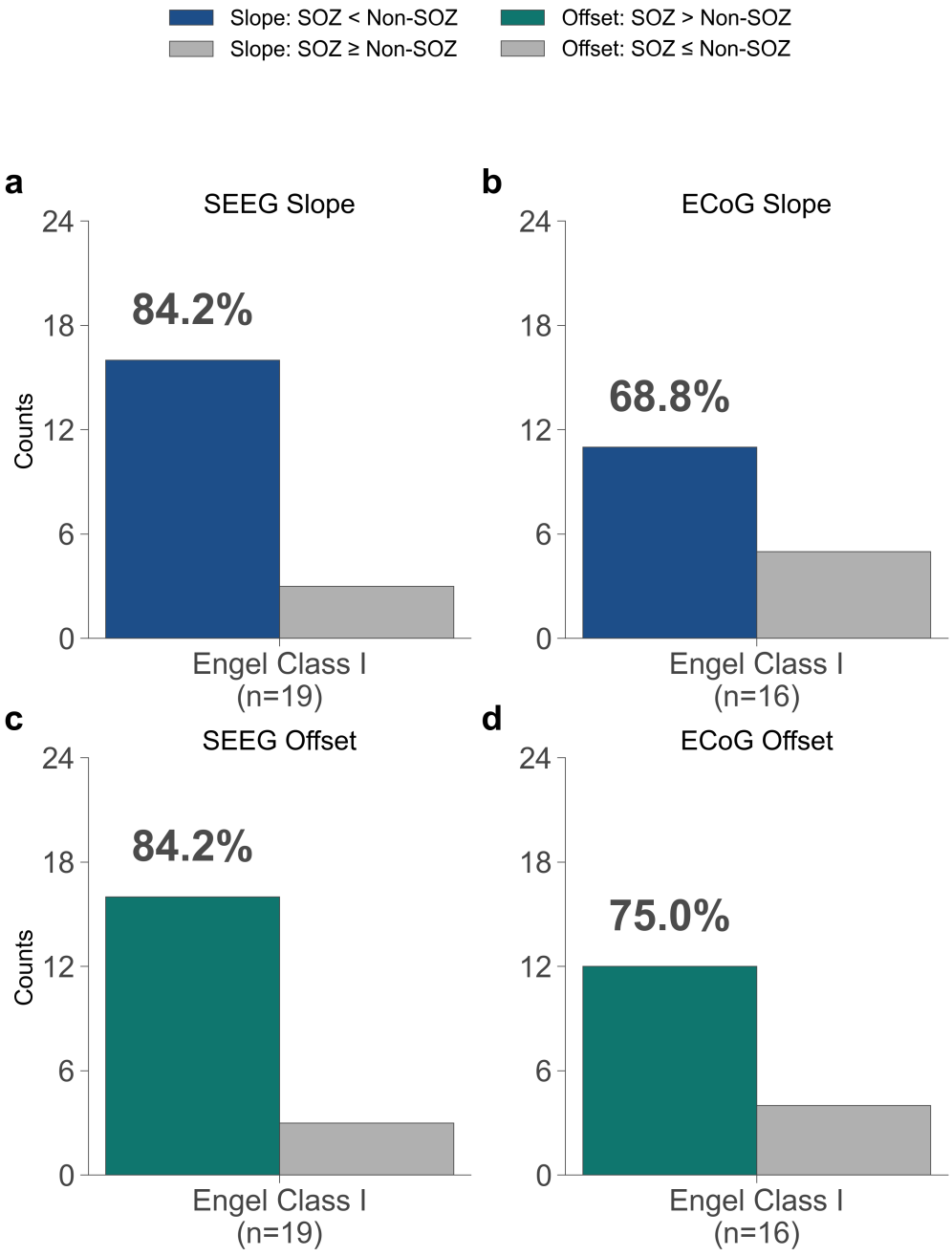
## Supplementary Note 1: Across-patient sensitivity of interictal aperiodic abnormalities in Engel class I patients

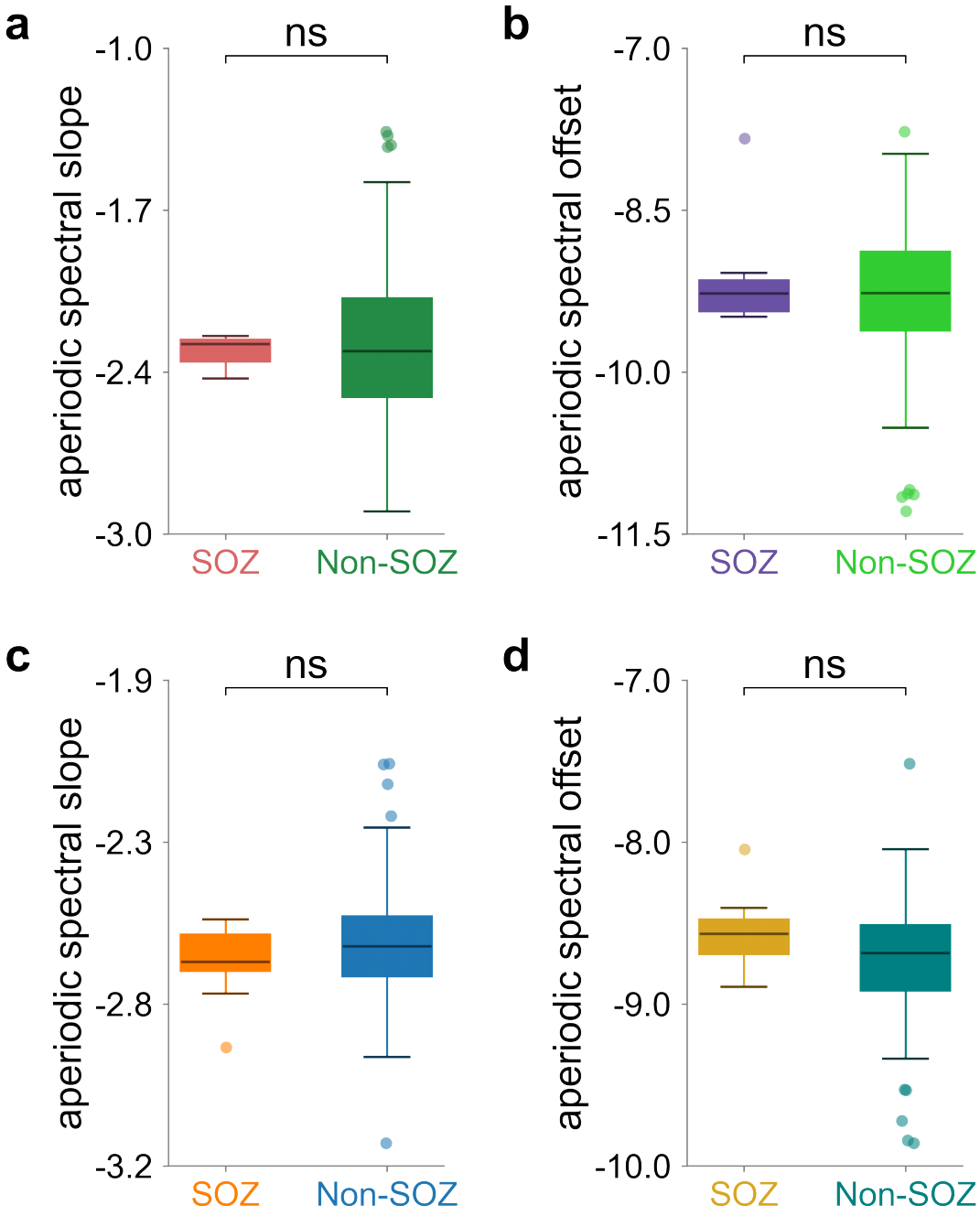
Supplementary Fig. 1 summarizes across-patient sensitivity of interictal SOZ aperiodic abnormalities in Engel class I patients across 19 SEEG and 16 ECoG cases. Sensitivity was defined by the proportion of patients whose SOZ–non-SOZ contrast followed the hypothesized direction, and was further evaluated using group-level one-sided Wilcoxon signed-rank tests of $\Delta$ against $0$, together with paired Cohen's $d_z$ effect sizes. In SEEG, both slope and offset showed high sensitivity, with 16/19 patients (84.2%) supporting the hypothesized direction for each feature, and both remained significant at the group level (slope: $P = 3.918 \times 10^{-3}$, $d_z = -0.739$; offset: $P = 3.918 \times 10^{-3}$, $d_z = 0.775$). In ECoG, slope was directionally consistent in 11/16 patients (68.8%) and also remained significant at the group level ($P = 3.845 \times 10^{-2}$, $d_z = -0.533$), whereas offset was directionally consistent in 12/16 patients (75.0%) but did not reach group-level significance ($P = 1.742 \times 10^{-1}$, $d_z = 0.281$). Overall, interictal aperiodic abnormalities were more robust in SEEG than in ECoG. All reported $P$ values are BH-FDR corrected.




