

# Deep Learning Transforming Sleep Research: from Labs to Home

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August 12, 2021

Introduction  
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Automatic Sleep Staging  
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Multi-view Learning  
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Explanability and Uncertainty  
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Outlooks  
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# How was your **SLEEP** last night?

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# Sleep Monitoring: A Modern Need



Source: The Great British Sleep Survey 2012, <https://www.sleepio.com/2012report/>



# How Sleep Studies Are Done?

## SLEEP LAB



# How Sleep Studies Are Done?

## SLEEP LAB



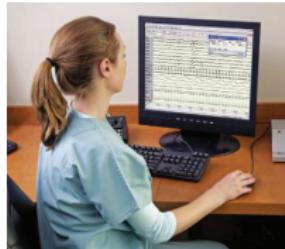
# How Sleep Studies Are Done?

## SLEEP LAB

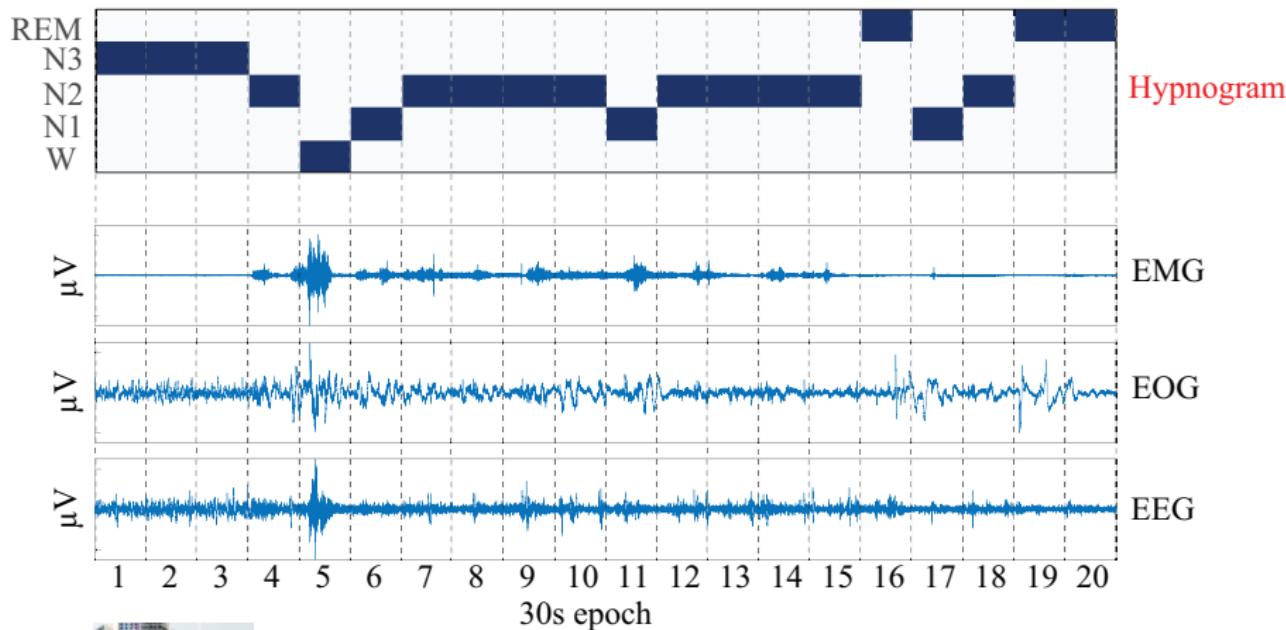


# How Sleep Studies Are Done?

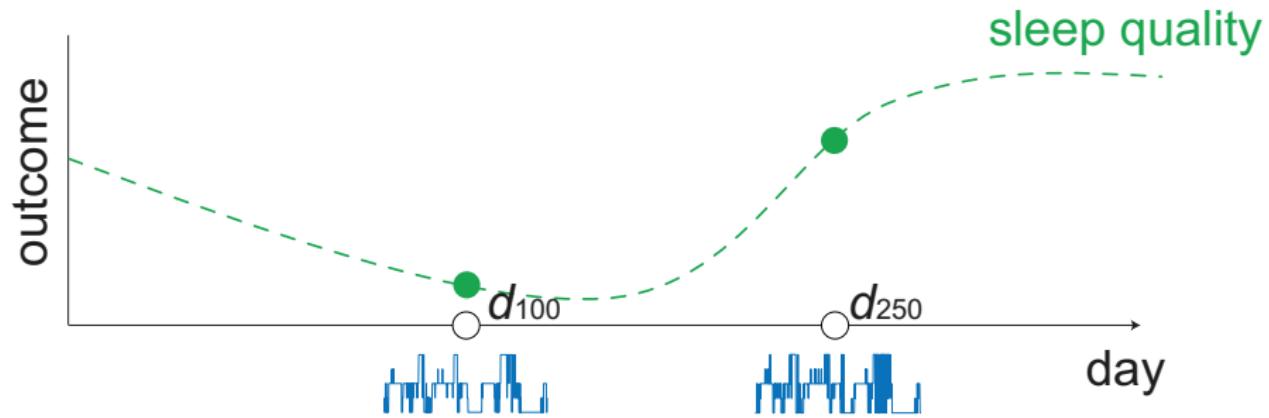
## SLEEP LAB



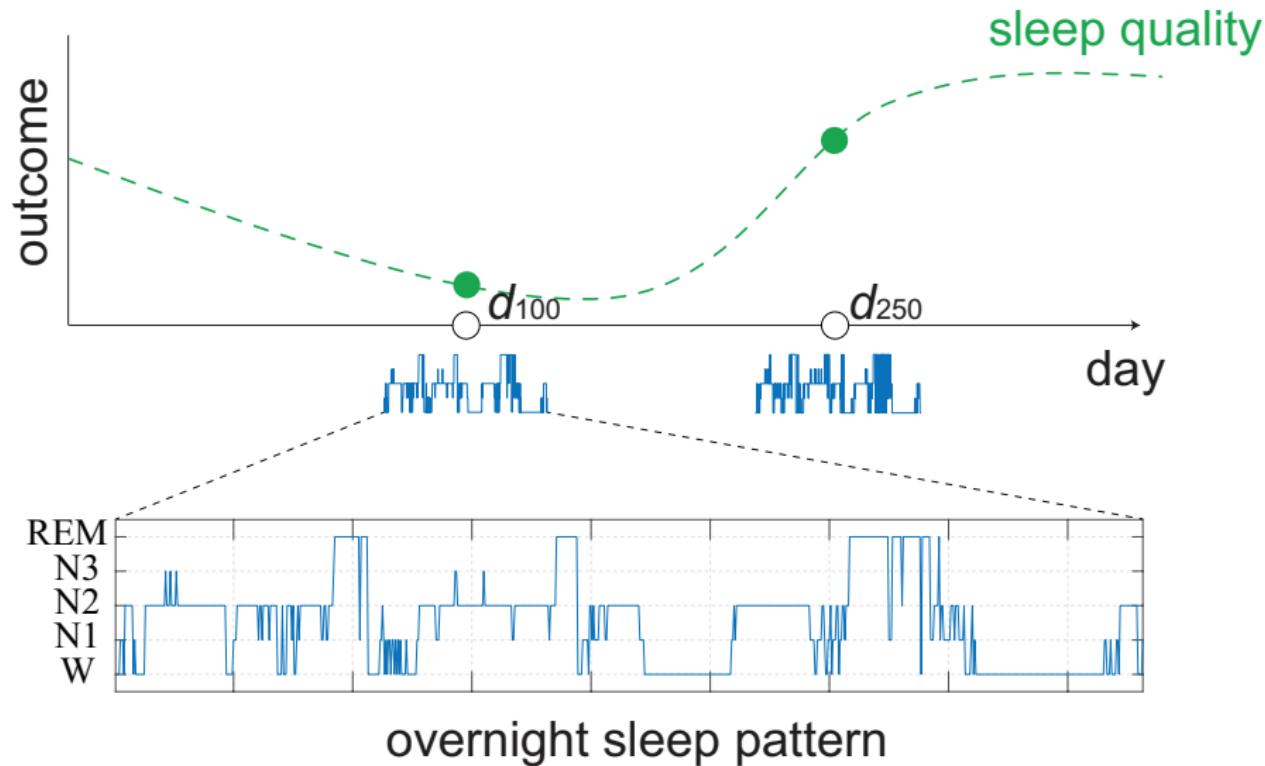
# Automatic Sleep Staging



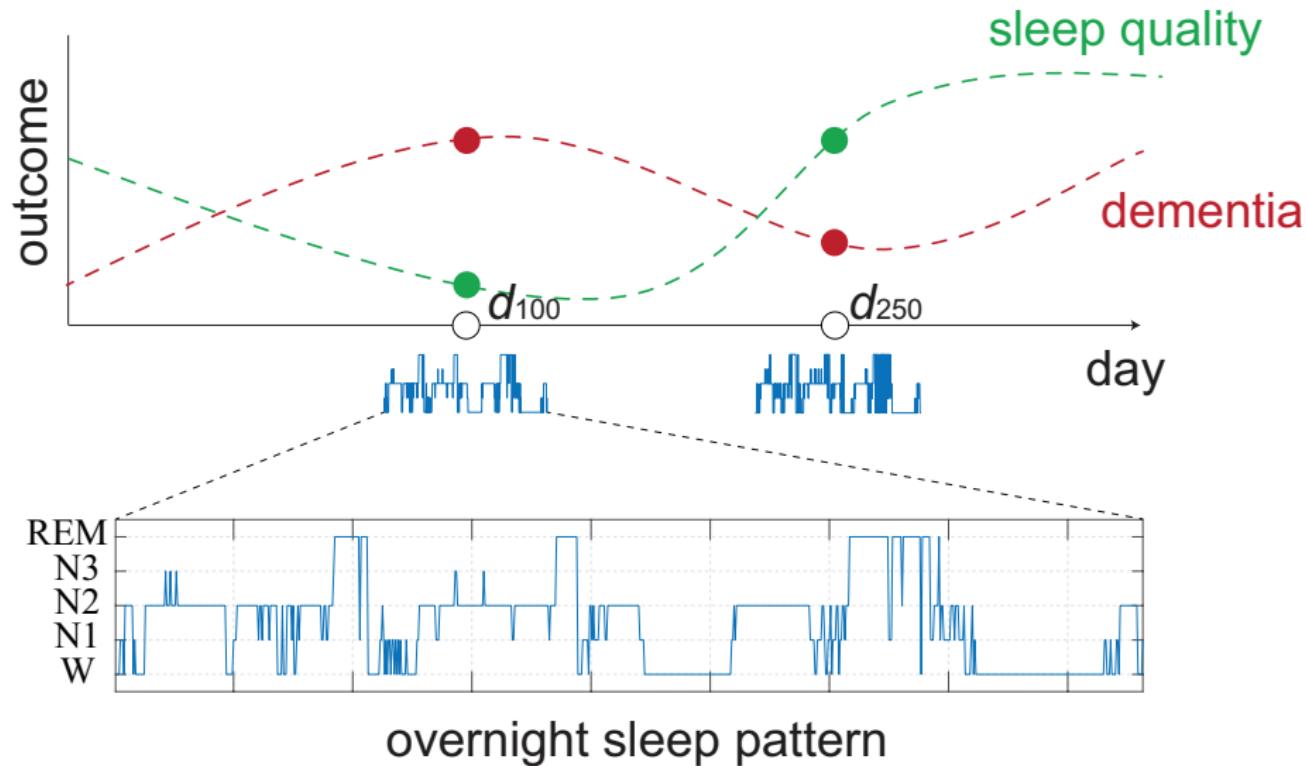
# Longitudinal Sleep Monitoring



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# Longitudinal Sleep Monitoring



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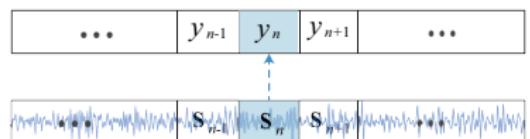
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# Automatic Sleep Staging

