CoffEEG

An Analysis of Caffeine's Influence on Brain Waves

By: Annabel Frake, Madison Grigg, Martin Goessweiner, Amulya Mathur, Dinesh Sangadi, and Jingkai Wen

Table of Contents

01 Background

02 Data Collection

03 Data Preprocessing

04 Machine Learning & Results

05 Discussion & Future Work

01

Background

Enhancing physical and mental endurance

Historical impact of Coffee

16th Century Middle East

"A beverage as black as ink, useful against numerous illnesses (...), composed of water and the fruit from a bush called bunnu."

-Léonard Rauwolf, Reise in die Morgenländer, 1583 AD

18th Century Europe

- Caffeine induced **raise of alertness** of workers during the industrial revolution
- Caffeine **sparked original ideas** during the debates in European coffee houses

Today

- **200bn$ Market** aiming at enhancing physical and mental endurance

But why?

[1]

Physiological impact of Coffee

Enhancing physical and mental **performance** and endurance

Caffeine as **psychoactive substance** affects Central as well as Peripheral Nervous System (CNS/PNS)

Caffeine as **adenosine mimeticum** (specifically adenosine receptor blocker) → catecholamine secretion → sympathetic activation:

- **Peripheral activation**:
  - Positive contractability
  - Positive pulsatility
  - Bronchodilation
  - Vasodilation
  - Increased glycogenolysis
- **Central activation**:
  - Blocking of A2a receptors → signaling cell fitness
  - Central vasoconstriction

Effects not fully understood, but observable

[2], [3], [4]

Observable impact of Coffee

Conflicting reports of observable impact of caffeine — especially on EEG

Seems to **increase delta and beta** bandwidths, but has **no effect on theta or alpha** bandwidths

Problem:

Lack of adequate controls for withdrawal and withdrawal reversal
Baseline Caffeine Consumption varies greatly → control of absolute caffeine often useless
Effect of sleep, sugar intake, stress not controlled for

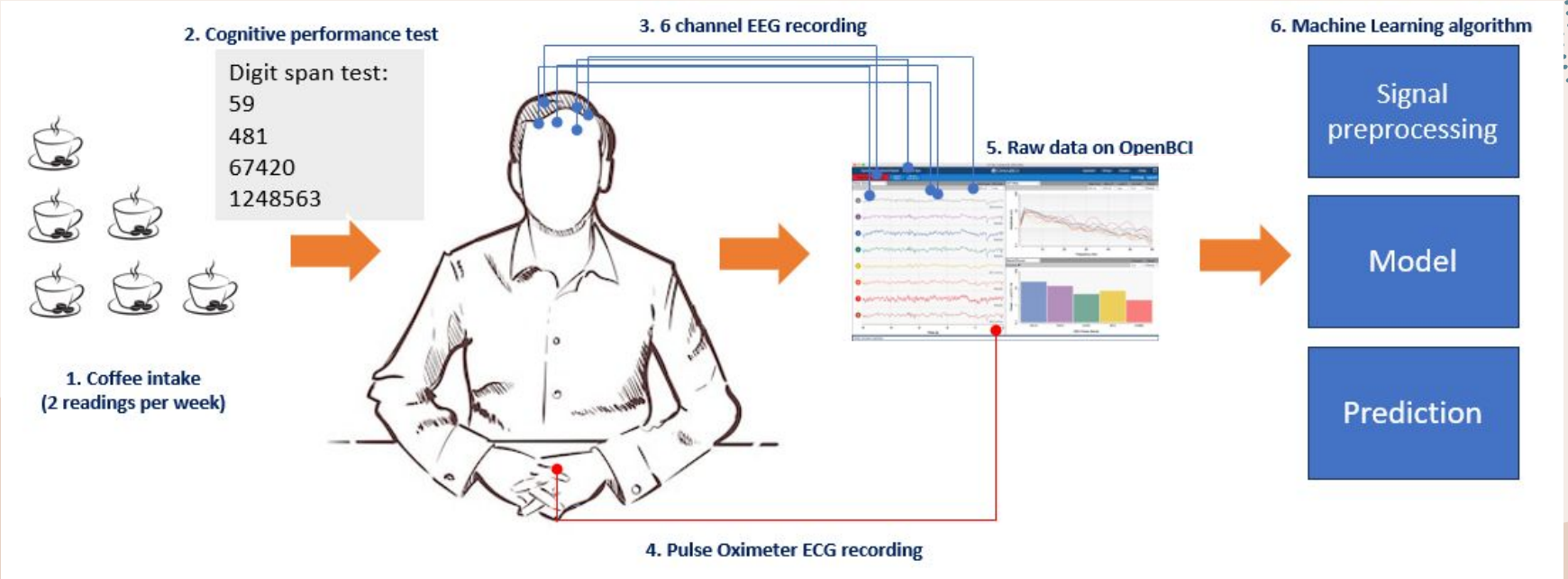
Gap:

Control for baseline caffeine intake → 3 conditions:

No caffeine (withdrawal)
Baseline
Doubling Baseline

[5], [6]

Approaching the Gap



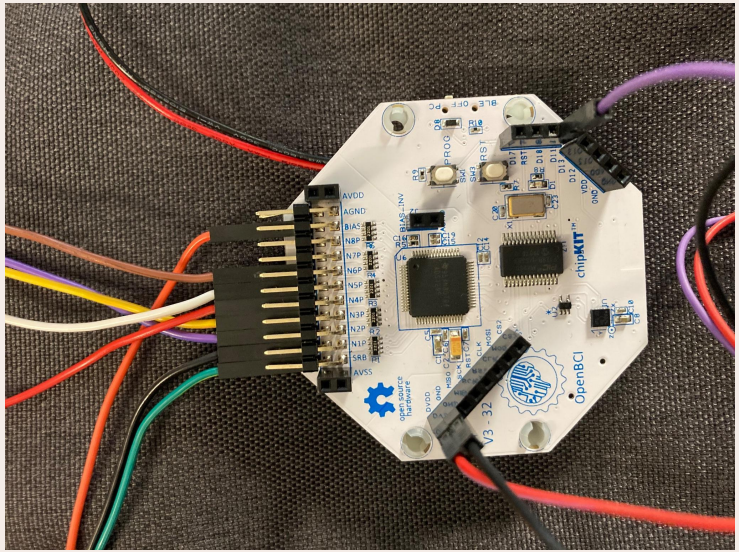
EEG
Pulse Ox
Performance
OpenBCI
Raw Data
Preprocessing and Feature Extraction
Processed Data
Algorithm
Prediction