**Supplementary Figure 1. Across-patient sensitivity of interictal SOZ aperiodic abnormalities in Engel class I patients.** Patient-level SOZ–non-SOZ contrasts were classified according to whether $\Delta = \mathrm{median}(z_{\mathrm{SOZ}}) - \mathrm{median}(z_{\text{non-SOZ}})$ followed the hypothesized direction. Colored bars denote patients supporting the hypothesized direction, and gray bars denote patients not supporting it; percentage labels indicate sensitivity. Group-level deviation of $\Delta$ from $0$ was assessed using one-sided Wilcoxon signed-rank tests with paired Cohen's $d_z$ effect sizes. SEEG results were significant for slope (16/19; $P = 3.918 \times 10^{-3}$, $d_z = -0.739$) and offset (16/19; $P = 3.918 \times 10^{-3}$, $d_z = 0.775$). ECoG results were significant for slope (11/16; $P = 3.845 \times 10^{-2}$, $d_z = -0.533$) but not for offset (12/16; $P = 1.742 \times 10^{-1}$, $d_z = 0.281$). All reported $P$ values are BH-FDR corrected.

## Supplementary Note 2: Representative Engel class II–IV failure cases

Supplementary Fig. 2 presents representative Engel class II–IV failure cases showing weak or negligible interictal SOZ–non-SOZ separation in aperiodic slope and offset. These SEEG and ECoG examples illustrate the limited and heterogeneous within-patient specificity observed in the unfavorable-outcome cohort.




**Supplementary Figure 2. Illustrative failure cases show weak or absent SOZ–non-SOZ separation in interictal aperiodic slope and offset. a**, Representative SEEG failure case showing limited SOZ–non-SOZ separation in aperiodic slope (sub-HUP171; $n_{\text{SOZ}} = 3$, $n_{\text{non-SOZ}} = 145$, $P = 0.898$, $d = 0.091$, $\delta = 0.048$). **b**, Representative SEEG failure case showing similarly minimal SOZ–non-SOZ separation in aperiodic offset (sub-HUP151; $n_{\text{SOZ}} = 7$, $n_{\text{non-SOZ}} = 165$, $P = 0.785$, $d = -0.007$, $\delta = 0.063$). **c,d**, Representative ECoG failure case (sub-HUP086) showing weak SOZ–non-SOZ differentiation for slope (**c**; $n_{\text{SOZ}} = 10$, $n_{\text{non-SOZ}} = 90$, $P = 0.386$, $d = -0.266$, $\delta = -0.169$) and offset (**d**; $P = 0.222$, $d = 0.332$, $\delta = 0.269$). Together, these examples illustrate that interictal aperiodic slope and offset abnormalities were weak, variable, and not clearly separable between SOZ and non-SOZ contacts in failure cases. Here, $P$ denotes the BH-FDR corrected two-sided Mann–Whitney test, $d$ denotes Cohen's $d$, and $\delta$ denotes Cliff's delta.

## Supplementary Note 3: Within-patient SOZ–non-SOZ separability of interictal aperiodic slope and offset in success cases

We assessed whether aperiodic slope and broadband offset separated SOZ from non-SOZ contacts within individual SEEG and ECoG success cases using one-sided Mann–Whitney $U$ tests. Raw $P$ values were adjusted within feature using the BH-FDR corrected procedure. Supplementary Tables 1 and 2 report only patients with FDR-corrected $P < 0.05$, together with $\Delta$, Cliff's $\delta$, and Cohen's $d$.

Significant within-patient SOZ–non-SOZ separation was observed in 9/19 SEEG patients for slope and 10/19 for offset, and in 8/16 ECoG patients for slope and 7/16 for offset.

**Supplementary Table 1.** Patient-level within-patient SOZ–non-SOZ separability in SEEG success cases for aperiodic slope and broadband offset.

| Feature | Patient ID | $n_{\mathrm{SOZ}}$ | $n_{\mathrm{non\text{-}SOZ}}$ | $\Delta$ median | Raw $p$ | FDR-corrected $P$ | Cliff's $\delta$ | Cohen's $d$ |
|---|---|---|---|---|---|---|---|---|
| Slope | sub-HUP142 | 10 | 98 | -0.454 | 1.514e-06 | 1.439e-05 | -0.900 | -2.115 |
| Slope | sub-HUP141 | 13 | 100 | -0.434 | 1.983e-07 | 3.767e-06 | -0.868 | -1.331 |
| Slope | sub-HUP163 | 8 | 148 | -0.485 | 4.926e-05 | 3.120e-04 | -0.750 | -1.566 |
| Slope | sub-HUP157 | 6 | 158 | -0.273 | 2.241e-03 | 6.349e-03 | -0.654 | -0.961 |
| Slope | sub-HUP146 | 7 | 115 | -0.185 | 2.339e-03 | 6.349e-03 | -0.615 | -1.009 |
| Slope | sub-HUP134 | 17 | 66 | -0.176 | 1.420e-03 | 5.745e-03 | -0.472 | -0.687 |
| Slope | sub-HUP177 | 16 | 156 | -0.103 | 1.512e-03 | 5.745e-03 | -0.451 | -0.597 |
| Slope | sub-HUP139 | 11 | 62 | -0.272 | 1.293e-02 | 3.072e-02 | -0.425 | -0.869 |
| Slope | sub-HUP160 | 12 | 90 | -0.097 | 1.772e-02 | 3.742e-02 | -0.376 | -0.709 |
| Offset | sub-HUP141 | 13 | 100 | 1.245 | 3.994e-07 | 7.590e-06 | 0.845 | 1.708 |
| Offset | sub-HUP164 | 3 | 173 | 0.779 | 3.766e-03 | 7.951e-03 | 0.823 | 1.302 |
| Offset | sub-HUP157 | 6 | 158 | 1.140 | 3.111e-04 | 1.478e-03 | 0.757 | 1.411 |
| Offset | sub-HUP142 | 10 | 98 | 0.759 | 7.888e-05 | 5.313e-04 | 0.729 | 1.398 |
| Offset | sub-HUP163 | 8 | 148 | 0.863 | 5.045e-04 | 1.917e-03 | 0.655 | 1.560 |
| Offset | sub-HUP146 | 7 | 115 | 0.441 | 2.153e-03 | 5.843e-03 | 0.620 | 1.100 |
| Offset | sub-HUP134 | 17 | 66 | 0.617 | 8.390e-05 | 5.313e-04 | 0.595 | 1.011 |
| Offset | sub-HUP160 | 12 | 90 | 0.464 | 1.191e-03 | 3.771e-03 | 0.543 | 1.112 |
| Offset | sub-HUP177 | 16 | 156 | 0.394 | 2.582e-03 | 6.133e-03 | 0.425 | 0.661 |
| Offset | sub-HUP144 | 15 | 96 | 0.390 | 9.817e-03 | 1.865e-02 | 0.376 | 0.564 |