# Sequence-to-Sequence Sleep Staging

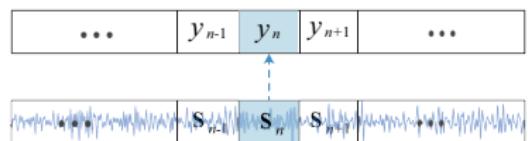
## One-to-One



$$P(y \mid \mathbf{S})$$

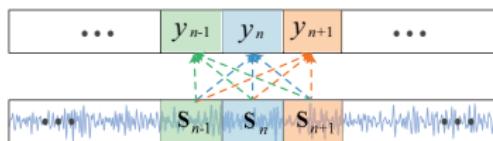
# Sequence-to-Sequence Sleep Staging

One-to-One



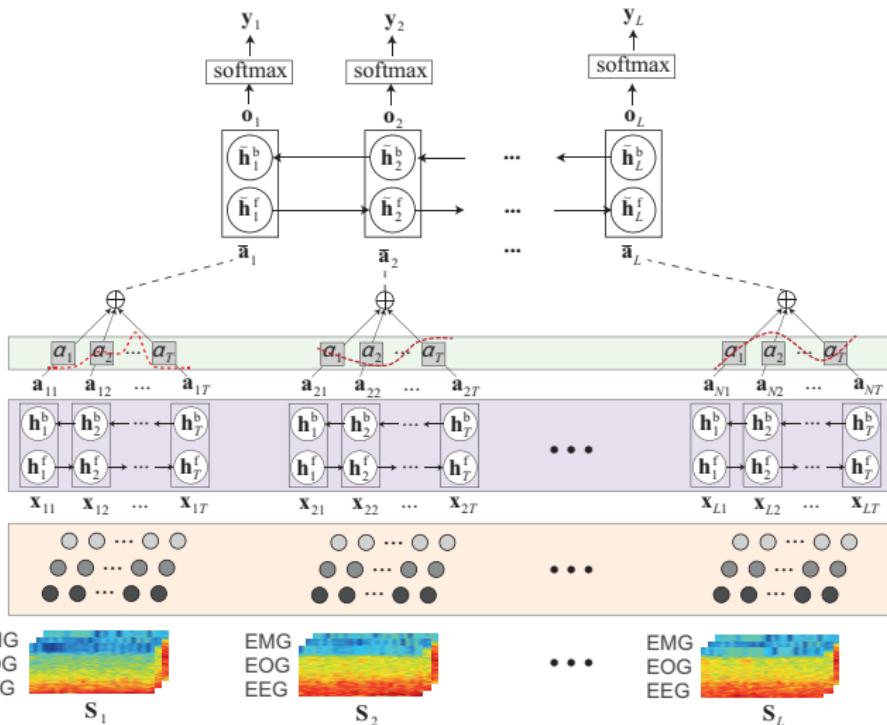
$$P(y \mid \mathbf{S})$$

Sequence-to-Sequence

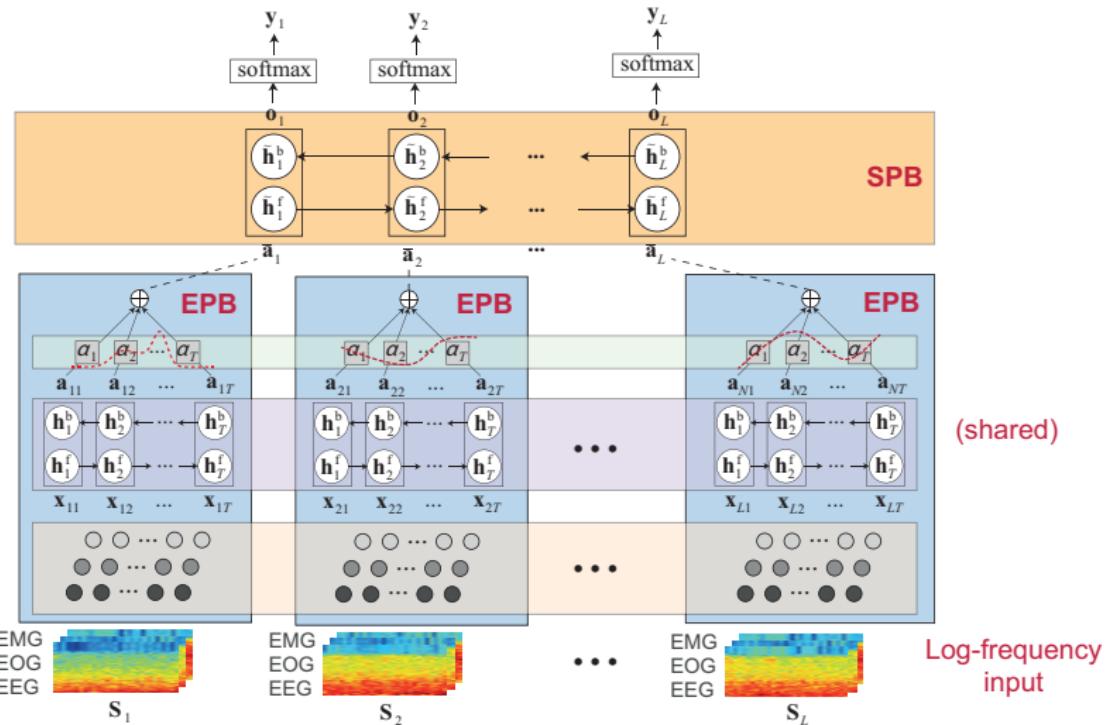


$$P(y_1, y_2, \dots, y_L \mid \mathbf{S}_1, \mathbf{S}_2, \dots, \mathbf{S}_L)$$

# SeqSleepNet



# SeqSleepNet



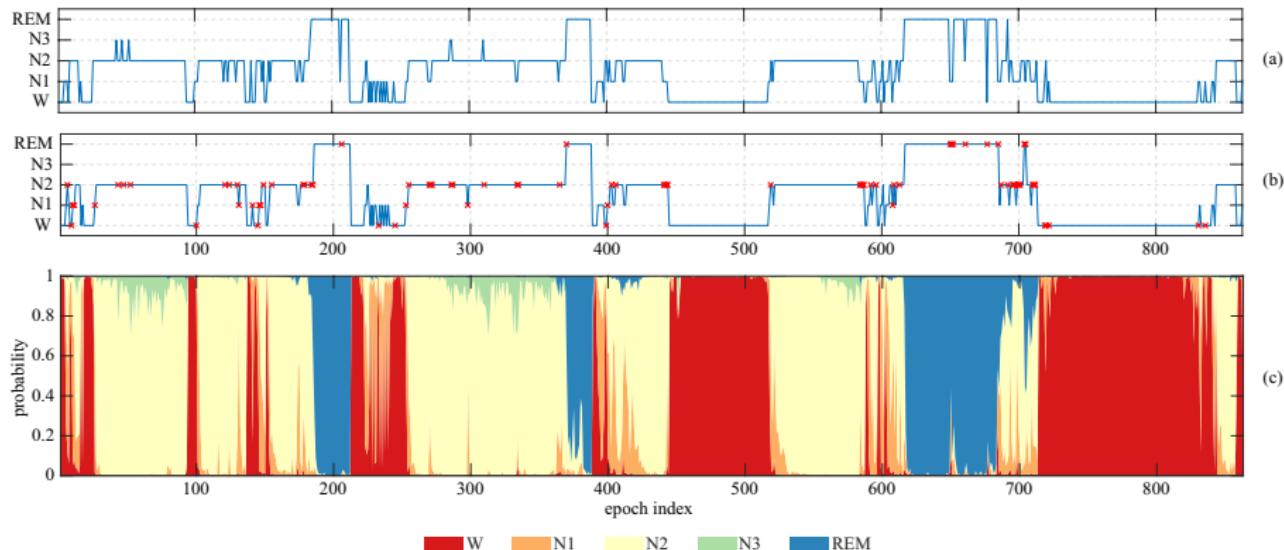
# Performance

| Method             | Input       | Acc.        | Macro F1    | <i>kappa</i> |
|--------------------|-------------|-------------|-------------|--------------|
| <b>SeqSleepNet</b> | EEG·EOG·EMG | <b>87.0</b> | <b>83.2</b> | <b>0.814</b> |
| <b>SeqSleepNet</b> | EEG·EOG     | <b>86.5</b> | <b>82.4</b> | <b>0.808</b> |
| <b>SeqSleepNet</b> | EEG         | <b>84.5</b> | <b>79.8</b> | <b>0.778</b> |
| <b>SeqSleepNet</b> | EOG         | <b>83.9</b> | <b>79.1</b> | <b>0.769</b> |
| Attentional RNN    | EEG·EOG·EMG | 83.5        | 78.3        | 0.76         |
| 1-Max CNN          | EEG·EOG·EMG | 82.7        | 77.6        | 0.75         |
| Chambon Net        | EEG·EOG·EMG | 79.9        | 76.7        | 0.73         |
| Tsinalis Net       | EEG·EOG·EMG | 77.9        | 70.4        | 0.68         |