02

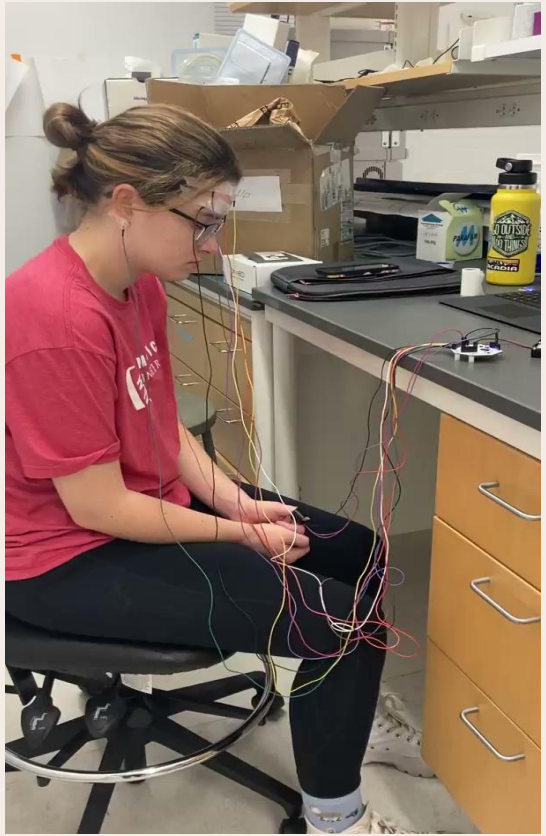
Data Collection

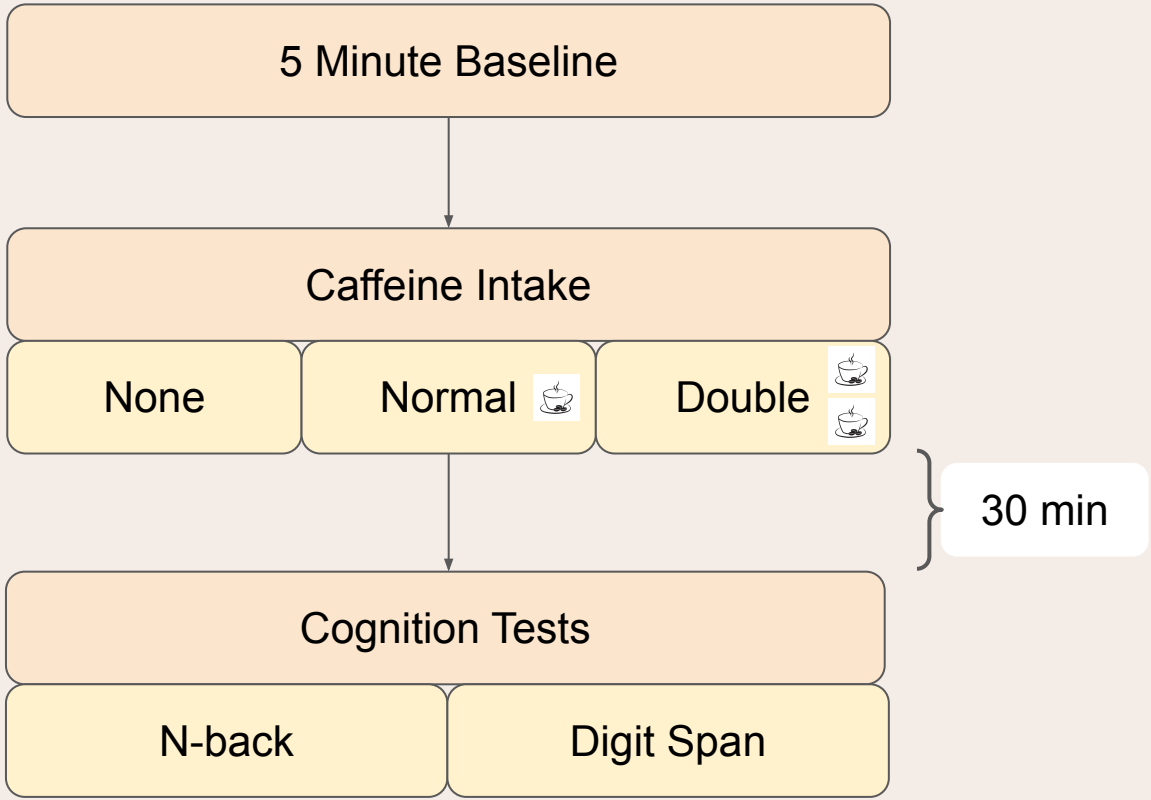
2. Data Collection

- EEG Data
  - 6 electrodes over prefrontal cortex
  - 2 reference electrodes on earlobes
  - NP1-NP6 channels in OpenBCI
- PPG Data
  - Pulse oximeter sensor [7]
  - Analog signal in OpenBCI