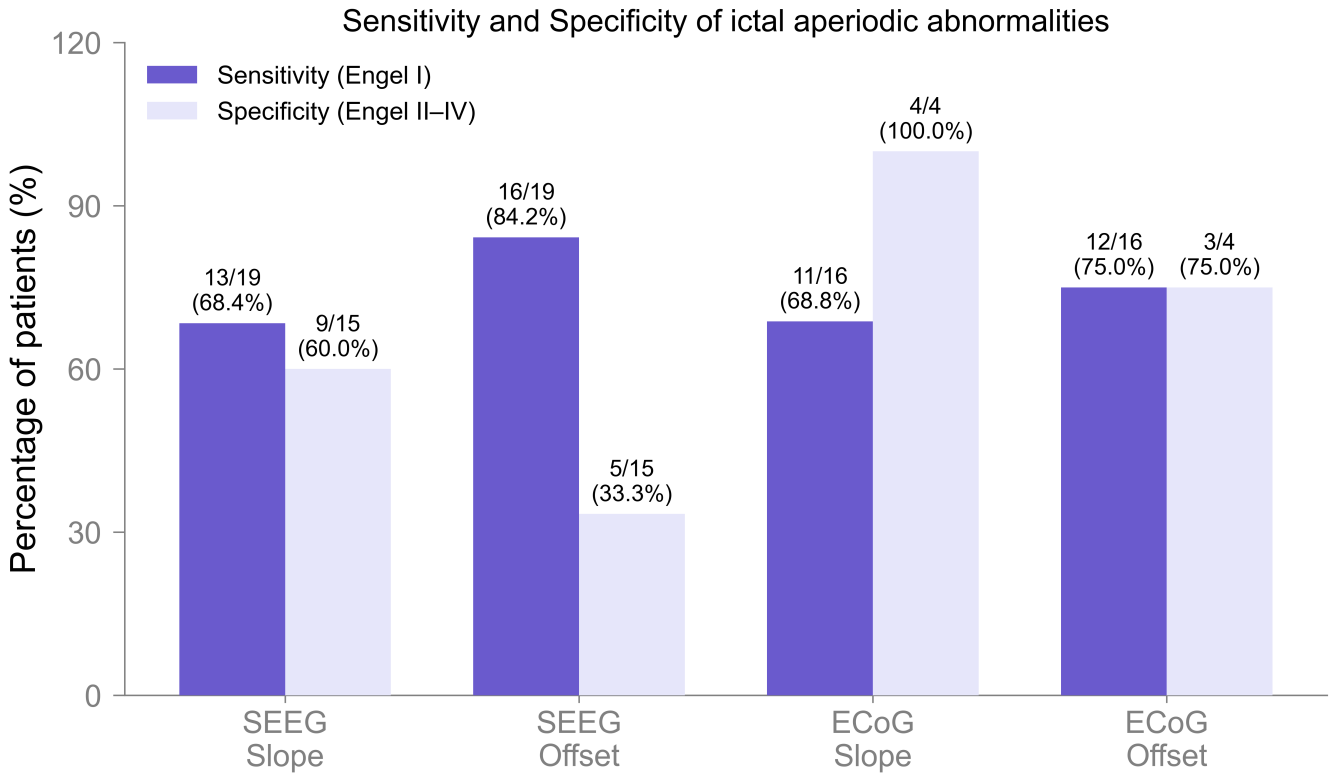
**Supplementary Table 2.** Patient-level within-patient SOZ–non-SOZ separability in ECoG success cases for aperiodic slope and offset.

| Feature | Patient ID | $n_{\mathrm{SOZ}}$ | $n_{\mathrm{non\text{-}SOZ}}$ | $\Delta$median | Raw $p$ | FDR-corrected $P$ | Cliff's $\delta$ | Cohen's $d$ |
|---|---|---|---|---|---|---|---|---|
| Slope | sub-HUP126 | 9 | 116 | -0.336 | 1.138e-05 | 7.637e-05 | -0.851 | -1.456 |
| Slope | sub-HUP089 | 10 | 84 | -0.224 | 6.352e-05 | 2.033e-04 | -0.745 | -1.752 |
| Slope | sub-HUP106 | 10 | 105 | -0.238 | 5.529e-05 | 2.033e-04 | -0.743 | -1.831 |
| Slope | sub-HUP111 | 7 | 94 | -0.317 | 2.155e-04 | 4.926e-04 | -0.742 | -1.378 |
| Slope | sub-HUP065 | 15 | 49 | -0.292 | 1.432e-05 | 7.637e-05 | -0.720 | -1.551 |
| Slope | sub-HUP123 | 21 | 96 | -0.221 | 1.247e-05 | 7.637e-05 | -0.589 | -1.030 |
| Slope | sub-HUP097 | 15 | 77 | -0.360 | 6.810e-04 | 1.362e-03 | -0.526 | -0.960 |
| Slope | sub-HUP107 | 23 | 94 | -0.135 | 9.409e-05 | 2.509e-04 | -0.504 | -0.812 |
| Offset | sub-HUP089 | 10 | 84 | 0.529 | 9.618e-06 | 1.411e-04 | 0.831 | 1.834 |
| Offset | sub-HUP065 | 15 | 49 | 1.123 | 1.763e-05 | 1.411e-04 | 0.712 | 1.624 |
| Offset | sub-HUP106 | 10 | 105 | 0.376 | 5.181e-04 | 2.763e-03 | 0.630 | 1.339 |
| Offset | sub-HUP126 | 9 | 116 | 0.232 | 1.845e-02 | 4.217e-02 | 0.420 | 1.057 |
| Offset | sub-HUP123 | 21 | 96 | 0.480 | 2.773e-03 | 1.109e-02 | 0.388 | 0.644 |
| Offset | sub-HUP097 | 15 | 77 | 0.436 | 1.359e-02 | 3.623e-02 | 0.363 | 0.607 |
| Offset | sub-HUP107 | 23 | 94 | 0.157 | 1.089e-02 | 3.485e-02 | 0.310 | 0.473 |