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C. O'Reilly *et al.*, "Montreal archive of sleep studies: An open-access resource for instrument benchmarking & exploratory research," *Journal of Sleep Research*, pp. 628–635, 2014

# Probability Output



# Necessity of Going Wearables

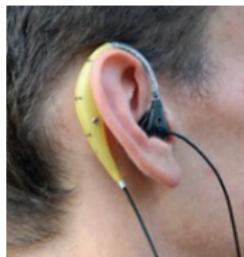
Traditional PSG



Commercial devices



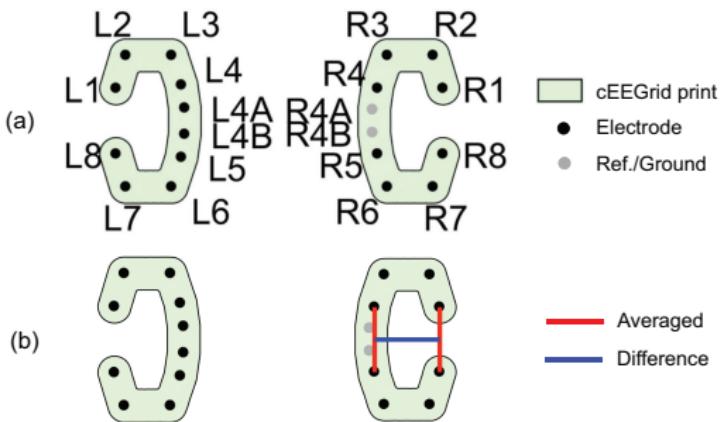
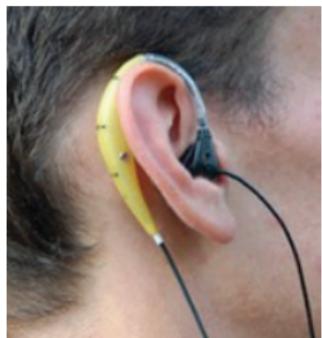
Around-the-ear EEG



In-ear EEG



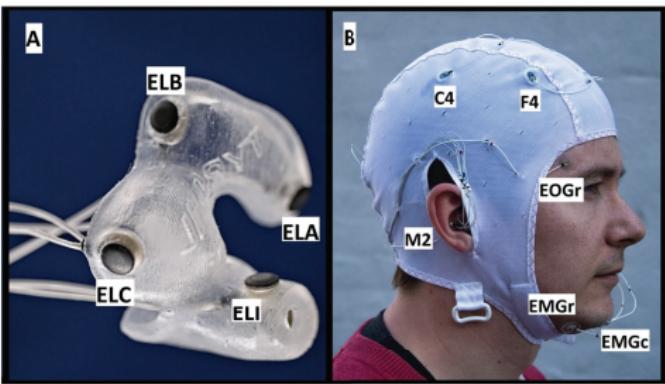
# Around-the-ear EEG (cEEGrid)



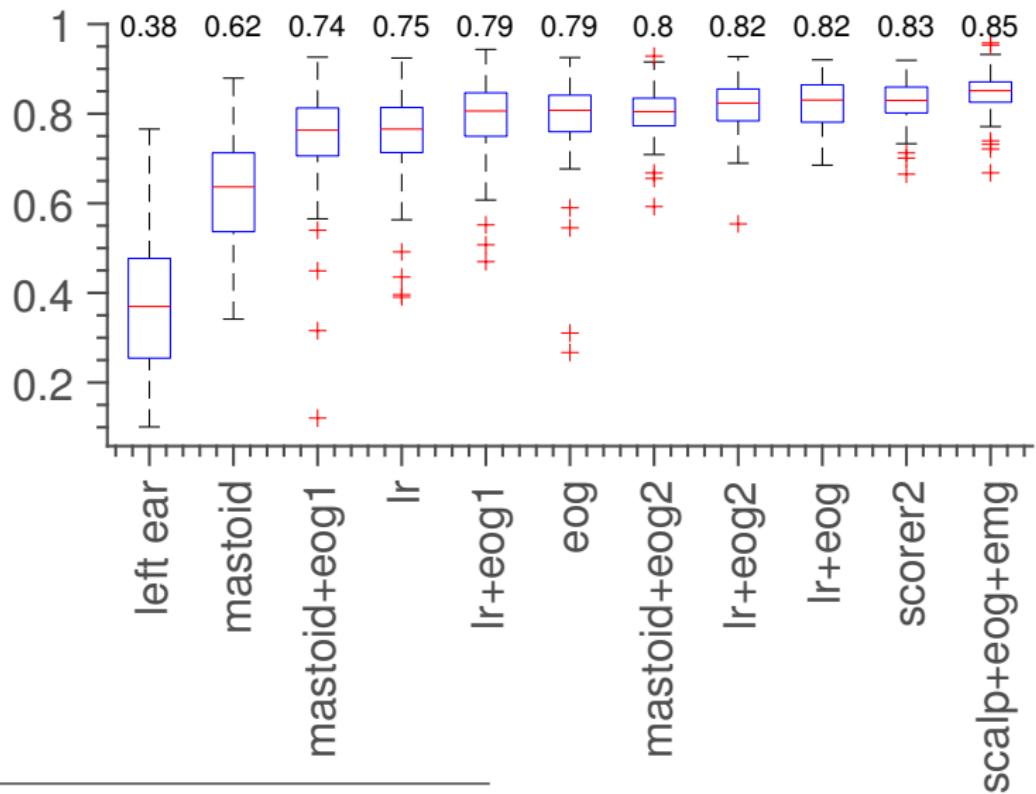
# SleepNet on cEEGrid

| Method          | Input       | Acc.        | MF1         | <i>kappa</i> |
|-----------------|-------------|-------------|-------------|--------------|
| <b>SleepNet</b> | EEG·EOG·EMG | <b>82.1</b> | <b>67.6</b> | <b>0.748</b> |
| <b>SleepNet</b> | EEG·EOG     | <b>81.5</b> | <b>66.4</b> | <b>0.739</b> |
| <b>SleepNet</b> | EEG         | <b>71.9</b> | <b>55.2</b> | <b>0.597</b> |
| DeepSleepNet    | EEG·EOG·EMG | 65.6        | 57.3        | 0.535        |
| DeepSleepNet    | EEG·EOG     | 65.4        | 57.4        | 0.534        |
| DeepSleepNet    | EEG         | 42.5        | 30.3        | 0.195        |
| Random Forest   | EEG·EOG·EMG | —           | —           | —            |
| Random Forest   | EEG·EOG     | 72.0        | —           | 0.600        |
| Random Forest   | EEG         | 70.0        | —           | 0.580        |

# EarEEG



# SeqSleepNet on EarEEG





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An advertisement for "SMARTING SLEEP". On the left, there's a tablet showing a green circular electrode map and a white rectangular device labeled "drem O2 sensor". In the center, the text "EASE. COMFORT. RELIABILITY." is above "SMARTING SLEEP". Below it, a paragraph reads: "Multimodal EEG recordings provide a more choice for better sleep quality. Collect all relevant physiological data while your subjects are sound asleep." Three icons are listed: "Wireless streaming" (a signal icon), "High signal quality" (a signal icon), and "Vibrant battery life" (a battery icon). On the right, a man is sleeping peacefully in bed, wearing a black sleep monitoring headband. He is resting his head on a white pillow.