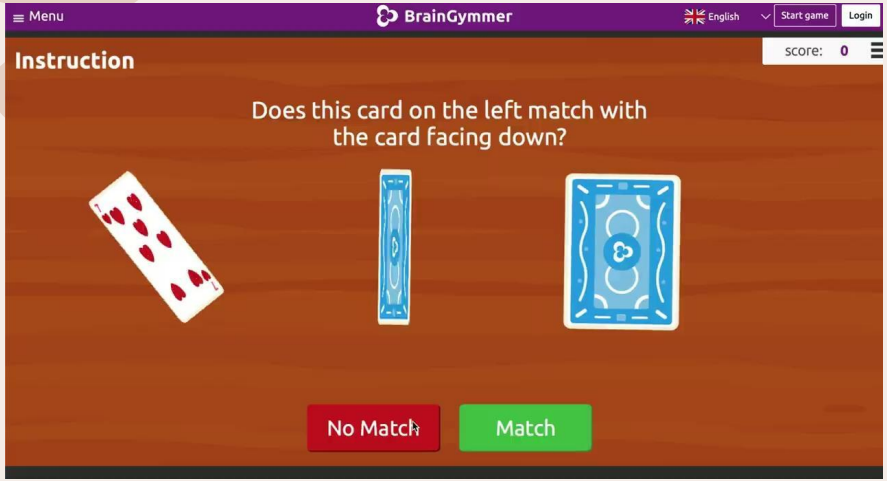


5 Minute Baseline




5 Minute Baseline
Caffeine Intake
None
Normal
Double
30 min
Cognition Tests
N-back
Digit Span

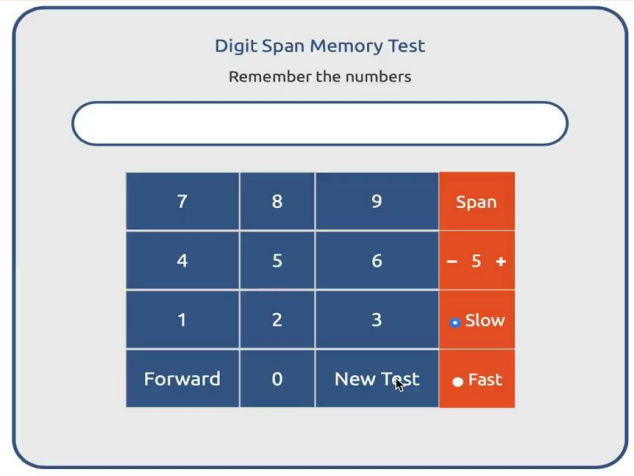
N-Back



Scores ranging from 2000-5000

[8]

Digit Span

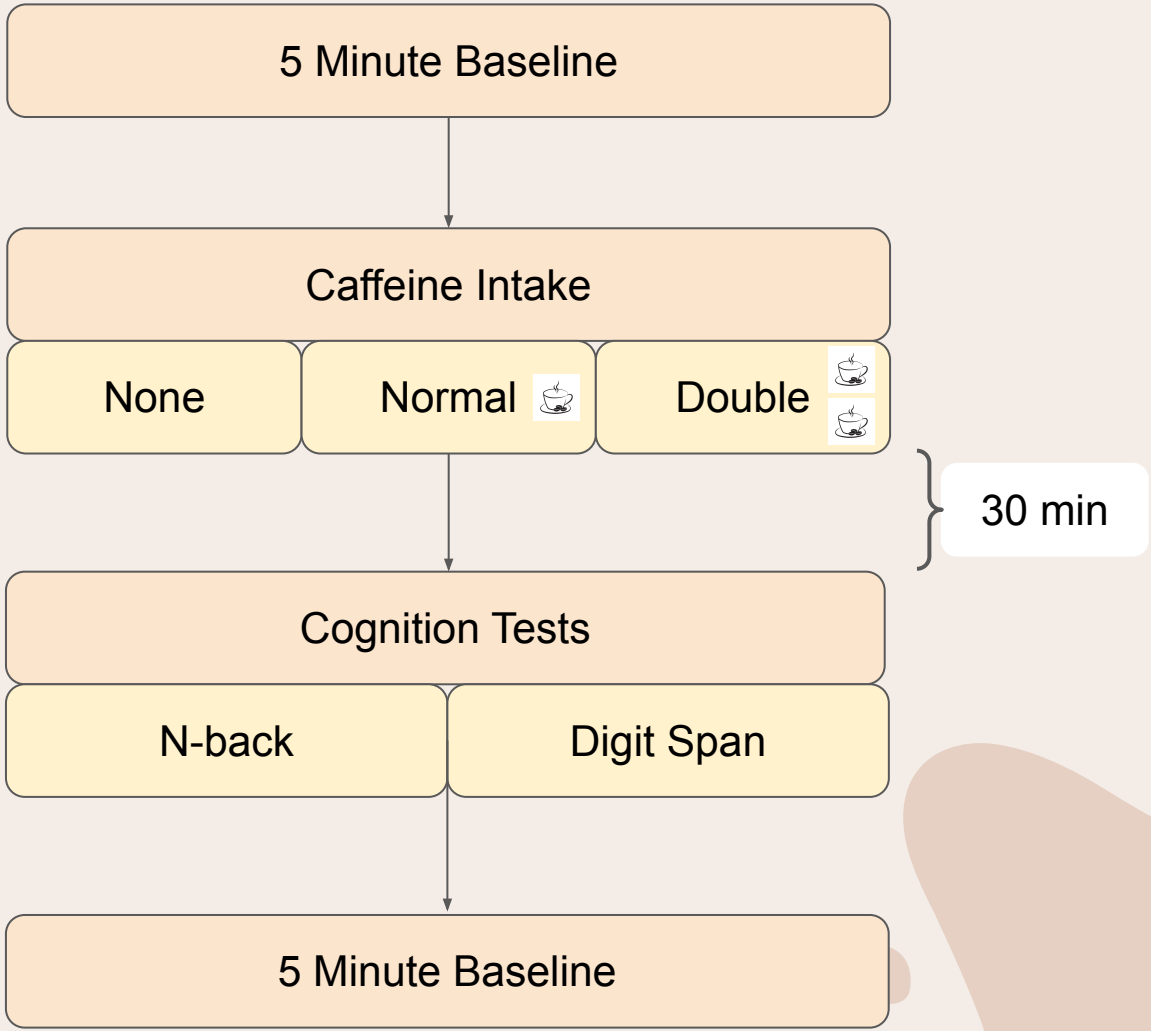


correct / # attempted

[9]