## Supplementary Note 4: Sensitivity and specificity of ictal aperiodic slope and offset during the first 40 s after seizure onset

To determine whether early ictal aperiodic abnormalities provide sensitive markers of epileptogenic tissue, we analyzed the first 40 s after seizure onset in Engel class I patients using patient-level SOZ–non-SOZ median contrasts. In SEEG, aperiodic slope contrasts were negative in 13/19 patients (68.4%) and remained significant at the group level ($P = 3.64 \times 10^{-2}$, $d_z = -0.485$), whereas broadband offset contrasts were positive in 16/19 patients (84.2%) and showed a stronger effect ($P = 8.39 \times 10^{-4}$, paired Cohen's $d_z = 1.108$). In ECoG, slope contrasts were negative in 11/16 patients (68.8%) and were also significant at the group level ($P = 3.64 \times 10^{-2}$, paired Cohen's $d_z = -0.571$), whereas offset contrasts were positive in 12/16 patients (75.0%) and likewise remained significant ($P = 2.50 \times 10^{-2}$, paired Cohen's $d_z = 0.513$). Overall, during the first 40 s after seizure onset, both ictal slope flattening and offset elevation remained significantly associated with the SOZ in Engel class I patients, with broadband offset showing the strongest early ictal sensitivity across modalities.

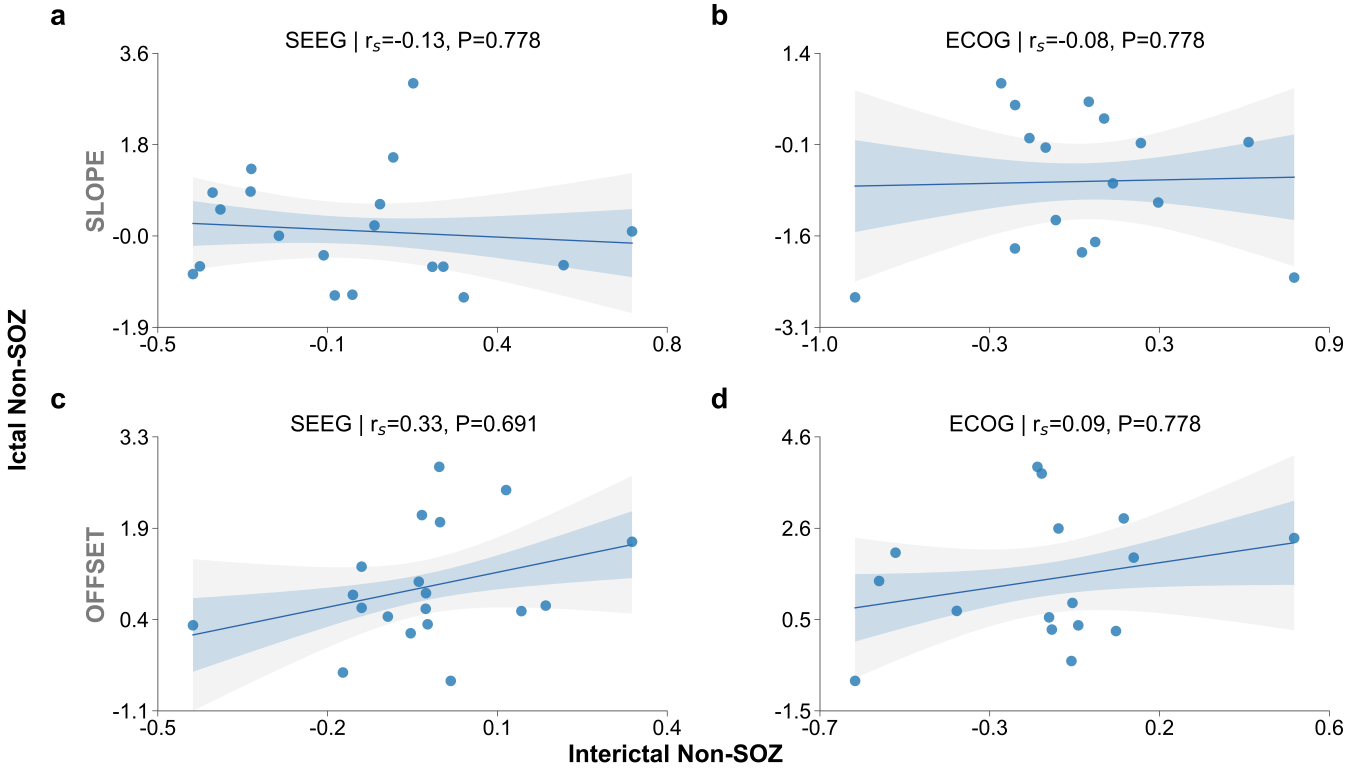
We next asked whether these early ictal abnormalities remained specifically associated with favorable outcome during the same after-onset window. In poor-outcome SEEG, specificity was modest for slope at 60.0% (9/15) and lower for offset at 33.3% (5/15). Group-level slope contrasts were not significant ($P = 4.54 \times 10^{-1}$, $d_z = -0.22$), and offset showed only a weak trend that did not survive global correction ($P = 6.03 \times 10^{-2}$, paired Cohen's $d_z = 0.71$). In poor-outcome ECoG, specificity was 100.0% (4/4) for slope and 75.0% (3/4) for offset, but neither group-level contrast was significant (slope: $P = 6.06 \times 10^{-1}$, $d_z = 0.68$; offset: $P = 6.25 \times 10^{-1}$, $d_z = 0.20$). Thus, although ictal aperiodic slope and offset during the first 40 s after seizure onset were SOZ-concordant in Engel class I patients, their outcome-consistent specificity was weaker than in the centered-onset analysis and was not supported by significant group-level effects in poor-outcome cases.




**Supplementary Figure 3. Across-patient sensitivity and outcome-consistent specificity of ictal aperiodic abnormalities during the first 40 s after seizure onset.** Bar plots summarize the proportion of patients whose SOZ aperiodic abnormalities followed the hypothesized direction for aperiodic slope and broadband offset in SEEG and ECoG. In Engel class I patients, after-onset sensitivity was 68.4% (13/19) for SEEG slope ($P = 3.642 \times 10^{-2}$, $d_z = -0.429$), 84.2% (16/19) for SEEG offset ($P = 8.392 \times 10^{-4}$, $d_z = 0.959$), 68.8% (11/16) for ECoG slope ($P = 3.642 \times 10^{-2}$, $d_z = -0.545$), and 75.0% (12/16) for ECoG offset ($P = 2.496 \times 10^{-2}$, $d_z = 0.668$); all four cohort-level effects remained significant after correction, with the strongest effect observed for SEEG broadband offset. In Engel class II–IV patients, outcome-consistent specificity was 60.0% (9/15) for SEEG slope ($P = 6.057 \times 10^{-1}$, paired Cohen's $d_z = -0.224$), 33.3% (5/15) for SEEG offset ($P = 6.030 \times 10^{-2}$, $d_z = 0.713$), 100.0% (4/4) for ECoG slope ($P = 6.057 \times 10^{-1}$, $d_z = 0.681$), and 75.0% (3/4) for ECoG offset ($P = 6.250 \times 10^{-1}$, $d_z = 0.205$); however, no poor-outcome cohort-level contrast remained significant after correction. These results show that early ictal slope flattening and offset elevation remained significantly enriched in the SOZ of surgically successful patients, whereas outcome-consistent specificity was weaker than in the centered-onset analysis. All reported $P$ values are BH-FDR corrected.