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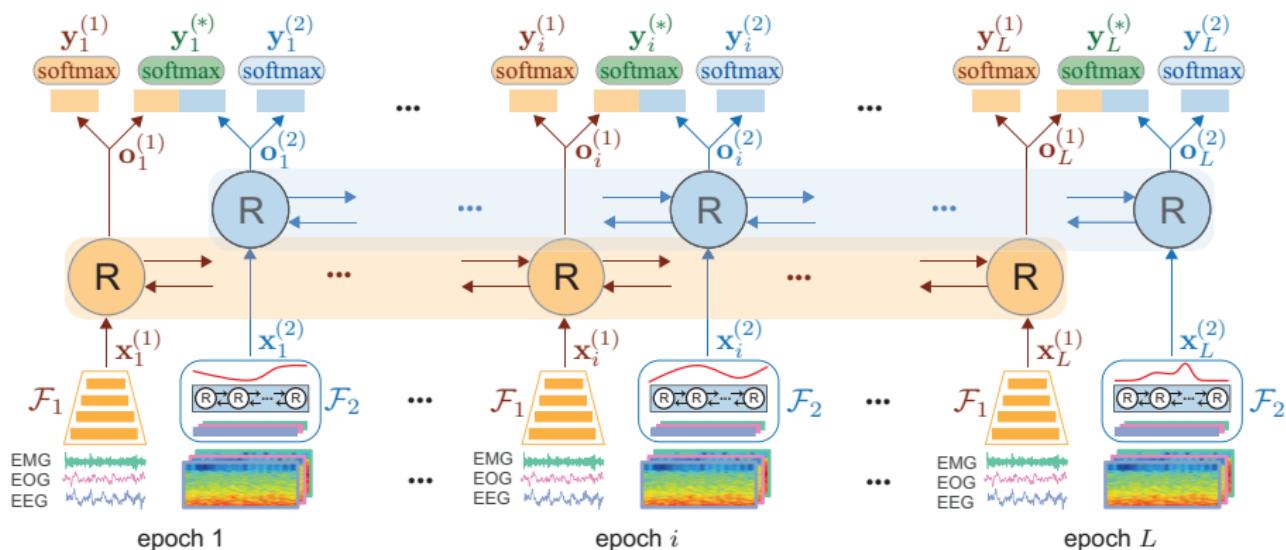
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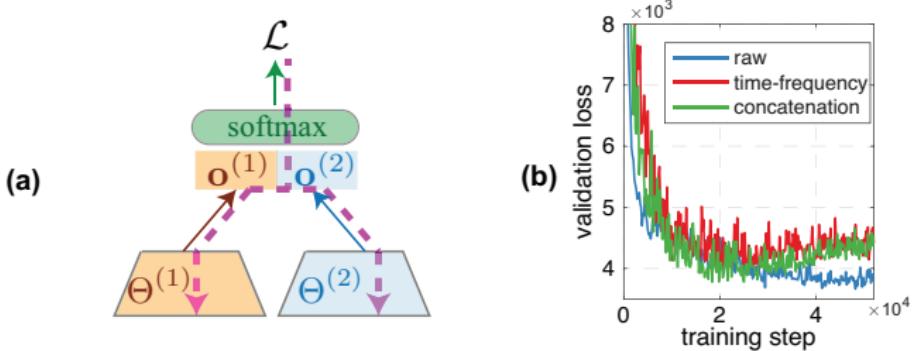
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# Multi-view Learning for Robustness

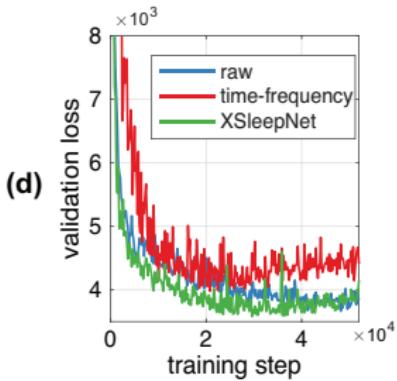
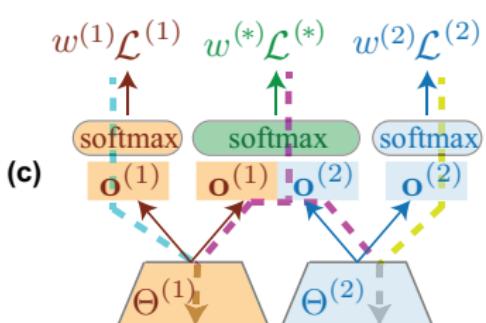
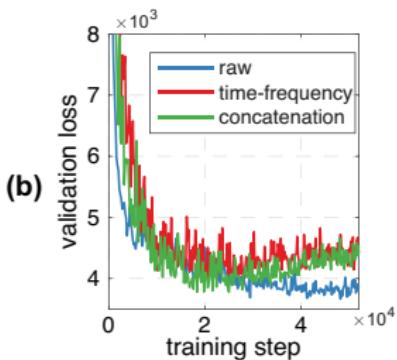
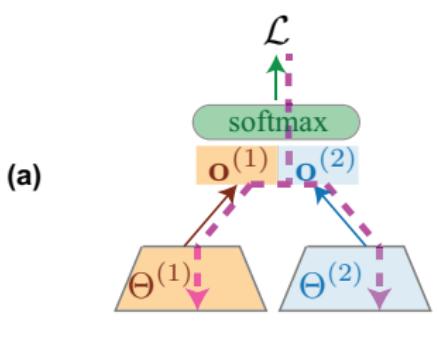
XSleepNet for Multi-view Learning