3 participants

147 recordings



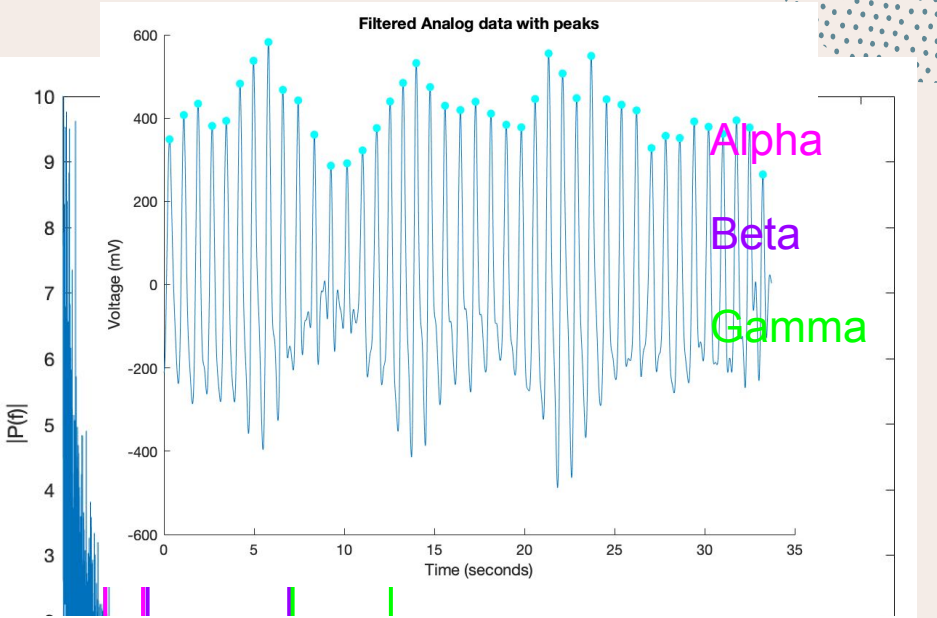
EEG
Pulse Ox
Performance
OpenBCI
Raw Data
Preprocessing and Feature Extraction
Processed Data
Algorithm
Prediction