## Supplementary Note 5: Non-SOZ cross-epoch correlations of aperiodic slope and offset in 40 s windows

We next examined whether patient-level non-SOZ aperiodic slope and offset remained stable across interictal and ictal 40 s windows.




**Supplementary Figure 4. Non-SOZ cross-epoch correlations of aperiodic slope and offset in 40 s windows.** (a,b) Patient-level non-SOZ slope estimates computed from 40 s windows are plotted for ictal versus interictal epochs (x-axis: interictal non-SOZ; y-axis: ictal non-SOZ), shown separately for SEEG (a) and ECoG (b). (c,d) The same comparison is shown for non-SOZ offset (SEEG in c; ECoG in d). Each point denotes one patient. Spearman correlation coefficients ($r_s$) and corresponding $P$ values are reported in each panel. Solid lines indicate the fitted trend, and shaded bands indicate uncertainty around the fit. Overall, non-SOZ aperiodic estimates show weak interictal–ictal coupling, consistent with non-SOZ values remaining near baseline across epochs.

## Supplementary Note 6: Aperiodic interictal slope and offset diagnostic metrics overview

Supplementary Tables 3 and 4 summarize patient-level diagnostic classification performance for aperiodic slope and offset, together with the corresponding group-level SOZ–non-SOZ contrast statistics (Wilcoxon signed-rank $P$-values and Cohen's $d$ effect sizes). These analyses were derived from the patient-level SOZ–non-SOZ contrast $D = \tilde{x}_{\mathrm{SOZ}} - \tilde{x}_{\mathrm{non\text{-}SOZ}}$, computed in robust z-scores. A patient was classified as test-positive when $D < 0$ for slope or $D > 0$ for offset, consistent with the SOZ pattern supported by the group-level SOZ–non-SOZ contrast statistics. Sensitivity (TPR) was defined as the fraction of Engel class I patients classified as test-positive, whereas outcome-consistent specificity (TNR) was defined as the fraction of Engel class II–IV patients classified as test-negative.

**Supplementary Table 3. Patient-level diagnostic classification metrics for aperiodic slope and offset in SEEG.**

| Diagnostic Accuracy and Error Rate Analysis | | | | | | |
|---|---|---|---|---|---|---|
| **Feature** | **Accuracy** | **Precision (PPV)** | **Sensitivity (TPR)** | **Specificity (TNR)** | **False Positive Rate** | **False Negative Rate** |
| Slope | 60.0% (21/35) | 59.3% (16/27) | 84.2% (16/19) | 31.2% (5/16) | 68.8% (11/16) | 15.8% (3/19) |
| Offset | 62.9% (22/35) | 61.5% (16/26) | 84.2% (16/19) | 37.5% (6/16) | 62.5% (10/16) | 15.8% (3/19) |

**Supplementary Table 4. Patient-level diagnostic classification metrics for aperiodic slope and offset in ECoG.**

| Diagnostic Accuracy and Error Rate Analysis | | | | | | |
|---|---|---|---|---|---|---|
| **Feature** | **Accuracy** | **Precision (PPV)** | **Sensitivity (TPR)** | **Specificity (TNR)** | **False Positive Rate** | **False Negative Rate** |
| Slope | 60.0% (12/20) | 78.6% (11/14) | 68.8% (11/16) | 25.0% (1/4) | 75.0% (3/4) | 31.2% (5/16) |
| Offset | 70.0% (14/20) | 85.7% (12/14) | 75.0% (12/16) | 50.0% (2/4) | 50.0% (2/4) | 25.0% (4/16) |

## Supplementary Note 7: High-frequency aperiodic analyses and within-patient Mann–Whitney U statistics in Engel class I patients

To further characterize within-patient SOZ abnormalities in the high-frequency range (85–155 Hz), we performed node-wise Mann–Whitney U analyses comparing SOZ and non-SOZ contacts within individual Engel class I patients across 30 s interictal, preictal, and ictal epochs. These analyses assessed within-patient SOZ–non-SOZ separation for both high-frequency slope and high-frequency offset in SEEG and ECoG. Unless otherwise noted, all reported $P$ values denote BH-FDR corrected $P$ values.

### Interictal within-patient analyses

During interictal epochs, significant within-patient SOZ decreases in high-frequency slope were observed in 11/19 SEEG patients (57.9%) and 2/16 ECoG patients (12.5%), whereas significant within-patient SOZ increases in high-frequency offset were observed in 8/19 SEEG patients (42.1%) and 2/16 ECoG patients (12.5%), respectively, at $P < 0.05$. Cohen's $d$ values among significant patients ranged from medium to large for SEEG slope, from small to large for SEEG offset, were large for ECoG slope, and ranged from medium to large for ECoG offset. As a representative SEEG case, patient sub-HUP164 ($n_{\mathrm{SOZ}} = 3$, $n_{\text{non-SOZ}} = 173$) showed lower SOZ than non-SOZ high-frequency slope ($P = 1.053 \times 10^{-2}$, $d = -1.871$) together with higher SOZ high-frequency offset ($P = 4.725 \times 10^{-3}$, $d = 2.070$). As a representative ECoG case, patient sub-HUP065 ($n_{\mathrm{SOZ}} = 15$, $n_{\text{non-SOZ}} = 49$) showed lower SOZ high-frequency slope ($P = 1.216 \times 10^{-3}$, $d = -1.442$) and higher SOZ high-frequency offset ($P = 1.141 \times 10^{-3}$, $d = 1.469$).

### Preictal within-patient analyses

During preictal epochs, significant within-patient SOZ decreases in high-frequency slope were observed in 7/19 SEEG patients (36.8%) and 6/16 ECoG patients (37.5%), whereas significant within-patient SOZ increases in high-frequency offset were observed in 7/19 SEEG patients (36.8%) and 5/16 ECoG patients (31.2%), respectively, at $P < 0.05$. Cohen's $d$ values among significant patients ranged from small to large for SEEG slope, from medium to large for SEEG offset, and were uniformly

large for both slope and offset in ECoG. As a representative SEEG case, patient sub-HUP164 showed lower SOZ than non-SOZ high-frequency slope ($P = 1.489 \times 10^{-4}$, $d = -2.495$) together with higher SOZ high-frequency offset ($P = 1.489 \times 10^{-4}$, $d = 2.810$). As a representative ECoG case, patient sub-HUP094 ($n_{\text{SOZ}} = 3$, $n_{\text{non-SOZ}} = 80$) showed lower SOZ high-frequency slope ($P = 1.350 \times 10^{-3}$, $d = -1.453$) and higher SOZ high-frequency offset ($P = 6.060 \times 10^{-3}$, $d = 1.232$).