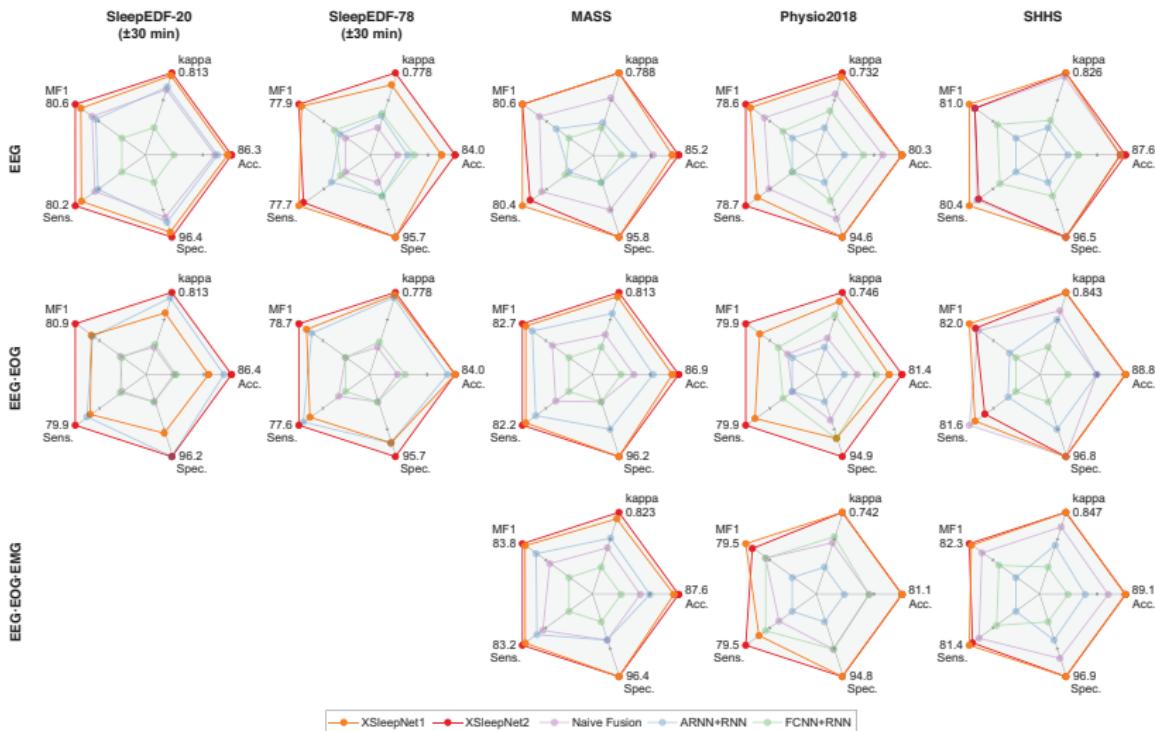
# XSleepNet for Multi-view Learning



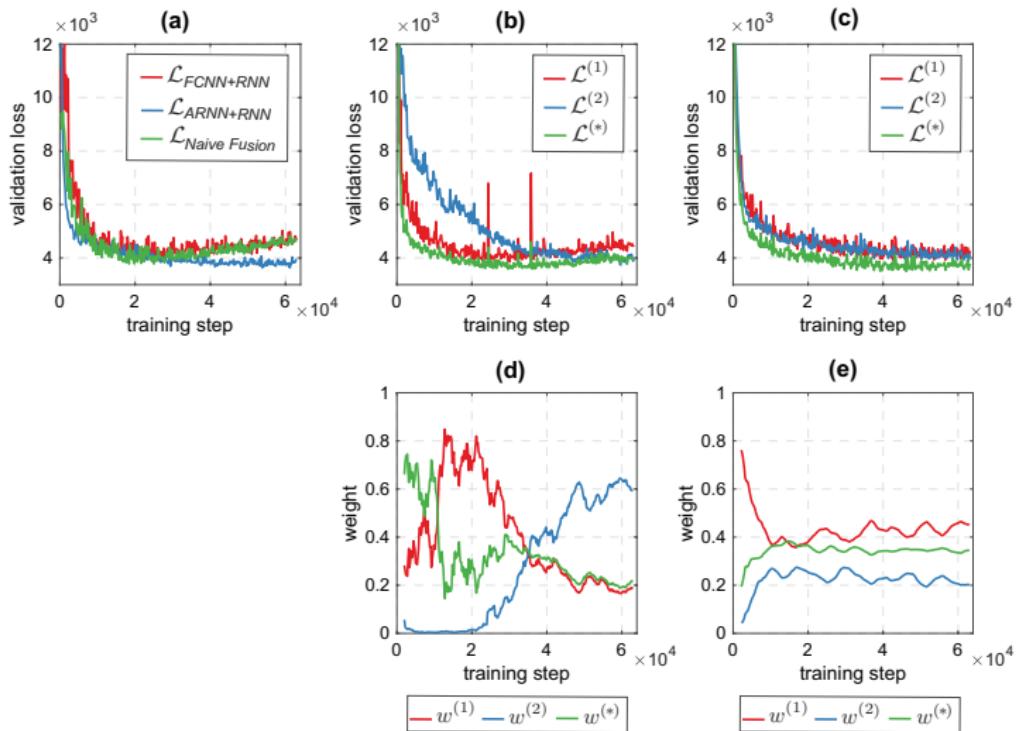
# XSleepNet for Multi-view Learning



# Performance



# Adaptive Weights



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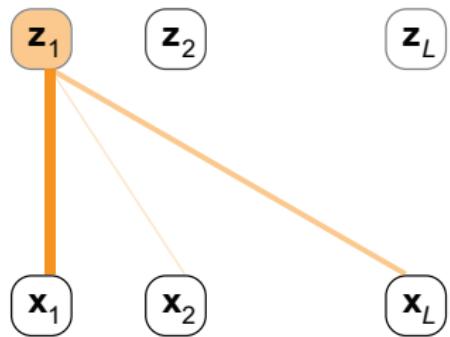
Multi-view Learning  
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Explanability and Uncertainty  
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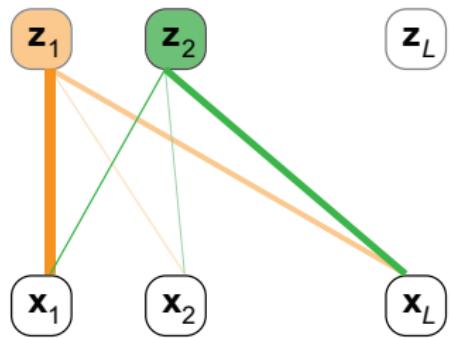
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# Explanability and Uncertainty for Trust and Interaction

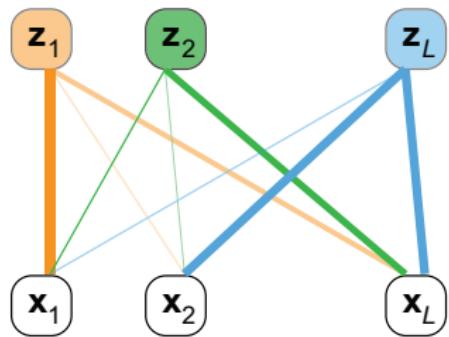
# Self-attention



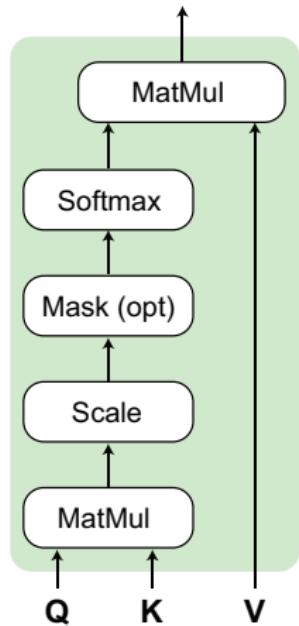
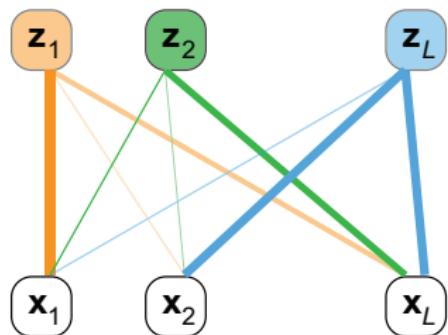
# Self-attention