03

Data Preprocessing

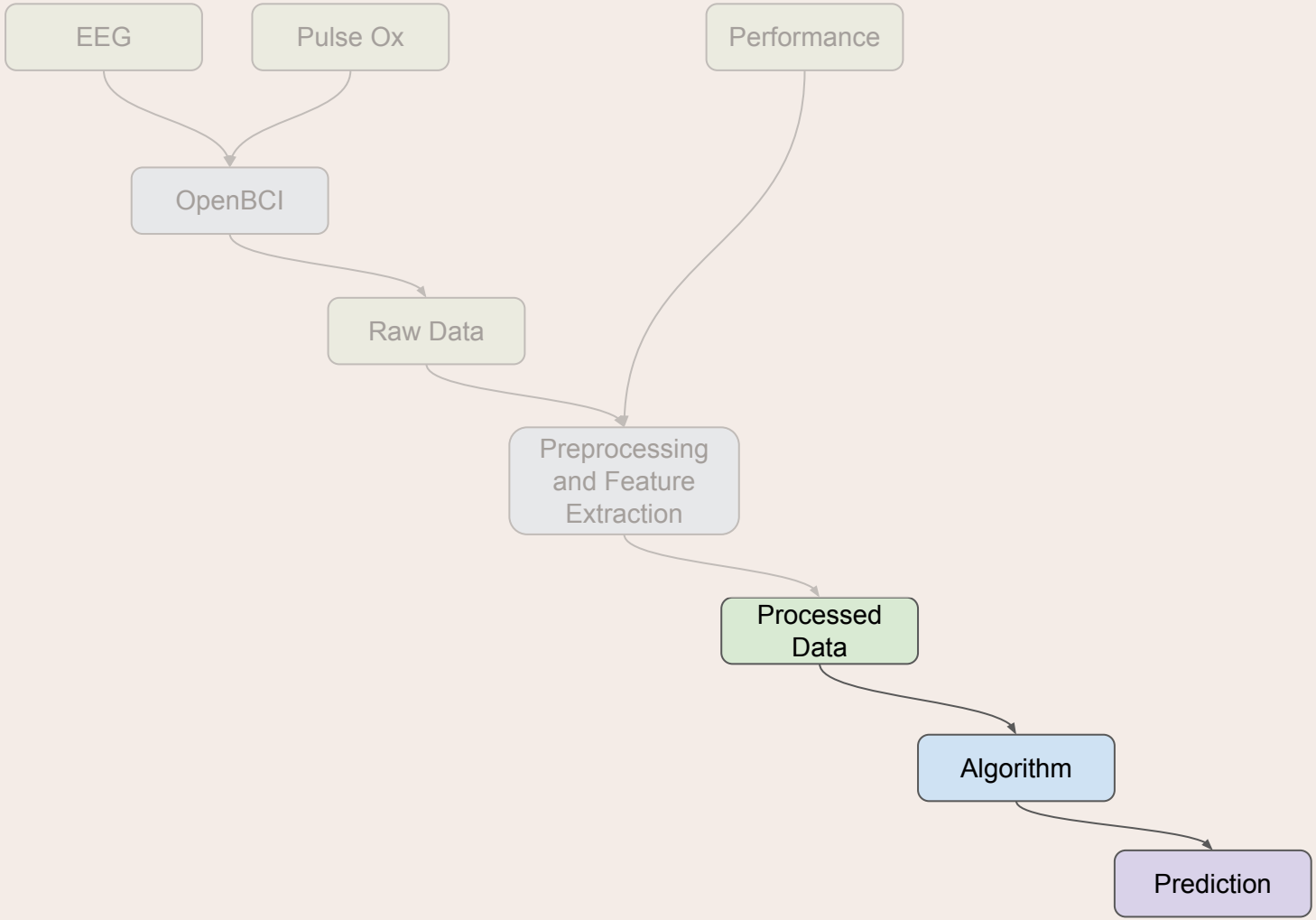
3. Data Preprocessing

- EEG
  - Bandpass filtering 1-50 Hz
  - Segmentation into alpha (8-13 Hz), beta (13-35 Hz), and gamma (35-50 Hz) bands
  - Mean power calculation
  - Baseline subtraction
- PPG
  - Bandpass filter 1-3.3 Hz [10]
  - Peak identification
  - HR and HRV Calculation
- Performance
  - Normalization of scores to average score during normal caffeine consumption



$$Heart\ Rate\ (beats\ per\ minute) = \left(\frac{1}{intervals\ (seconds)}\right) * \left(\frac{60\ seconds}{1\ minute}\right)$$

$$Heart\ Rate\ Variability\ (seconds) = \frac{\sqrt{\sum_{i=1}^{N-1} (RRi+1 - RRi)^2}}{N-1}$$


EEG
Pulse Ox
Performance
OpenBCI
Raw Data
Preprocessing and Feature Extraction
Processed Data
Algorithm
Prediction

Heart Rate & Variability

HR Data

	HR	HRV
Avg 0	86.914	52.35259
Avg 1	85.63243	48.08717
Avg 2	88.89657	43.31374

	HR	HRV
Avg 0	94.36562	96.16822
Avg 1	97.29445	102.3703
Avg 2	89.64739	104.3201

Maddie:

HR **increased** outside of baseline

HRV **decreased** with increasing caffeine

Martin:

HR **decreased** outside of baseline

HRV **increased** with increase caffeine

Cognitive Scores

Maddie:

Best Digit: No Caffeine

Best N-back: Double Caffeine

Best Normalized: No Caffeine

Martin:

Best Digit: No Caffeine

Best N-back: No Caffeine

Best Normalized: No Caffeine

Scores

	Norm	Nback	Digit
Avg 0	1.004618	3877.75	0.930208
Avg 1	1	4053.75	0.883681
Avg 2	0.980638	4176.2	0.825

	Norm	Nback	Digit
Avg 0	1.143392	4023.3	0.84
Avg 1	1	3496.1	0.739444
Avg 2	1.114471	3852.6	0.833333

BONUS QUESTION

Annabel recorded a session of data even though she does not normally consume caffeine

What would you classify her as:

No Caffeine or Baseline Caffeine?

What did the model classify her as?

No Coffee!
(66.7 %)

04

Machine Learning & Results

4. Machine Learning

		Difference In Mean Absolute Power - (Alpha-Pre)						Difference In Mean Absolute Power - Beta						Difference In Mean Absolute Power - Gamma										
Instances		Electrode 1	Electrode 2	Electrode 3	Electrode 4	Electrode 5	Electrode 6	Electrode 1	Electrode 2	Electrode 3	Electrode 4	Electrode 5	Electrode 6	Electrode 1	Electrode 2	Electrode 3	Electrode 4	Electrode 5	Electrode 6	Mean HR	HRV	Score	Norm Score	Classification
7-Nov	N-Back 1	3.5536	4.2227	0.4238	1.8395	1.1981	2.1099	2.529	1.6512	0.483	1.532	0.7188	1.5056	2.3669	1.1356	0.504	1.4885	0.6312	1.3244	89.2961	40.3034	3917	0.9662658	0
	N-Back 2	3.5902	1.6762	0.4594	1.649	0.7911	0.7743	3.497	1.6774	0.4239	1.5201	0.6366	0.7726	3.4885	1.6878	0.4254	1.5174	0.6428	0.7628	81.021	41.037	2816	0.6946654	0
	N-Back 3	4.2705	1.9126	0.3738	1.8058	0.6898	0.6034	4.0043	1.8427	0.3745	1.6327	0.6021	0.6306	4.0049	1.86	0.3676	1.6447	0.6008	0.6046	81.496	37.5704	2623	0.6470552	0
	Digit 1	5.7641	2.4892	0.4226	2.1487	0.7436	0.6334	5.3574	2.3824	0.4155	2.0282	0.6961	0.5782	5.3577	2.4081	0.4032	2.0614	0.6789	0.5345	86.2896	40.1221	1	1.1316306	0
	Digit 2	5.9589	2.5284	0.3932	2.137	0.708	0.4088	5.8986	2.5083	0.3937	2.0961	0.6597	0.4301	5.9055	2.5052	0.4064	2.0857	0.6779	0.4375	85.7409	49.1163	1	1.1316306	0
	Digit 3	6.1968	2.5097	0.3878	2.1346	0.6454	0.3356	6.1826	2.5227	0.4066	2.0917	0.6632	0.3888	6.2027	2.5512	0.4088	2.1069	0.6691	0.377	79.2694	74.8	0.9	1.0184676	0
14-Nov	N-Back 1	7.3637	18.8729	17.3243	24.7002	13.8652	17.4526	3.8175	9.5874	11.3333	8.4568	6.9265	20.5231	2.8601	7.5798	10.1139	4.9875	5.4309	21.0289	88.9966	30.2817	4032	0.9946346	1
	N-Back 2	1.6211	9.4804	12.0009	7.1912	6.3453	13.4263	1.8138	9.4138	11.893	7.1258	6.5949	20.5415	1.8616	9.4245	11.8931	7.1203	6.6555	21.9644	86.504	28.0863	3984	0.9827937	1
	N-Back 3	1.6769	9.8374	12.3818	7.3482	6.6111	15.2732	2.1479	10.0311	12.4957	7.2557	6.9583	23.2527	2.2085	10.0661	12.5073	7.2722	7.0107	24.6661	85.417	33.9706	4184	1.0321307	1
	Digit 1	2.2387	13.7465	16.6934	10.5472	9.5057	20.5214	2.244	13.6235	16.6179	10.4549	9.4014	27.1808	2.2297	13.5728	16.5929	10.4511	9.3731	28.2989	90.6102	61.0164	0.63	0.7072692	1
	Digit 2	4.2977	-0.4925	-0.2327	-0.225	5.4315	18.3273	4.3311	-0.4475	-0.1992	-0.3271	5.3471	26.2987	4.337	-0.4562	-0.2159	-0.3401	5.3244	27.5425	85.3093	20.315	1.00	1.1316306	1
	Digit 3	1.2325	12.7058	15.5606	8.0647	8.3543	16.7509	1.6096	12.7077	15.3794	7.6231	8.4233	24.3178	1.6832	12.711	15.3724	7.5797	8.5	25.807	86.2664	28.444	0.89	1.0058939	1
17-Nov	N-Back 1	11.127	3.366	2.6814	3.6958	14.2993	21.309	2.4879	2.258	2.7603	3.01	7.3247	9.5273	0.6445	2.0121	2.7674	2.8154	5.782	6.6109	94.5116	45.4118	4451	1.0979957	2
	N-Back 2	0.6586	1.2845	2.8787	2.6902	7.0039	3.8686	1.0674	2.2532	2.7766	2.4557	7.3235	4.1764	1.1311	2.499	2.8012	2.4588	7.4122	4.2705	86.7233	22.1972	3793	0.9356768	2
	N-Back 3	0.6413	1.1251	2.7527	2.4327	6.7459	3.5715	0.9504	2.2603	2.8582	2.4767	7.433	4.0869	1.0254	2.4828	2.8542	2.465	7.4957	4.1248	92.5441	45.3158	4617	1.1389454	2
	N-Back 4	0.5828	1.368	3.1252	2.8941	7.5977	3.7315	0.9977	2.3709	3.0622	2.7102	7.9721	4.0824	1.0859	2.5847	3.0473	2.6775	8.0158	4.1239	92.7277	39	4233	1.0442183	2
	N-Back 5	0.6861	1.2087	3.0017	2.7802	7.4022	3.3289	1.0238	2.3024	3.0543	2.719	7.9927	3.8294	1.0927	2.5407	3.0742	2.7278	8.1083	3.9164	98.8315	68.5	4078	1.0059821	2