**Ictal within-patient analyses**

During ictal epochs, significant within-patient SOZ decreases in high-frequency slope were observed in 10/19 SEEG patients (52.6%) and 7/16 ECoG patients (43.8%), whereas significant within-patient SOZ increases in high-frequency offset were observed in 12/19 SEEG patients (63.2%) and 8/16 ECoG patients (50.0%), respectively, at $P < 0.05$. Cohen's $d$ values among significant patients ranged from medium to large for both SEEG features, whereas all significant ECoG effects were large for both slope and offset. As a representative SEEG case, patient sub-HUP164 showed lower SOZ than non-SOZ high-frequency slope ($P = 4.963 \times 10^{-5}$, $d = -2.792$) together with higher SOZ high-frequency offset ($P = 1.418 \times 10^{-5}$, $d = 3.112$). As a representative ECoG case, patient sub-HUP065 showed lower SOZ high-frequency slope ($P = 2.325 \times 10^{-7}$, $d = -2.703$) and higher SOZ high-frequency offset ($P = 2.229 \times 10^{-7}$, $d = 2.770$).

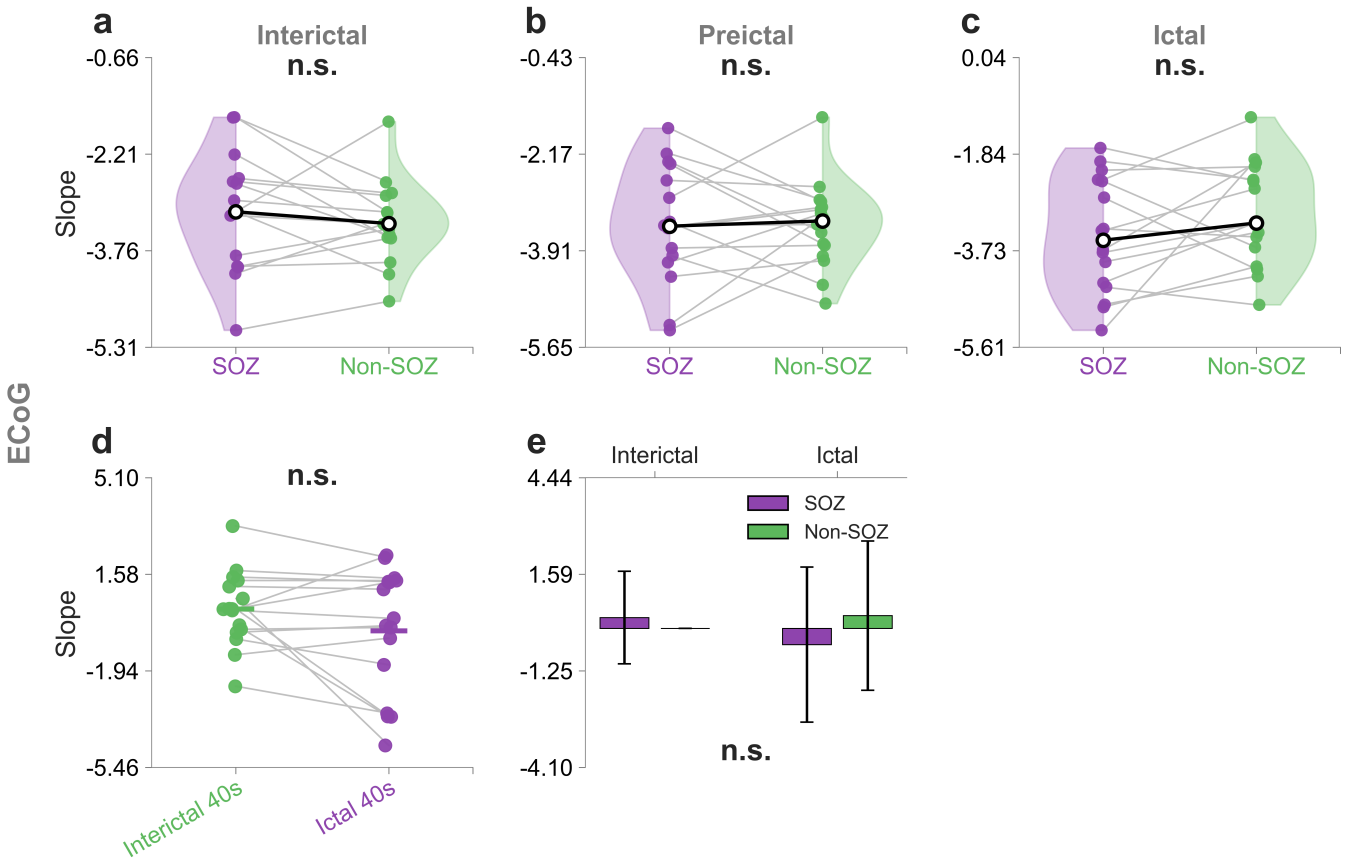
Overall, these within-patient Mann–Whitney U analyses indicate that high-frequency aperiodic SOZ abnormalities were detectable across interictal, preictal, and ictal states in both modalities, with the strongest and most consistent within-patient separation generally observed during ictal epochs.