# Self-attention

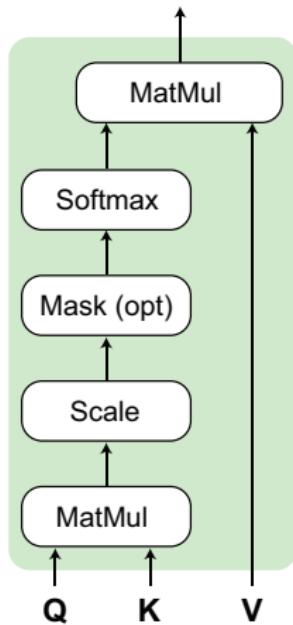


# Self-attention

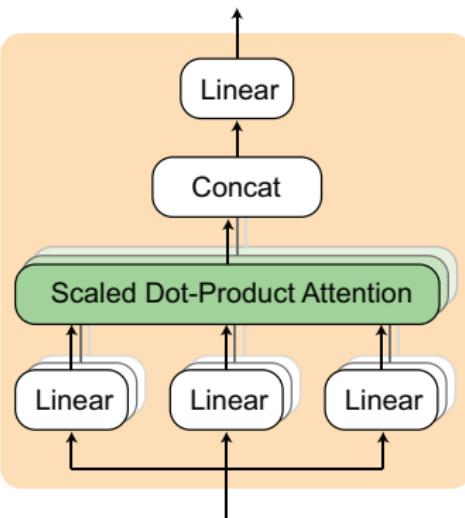


**Scaled dot-product attention**

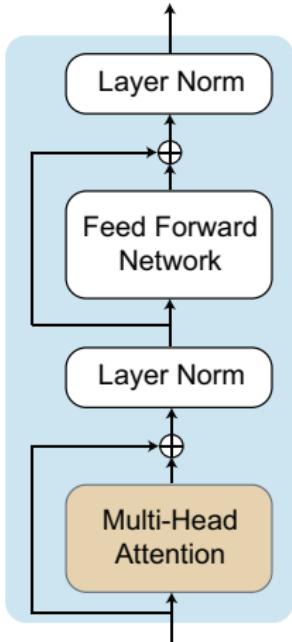
# Transformer



(a) Scaled dot-product attention

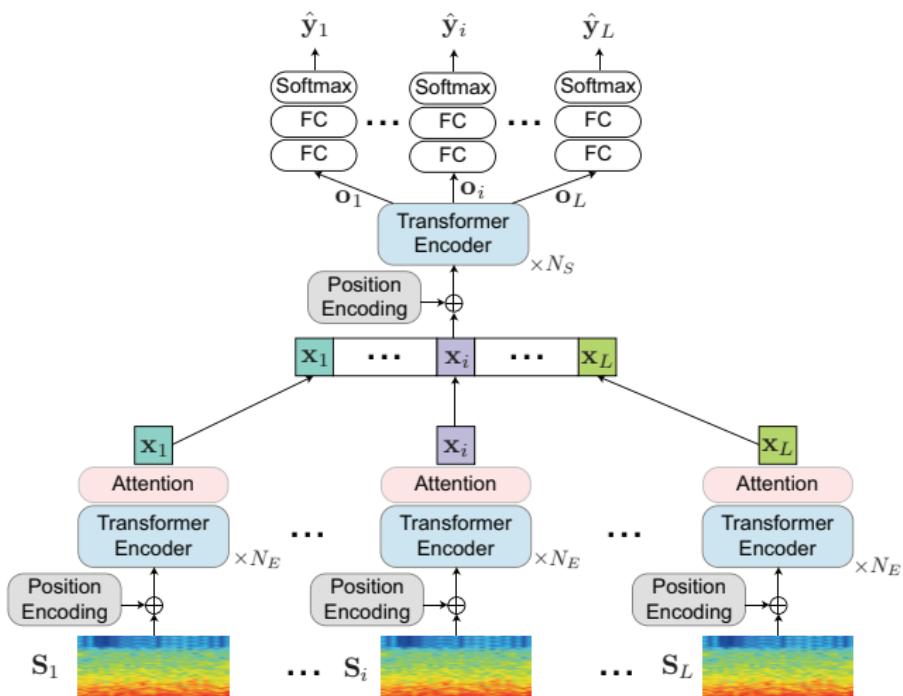


(b) Multi-head attention

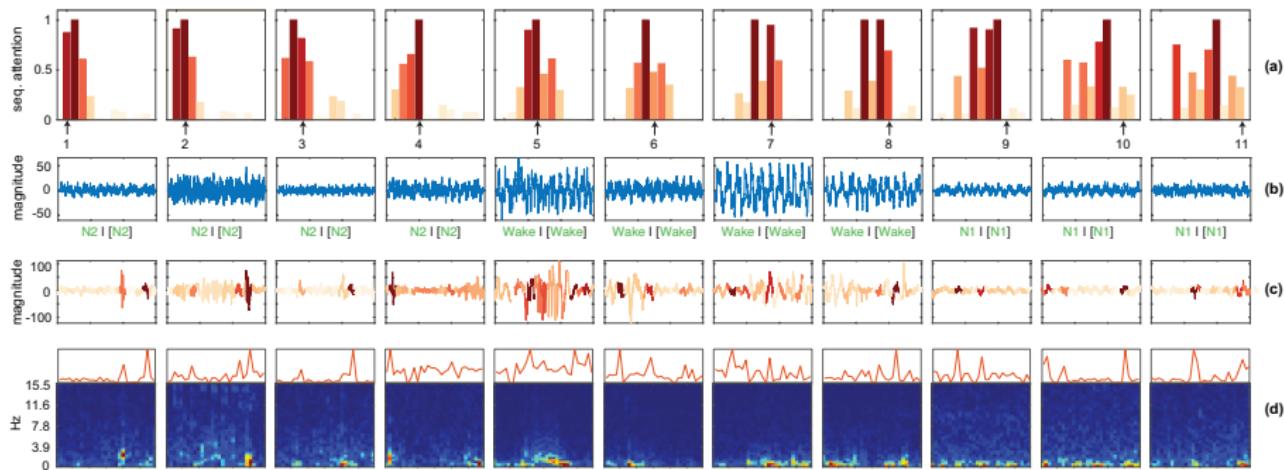


(c) Transformer encoder

# Sleep Transformer



# Interpretability



# Uncertainty Quantification

- Normalized entropy for uncertainty quantification:

$$H(\hat{\mathbf{y}}) = - \sum_{c=1}^C \hat{y}_c \frac{\log(\hat{y}_c)}{\log C}$$

$$\hat{\mathbf{y}} = \left( \frac{1}{5}, \frac{1}{5}, \frac{1}{5}, \frac{1}{5}, \frac{1}{5} \right) \rightarrow H(\hat{\mathbf{y}}) = 0$$

$$\hat{\mathbf{y}} = (0, 1, 0, 0, 0) \rightarrow H(\hat{\mathbf{y}}) = 1$$

# Uncertainty Quantification

- Normalized entropy for uncertainty quantification:

$$H(\hat{\mathbf{y}}) = - \sum_{c=1}^C \hat{y}_c \frac{\log(\hat{y}_c)}{\log C}$$