1. **Split to X data and y data**
2. **Feature Engineering (X data)**
   - Removed/kept columns (e.g. Nback and Digit span scores)
   - Normalization
   - Scaling
   - DWT (approach 3)

X data

y data

(0, 1, 2)

Train Data

Validation data

3. Split to Train and Test data

4. Train 2 models

Model 1: Random Forest

Model 2: XG Boost

5. Predict using Test data

Classify & Predict

No Caffeine (0)

Normal Caffeine (1)

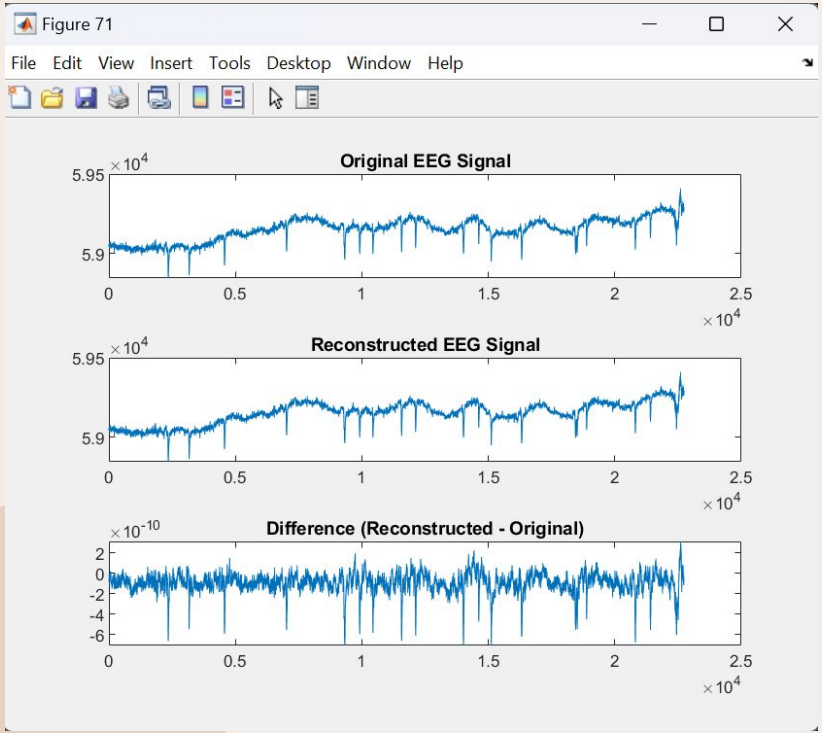
Double Caffeine (2)

Calculate Model accuracies

3 Machine learning approaches

1. **Approach 1:** FULL X dataset, FFT signal processing
2. **Approach 2:** EEG signal X dataset, FFT signal processing
3. **Approach 3:** EEG signal X dataset, DWT signal processing

Approach 3: Discrete Wavelet Transform



- **Discrete Wavelet Transform**
- Reference from Automated Detection of Caffeinated Coffee-Induced Short-Term Effects on ECG Signals Using EMD, DWT, and WPD [11]