## High-frequency ECoG aperiodic abnormalities are weaker and less consistent across states

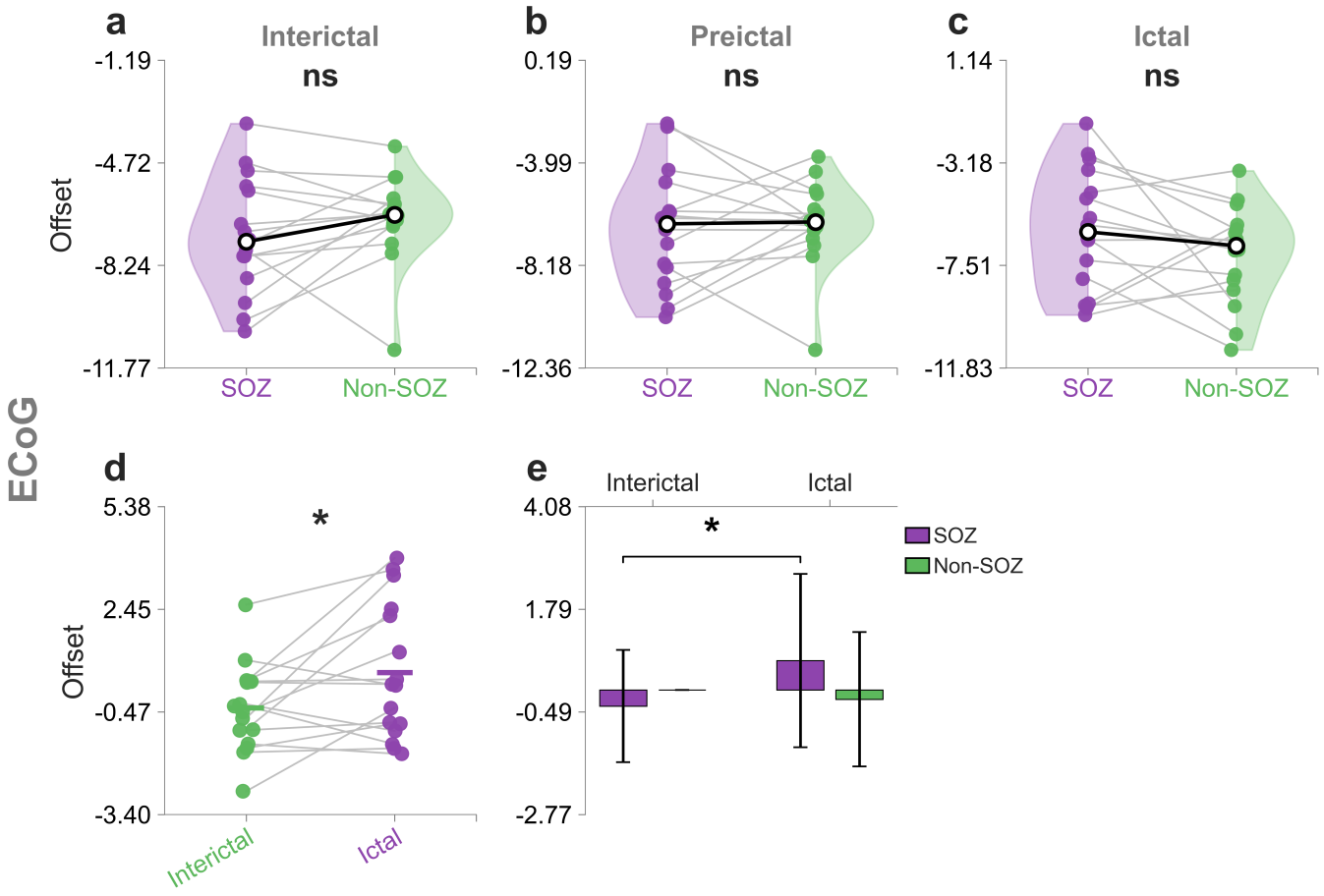
In ECoG Engel class I patients ($N = 16$), high-frequency slope and offset abnormalities were weaker and less consistent than in SEEG, and no within-epoch comparison remained significant after epoch-wise FDR-correction. During interictal epochs, slope and offset followed the hypothesized directions in only 6/16 patients (37.5%), and the group-level median contrasts were opposite to the hypothesized SOZ-supporting pattern (slope: median $\Delta_{\text{slope}} = 0.313$, IQR $[-0.457, 1.189]$, $P = 8.943 \times 10^{-1}$; offset: median $\Delta_{\text{offset}} = -0.385$, IQR $[-1.094, 0.394]$, $P = 8.943 \times 10^{-1}$). Results remained non-significant during the preictal period, where shifts were observed in 9/16 patients (56.2%; slope: median $\Delta_{\text{slope}} = -0.043$, IQR $[-1.316, 1.545]$, $P = 5.500 \times 10^{-1}$; offset: median $\Delta_{\text{offset}} = 0.029$, IQR $[-1.658, 1.175]$, $P = 5.500 \times 10^{-1}$). During the ictal state, directional consistency increased modestly to 10/16 patients (62.5%), but neither feature reached significance after correction (slope: median $\Delta_{\text{slope}} = -0.728$, IQR $[-2.235, 0.562]$, BH-FDR $P = 7.953 \times 10^{-2}$; offset: median $\Delta_{\text{offset}} = 0.485$, IQR $[-0.455, 2.284]$, BH-FDR $P = 7.778 \times 10^{-2}$).

Between epochs, paired within-SOZ interictal-to-ictal slope changes in ECoG did not reach significance (one-sided Wilcoxon signed-rank test; $N = 16$; Supplementary Fig. 5d). By contrast, SOZ offset increased modestly from interictal to ictal states (one-sided Wilcoxon signed-rank test; interictal $<$ ictal; $N = 16$; $p = 0.0288$; Supplementary Fig. 6d). Together, these findings indicate that high-frequency aperiodic abnormalities in ECoG were weaker and less consistent across patients than those observed in SEEG.

# ECoG aperiodic slope and offset across epochs High Frequency




**Supplementary Figure 5. ECoG aperiodic slope (high frequency). a–c,** SOZ versus non-SOZ patient-level paired medians across interictal, preictal and ictal epochs. **d,e,** SOZ interictal versus ictal comparisons in 30 s windows. Across panels, slope effects did not reach significance ($N = 16$).




**Supplementary Figure 6. ECoG aperiodic offset (high frequency). a–c,** SOZ versus non-SOZ patient-level paired medians across interictal, preictal and ictal epochs. **d,e,** SOZ offset increased from interictal to ictal in 30 s windows ($p = 0.0288$; $N = 16$).

# Supplementary Note 8: High-frequency specificity and diagnostic performance in Engel class II–IV patients

### Within-patient high-frequency specificity

We next assessed whether high-frequency (85–155 Hz) aperiodic slope avoided false positive reinforcement of the clinically labeled SOZ in patients with unsuccessful surgical outcomes (Engel classes II–IV). Specificity (true negative rate, TNR) was defined as the fraction of Engel class II–IV patients who were not test-positive in the hypothesized SOZ direction. A patient was considered test-positive only if the within-patient SOZ–nonSOZ contrast was in the hypothesized direction and remained significant after BH-FDR correction of the corresponding one-sided within-patient Mann–Whitney U test. Using this criterion, slope showed moderate specificity across epochs in the pooled cohort ($N = 20$): 60.0% (interictal; 12/20), 70.0% (preictal; 14/20), and 50.0% (ictal; 10/20).

Stratified by modality, SEEG ($N = 16$) specificity was 50.0% (interictal; 8/16), 62.5% (preictal; 10/16), and 37.5% (ictal; 6/16), whereas ECoG ($N = 4$) showed 100% specificity in all epochs (4/4 each), although interpretation of ECoG specificity is limited by the small failure cohort.

Representative true-negative examples included interictal SEEG sub-HUP166 ($n_{\mathrm{SOZ}} = 15$, $n_{\text{non-SOZ}} = 149$, $P = 1.261 \times 10^{-2}$, $\delta = 0.496$, $d = 0.848$), preictal SEEG sub-HUP166 ($P = 7.814 \times 10^{-3}$), ictal SEEG sub-HUP166 ($P = 3.848 \times 10^{-3}$), interictal ECoG sub-HUP086 ($P = 2.711 \times 10^{-6}$), preictal ECoG sub-HUP086 ($P = 5.920 \times 10^{-5}$), and ictal ECoG sub-HUP086 ($P = 5.735 \times 10^{-3}$).

### Across-epoch offset specificity

Using the same specificity criterion, 85–155 Hz aperiodic offset showed similar specificity across epochs. In the pooled cohort ($N = 20$), specificity was 65.0% (interictal; 13/20), 70.0% (preictal; 14/20), and 50.0% (ictal; 10/20).

In SEEG ($N = 16$), specificity was 50.0% (interictal; 8/16), 62.5% (preictal; 10/16), and 37.5% (ictal; 6/16), while ECoG ($N = 4$) again showed 100% specificity in all epochs, with the same caveat regarding small sample size.

Representative true-negative examples included interictal SEEG sub-HUP166 ($P = 5.174 \times 10^{-3}$),

preictal SEEG sub-HUP166 ($P = 3.931 \times 10^{-3}$), ictal SEEG sub-HUP166 ($P = 6.471 \times 10^{-4}$), and interictal ECoG sub-HUP086 ($P = 3.825 \times 10^{-6}$).