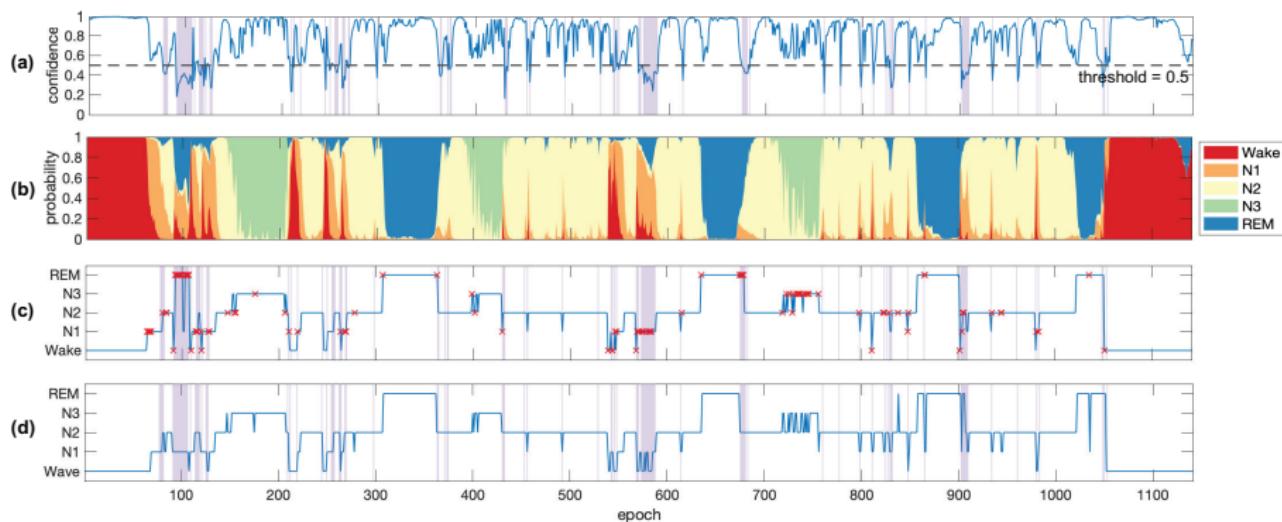
$$\hat{\mathbf{y}} = (\frac{1}{5}, \frac{1}{5}, \frac{1}{5}, \frac{1}{5}, \frac{1}{5}) \rightarrow H(\hat{\mathbf{y}}) = 0$$

$$\hat{\mathbf{y}} = (0, 1, 0, 0, 0) \rightarrow H(\hat{\mathbf{y}}) = 1$$

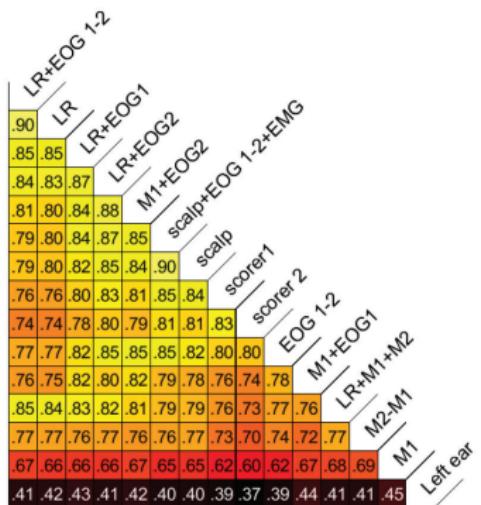
- Network's decision confidence:

$$Conf(\hat{\mathbf{y}}) = 1 - H(\hat{\mathbf{y}})$$

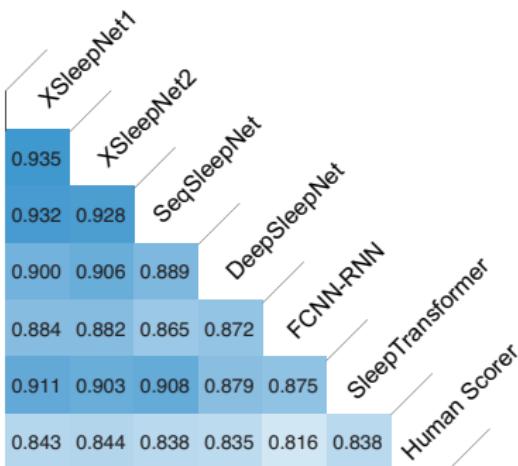
# Confidence



# Are we there yet?



Agreement between SeqSleepNet and human scorers

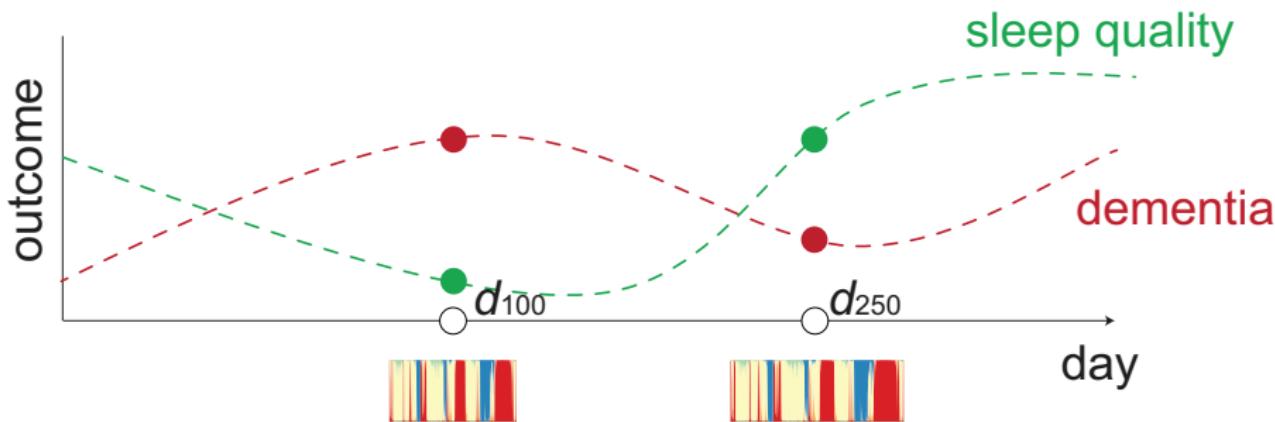


Agreement between different algorithms to one another and human scorer

# We are NOT there yet

- Heterogeneous data
- Domain adaptation
- Personalization
- Handling scorers' disagreement
- Interpretability
- Uncertainty estimation
- Privacy preservation
- Sleep stages, but what are they?

# Sleep Staging, then What?



- Automatic **assessment** of sleep diseases
- **Mapping** sleep patterns to outcome variables
- **Longitudinal** monitoring
- **Closed-loop** treatment/feedback

# Acknowledgement

- **Maarten De Vos**, KU Leuven & University of Oxford
- **Preben Kidmose**, Aarhus University
- **Kaare Mikkelsen**, Aarhus University
- **Oliver Y. Chén**, University of Oxford
- **Alfred Mertins**, University of Lübeck
- **Philipp Koch**, University of Lübeck
- **Mathias Baumert**, University of Adelaide

Thank you for your attention