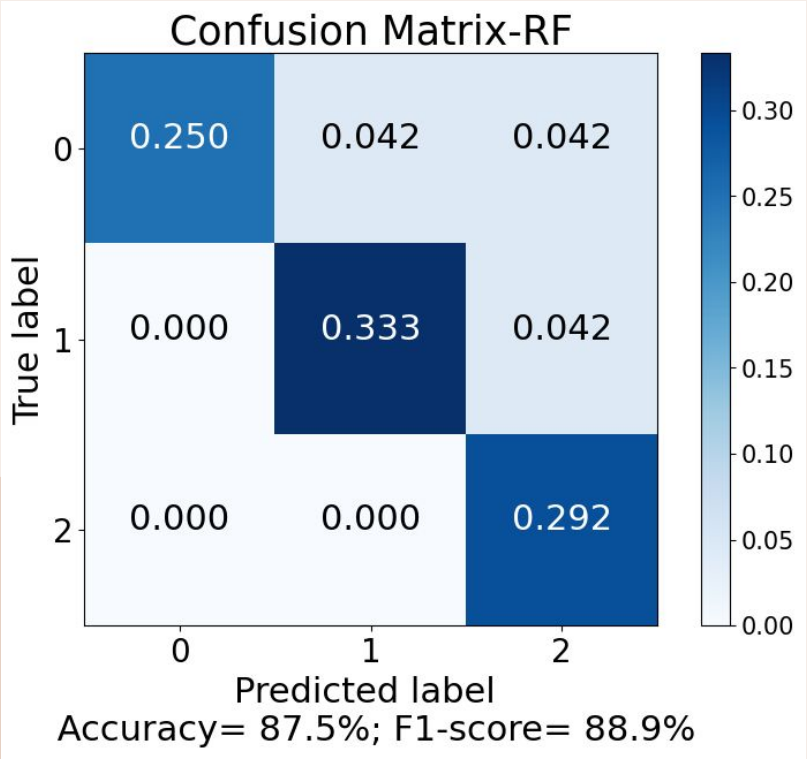
- Signal → decomposed into **approximate** (the low pass-filtered signal component) and **detailed** (the high pass-filtered signal component) **coefficients**
- **MATLAB parameters: 'db6' (waveletname), 'level8'(level)**

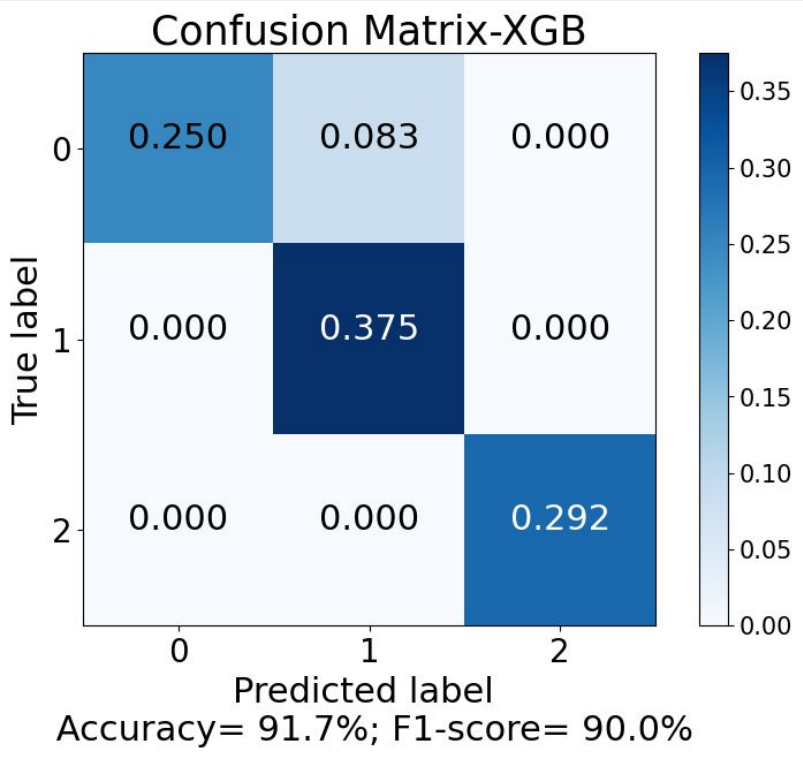
$$\Psi(t) = \frac{1}{\sqrt{s}}\Psi(t-u)/s$$

- Original signal constructed from coefficients

Classification Accuracies with approach 1

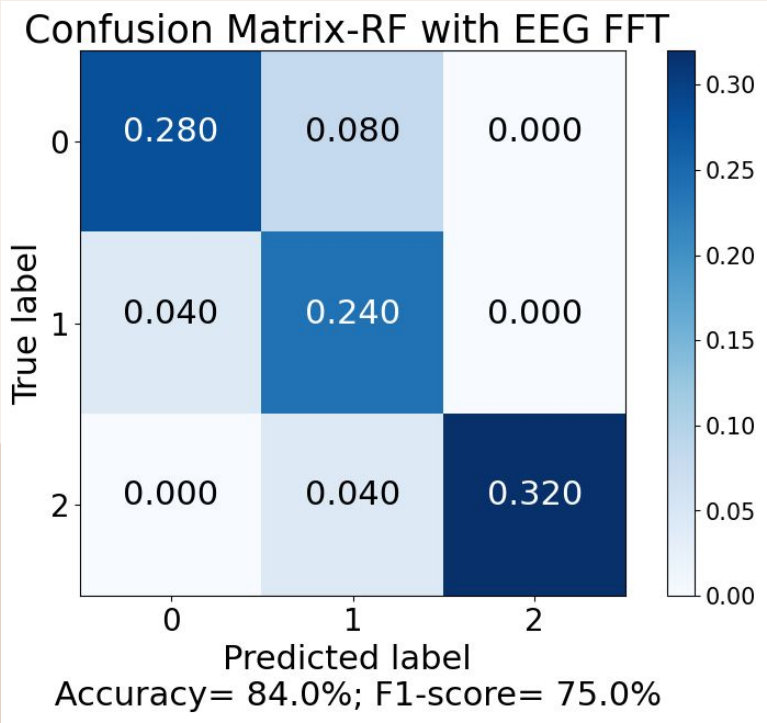
Parameters: X dataset with ALL features, FFT signal processing

