# Deep Learning for Brain-Computer Interfaces

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#### Introduction and Problem Statement

Is it possible to decode neural signals from during attempted speech, and translate it into words, in real time, with a high accuracy and a large vocabulary, using deep neural networks?



# Electrocorticography (ECoG)

- Electrocorticography (ECoG) presents an alternative to EEG
  - $\circ \quad \text{Implanted electrodes instead of surface of head}$
- Benefits of ECoG are two-fold:
  - (1) Higher spatial and temporal resolution
  - (2) Less susceptible to contamination from muscle movements and eye blinks



# Past Works

| Citation              | Method   | Performance  |
|-----------------------|--|--|
| Kellis et. al. (2010) | <ol> <li>PCA to extract features<br/>from neural signals</li> <li>Classified words in a<br/>predetermined vocabulary</li> </ol>                      | Roughly $85 \pm 13\%$ average accuracy over $45$ two-word combinations at best |
| Pei et. al. (2011)    | <ol> <li>Ranked phonetics using<br/>Maximum Relevance and<br/>Minimum Redundancy</li> <li>Naive Bayes classifier for<br/>final prediction</li> </ol> | Avg. classification accuracy<br>for both vowels and<br>consonants ~40%         |

# Past Works

| Citation   | Method   | Performance   |  |  |  |
|--|--|---|--|--|--|
| Mugler et. al. (2014)<br>First to propose phonemes | <ol> <li>Statistical analysis to<br/>identify and rank features</li> <li>Linear Discriminant<br/>Analysis (LDA)</li> </ol> | Phoneme classification<br>accuracy up to 36% for all,<br>63% for a single phoneme |  |  |  |
| Moses et. al. (2021)<br>Shift to neural networks   | <ol> <li>Stacked LSTM for speech<br/>detection</li> <li>Word classification using<br/>two GRUs</li> </ol>                  | Word error rate of 25.6% for a 50 word vocabulary                                 |  |  |  |

# State-of-the-Art Model | Willett et. al. (2023)

- Willett et. al. (2023) created a pipeline to decode ECoG data, achieving record-low error rates and record-high speed
- There are 10,850 sentences in the published dataset
- Dataset consists of spoken sentences and associated neuronal spike power from a 125,000 word vocabulary
- First successful demonstration of large-vocabulary decoding!

| E contoneoTaut V, collection V  |
|---|
| - sentence text x spiker ow x   |
| •• 280x86 char  |
| Nuclear rockets can destroy airfields with ease.                                |
| The best way to learn is to solve extra problems.                               |
| The spray will be used in first division matches next season.                   |
| Our experiment's positive outcome was unexpected.                               |
| Alimony harms a divorced man's wealth.  |
| She uses both names interchangeably.  |
| The misquote was retracted with an apology.                                     |
| Critics fear the erosion of consumer protections and environmental standards.   |
| Her lips, moist and parted, spoke his name.                                     |
| How do they turn out later?   |
| The eastern coast is a place for pure pleasure and excitement.                  |
| Please make your decision wisely to visit the Beach.                            |
| She encouraged her children to make their own Halloween costumes.               |
| Cleaned cloth must be protected against the redeposition of dispersed soil.     |
| Both figures would go higher in later years.                                    |
| She always jokes about too much garlic in his food.                             |
| If people were more generous, there would be no need for welfare.               |
| The dimensions of these waves dwarf all our usual standards of measurement.     |
| The knifelike pain in his groin nearly brought him down again.                  |
| Selecting bunks by economic comparison is usually an individual problem.        |
| Have a test-run on the family first, to be sure timing and seasoning are right. |
| A good attitude is unbeatable.  |
| Make lid for sugar bowl the same as jar lids, omitting design disk.             |
| It's healthier to cook without sugar.   |

| Matrix for one sentence   |  |
|---------------------------|--|
| (binned spike band power) |  |

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|                          |         | 2        | 393.8662                               | 389.5526              | 205.7366  | 415.641     | 0 965.63  | 42     | 567.4780       | 398.4393                         | 6.   |  |
|                          |         | 3        | 491.3916                               | 1.2935e+03            | 165.5639  | 359.350     | 9 453.10  | 39     | 364.7545       | 434.9090                         | 6    |  |
|                          |         | 4        | 550.9631                               | 515.8297              | 231.8535  | 395.322     | 5 507.32  | 41     | 338.7577       | 337.5614                         | 1.61 |  |
|                          |         | 5        | 606.0344                               | 359.8328              | 230.8190  | 346.930     | 5 333.09  | 45     | 283.6755       | 397.6845                         | 9,   |  |
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| orkspace                 |         | : 12     | 347.0639                               | 1.0780e+03            | 170.5331  | 368.280     | 9 743.31  | 60     | 729.5826       | 341.4114                         | 91   |  |
| e 🗄 Value 🗄 Size         | : Class | 13       | 338.8522                               | 651.4445              | 173.4445  | 765.277     | 7 542.24  | 16     | 512.9861       | 344.2398                         | 7:   |  |
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< 280 Sentences