## Patient-level within-epoch summary statistics

Supplementary Table 5 summarizes patient-level within-epoch high-frequency slope and offset analyses in the 85–155 Hz range for SEEG and ECoG in the Engel class I cohort. Within each epoch, one patient-level SOZ–nonSOZ contrast was computed per patient as $D = \tilde{x}_{\mathrm{SOZ}} - \tilde{x}_{\mathrm{nonSOZ}}$. Group-level significance was then assessed across patients using one-sided Wilcoxon signed-rank tests against $D = 0$, followed by BH-FDR correction within each epoch across the four tests (SEEG slope, SEEG offset, ECoG slope, ECoG offset). For slope, the hypothesized SOZ-supporting direction was $D < 0$, whereas for offset it was $D > 0$. Significant within-epoch effects were observed in SEEG across interictal, preictal, and ictal epochs for both slope and offset after epoch-wise false-discovery-rate correction, whereas no ECoG comparison survived correction.

**Supplementary Table 5.** Patient-level within-epoch high-frequency aperiodic summary statistics for SEEG and ECoG in Engel class I patients. Within each epoch, one patient-level SOZ–nonSOZ contrast was computed per patient in the 85–155 Hz range. The table reports the number of patients in the hypothesized direction (Direction $n$), percentage, median contrast ($\Delta$), interquartile range (IQR), Wilcoxon signed-rank statistic, raw $p$-value, and BH-FDR corrected $P$-value.

| **Modality** | **Feature** | **Epoch** | $N$ | **Direction** $n$ | **%** | **Median** $\Delta$ | **IQR** | $W$ | **Raw** $p$ | **BH-FDR** $P$ |
|---|---|---|---|---|---|---|---|---|---|---|
| SEEG | Slope | Interictal | 19 | 15 | 78.9 | -0.628 | [-0.740, -0.225] | 21.0 | $8.469\times10^{-4}$ | $2.399\times10^{-3}$ |
| SEEG | Slope | Preictal | 19 | 12 | 63.2 | -0.597 | [-0.892, 0.147] | 37.0 | $9.041\times10^{-3}$ | $1.808\times10^{-2}$ |
| SEEG | Slope | Ictal | 19 | 17 | 89.5 | -0.721 | [-1.591, -0.214] | 19.0 | $5.856\times10^{-4}$ | $1.171\times10^{-3}$ |
| SEEG | Offset | Interictal | 19 | 15 | 78.9 | 0.609 | [ 0.229, 0.802] | 167.0 | $1.200\times10^{-3}$ | $2.399\times10^{-3}$ |
| SEEG | Offset | Preictal | 19 | 13 | 68.4 | 0.597 | [-0.077, 0.858] | 153.0 | $9.041\times10^{-3}$ | $1.808\times10^{-2}$ |
| SEEG | Offset | Ictal | 19 | 17 | 89.5 | 1.103 | [ 0.417, 1.296] | 179.0 | $1.049\times10^{-4}$ | $4.196\times10^{-4}$ |
| ECoG | Slope | Interictal | 16 | 6 | 37.5 | 0.313 | [-0.457, 1.189] | 85.0 | $8.123\times10^{-1}$ | $8.943\times10^{-1}$ |
| ECoG | Slope | Preictal | 16 | 9 | 56.2 | -0.043 | [-1.316, 1.545] | 69.0 | $5.301\times10^{-1}$ | $5.500\times10^{-1}$ |
| ECoG | Slope | Ictal | 16 | 10 | 62.5 | -0.728 | [-2.235, 0.562] | 40.0 | $7.953\times10^{-2}$ | $7.953\times10^{-2}$ |
| ECoG | Offset | Interictal | 16 | 6 | 37.5 | -0.385 | [-1.094, 0.394] | 44.0 | $8.943\times10^{-1}$ | $8.943\times10^{-1}$ |
| ECoG | Offset | Preictal | 16 | 9 | 56.2 | 0.029 | [-1.658, 1.175] | 66.0 | $5.500\times10^{-1}$ | $5.500\times10^{-1}$ |
| ECoG | Offset | Ictal | 16 | 10 | 62.5 | 0.485 | [-0.455, 2.284] | 99.0 | $5.833\times10^{-2}$ | $7.778\times10^{-2}$ |

**Supplementary Table 6.** Across-patient directional diagnostic performance of high-frequency (85–155 Hz) aperiodic slope and offset across interictal, preictal, and ictal 30 s epochs in SEEG.

| Epoch | Feature | Accuracy | Precision (PPV) | Sensitivity (TPR) | Specificity (TNR) | False Positive Rate | False Negative Rate |
|---|---|---|---|---|---|---|---|
| Interictal | Slope | 67.6% (23/34) | 68.2% (15/22) | 78.9% (15/19) | 53.3% (8/15) | 46.7% (7/15) | 21.1% (4/19) |
| Interictal | Offset | 67.6% (23/34) | 68.2% (15/22) | 78.9% (15/19) | 53.3% (8/15) | 46.7% (7/15) | 21.1% (4/19) |
| Preictal | Slope | 61.8% (21/34) | 66.7% (12/18) | 63.2% (12/19) | 60.0% (9/15) | 40.0% (6/15) | 36.8% (7/19) |
| Preictal | Offset | 64.7% (22/34) | 68.4% (13/19) | 68.4% (13/19) | 60.0% (9/15) | 40.0% (6/15) | 31.6% (6/19) |
| Ictal | Slope | 61.8% (21/34) | 60.7% (17/28) | 89.5% (17/19) | 26.7% (4/15) | 73.3% (11/15) | 10.5% (2/19) |
| Ictal | Offset | 61.8% (21/34) | 60.7% (17/28) | 89.5% (17/19) | 26.7% (4/15) | 73.3% (11/15) | 10.5% (2/19) |

**Supplementary Table 7.** Across-patient directional diagnostic performance of high-frequency (85–155 Hz) aperiodic slope and offset across interictal, preictal, and ictal 30 s epochs in ECoG.

| Epoch | Feature | Accuracy | Precision (PPV) | Sensitivity (TPR) | Specificity (TNR) | False Positive Rate | False Negative Rate |
|---|---|---|---|---|---|---|---|
| Interictal | Slope | 50.0% (10/20) | 100.0% (6/6) | 37.5% (6/16) | 100.0% (4/4) | 0.0% (0/4) | 62.5% (10/16) |
| Interictal | Offset | 50.0% (10/20) | 100.0% (6/6) | 37.5% (6/16) | 100.0% (4/4) | 0.0% (0/4) | 62.5% (10/16) |
| Preictal | Slope | 65.0% (13/20) | 100.0% (9/9) | 56.2% (9/16) | 100.0% (4/4) | 0.0% (0/4) | 43.8% (7/16) |
| Preictal | Offset | 65.0% (13/20) | 100.0% (9/9) | 56.2% (9/16) | 100.0% (4/4) | 0.0% (0/4) | 43.8% (7/16) |
| Ictal | Slope | 70.0% (14/20) | 100.0% (10/10) | 62.5% (10/16) | 100.0% (4/4) | 0.0% (0/4) | 37.5% (6/16) |
| Ictal | Offset | 70.0% (14/20) | 100.0% (10/10) | 62.5% (10/16) | 100.0% (4/4) | 0.0% (0/4) | 37.5% (6/16) |

Supplementary Table 8: Overview of patient demographics in Dataset.

| 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-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-HUP165 | sub-HUP165 | F | 21 | 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 8.** Patient demographics of the included HUP cohort. All data was collected from the Hospital of the University of Pennsylvania (HUP).