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| * Files                      |             |        |       |     | sentenceText × spikePow ×                         |                |                |                |                |  |  |  |  |
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|                              | 280v1 uint8 | 280v1  | uint8 |     | 13  |                |                |                |                |  |  |  |  |
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| () spikePow                  | 1x280 cell  | 1x280  | cell  |     | 16  |                |                |                |                |  |  |  |  |
| () tx1                       | 1x280 cell  | 1x280  | cell  |     | 17  |                |                |                |                |  |  |  |  |
| () tx2                       | 1x280 cell  | 1x280  | cell  | Ŀ   |   | 4              |                |                |                |  |  |  |  |
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| () tx4 1x280 cell 1x280 cell |             |        |       | _   | New to MATLAB? See resources for Getting Started. |                |                |                |                |  |  |  |  |
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Area 6v Inferior

Area 44 Superior Area 6v Superior 192 193 208 216 160 165 178 185 062 051 043 035 094 087 079 078 194 195 209 217 162 167 180 184 060 053 041 033 095 086 077 076 196 197 211 218 164 170 177 189 063 054 047 044 093 084 075 074 198 199 210 219 166 174 173 187 058 055 048 040 092 085 073 072 200 201 213 220 168 176 183 186 059 045 046 038 091 082 071 070 061 049 042 036 090 083 069 068 202 203 212 221 172 175 182 191 204 205 214 223 161 169 181 188 056 052 039 034 089 081 067 066 206 207 215 222 163 171 179 190 057 050 037 032 088 080 065 064

<-- Anterior

Posterior -->

Area 44 Inferior 129 144 150 158 224 232 239 255 125 126 112 103 031 028 011 008 128 142 152 145 226 233 242 241 123 124 110 102 029 026 009 005 130 135 148 149 225 234 244 243 121 122 109 101 027 019 018 004 131 138 141 151 227 235 246 245 119 120 108 100 025 015 012 006 134 140 143 153 228 236 248 247 117 118 107 099 023 013 010 003 132 146 147 155 229 237 250 249 115 116 106 097 021 020 007 002 133 137 154 157 230 238 252 251 113 114 105 098 017 024 014 000 127 111 104 096 030 022 016 001 136 139 156 159 231 240 254 253

Inferior

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Map of placement of Sensor Channels

#### Method | Willett et. al. (2023)



#### Method | Willett et. al. (2023)

- 1. Trained a recurrent neural network (RNN) decoder to emit, at each 80 ms time step, the probability of each phoneme being spoken at that time
  - a. Used a 5 layer, stacked gated recurrent unit RNN
  - b. RNN runs at 4-bin frequency (20 ms bins) outputting a phoneme probability vector every 80 ms
- 2. These probabilities were then combined with a language model to infer **the most probable underlying sequence of words**, given both the phoneme probabilities and the statistics of the English language
  - a. Phoneme errors are often corrected by the language model
  - b. Language model translates the sequence of CTC labels into candidate sentences

# Method | Willett et. al. (2023)

Target sentence: we don't listen to the radio at work at all Decoded phonemes:



Decoded sentence: we don't listen to the reader at work at all

**Example Sentence** 

# Results | Willett et. al. (2023)

- Achieved 9.1% word error rate on 50-word vocabulary
  - $\circ$  2.7 times fewer errors than previous work
- Achieved 23.8% word error rate for the 125,000-word vocabulary
  - $\circ \quad \ \ {\rm First\ successful\ demonstration\ of\ large-vocabulary\ decoding}$
- Patient spoke at an average pace of 62 words per minute

#### An End-To-End Alternative

• Common approaches in past works used a chain of models to decode neural activity, with one or more intermediary steps

What if you have one, end-to-end model? Would that increase accuracy?

- An end-to-end transformer approach might work
  - No work yet applying transformers to ECoG data
  - A paper on EEG-To-Text was recently published, applying transformers to decode EEG signals to attempted speech

# An End-To-End Alternative

- Transformers have reached good performance on automated speech recognition
- Wang & Ji (2021) used a pre-trained BART to decode EEG into text
  - Inspired by Speech Recognition (Hinton et al. 2012)
- We are currently attempting to create an Encoder for an ECoG dataset



Thank you!

**Q&A** Session