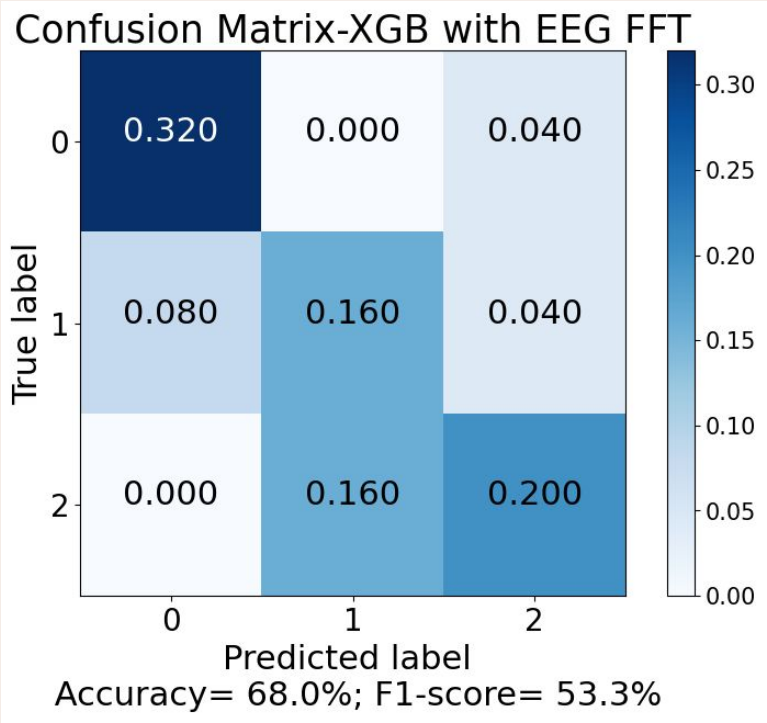




Classification Accuracies with approach 2

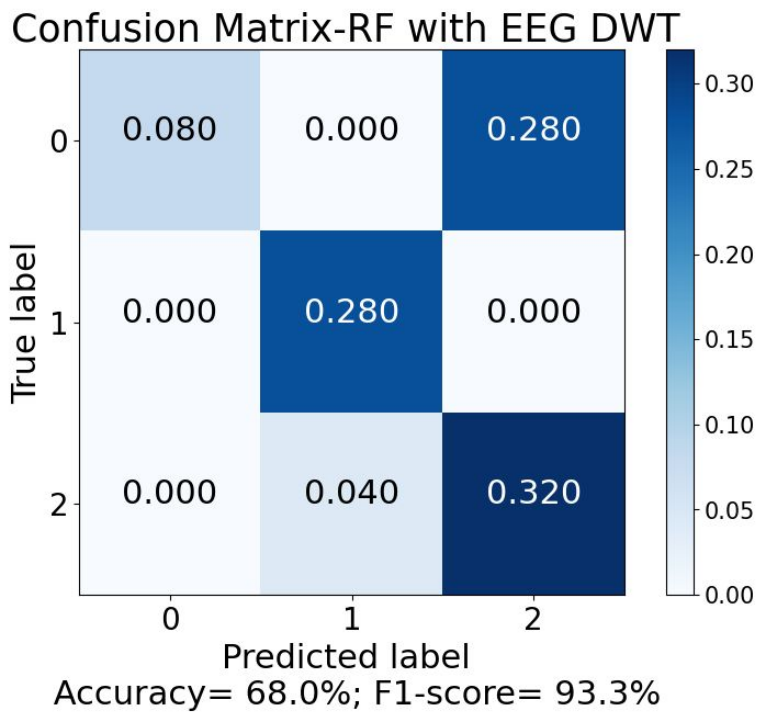
Parameters: X dataset without scores (EEG only), FFT signal processing

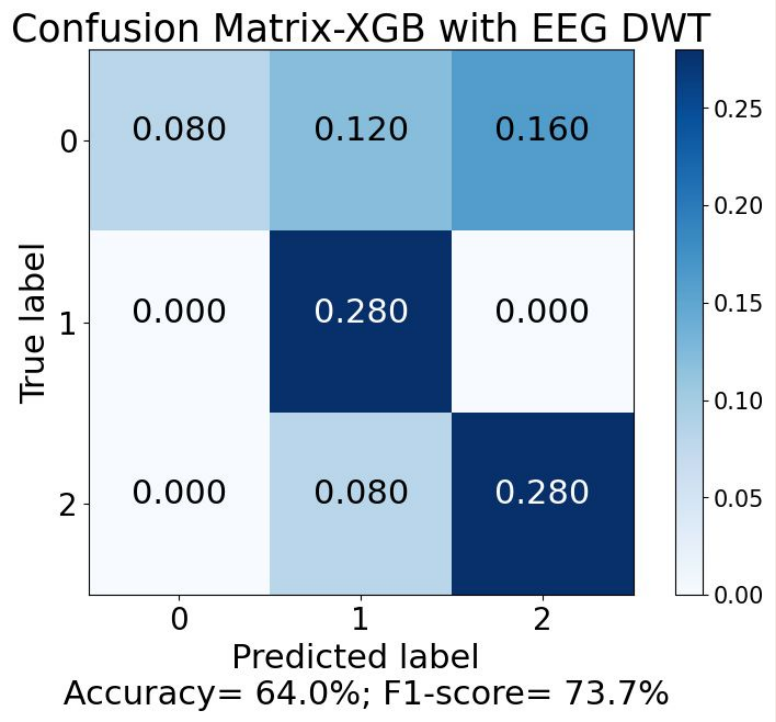




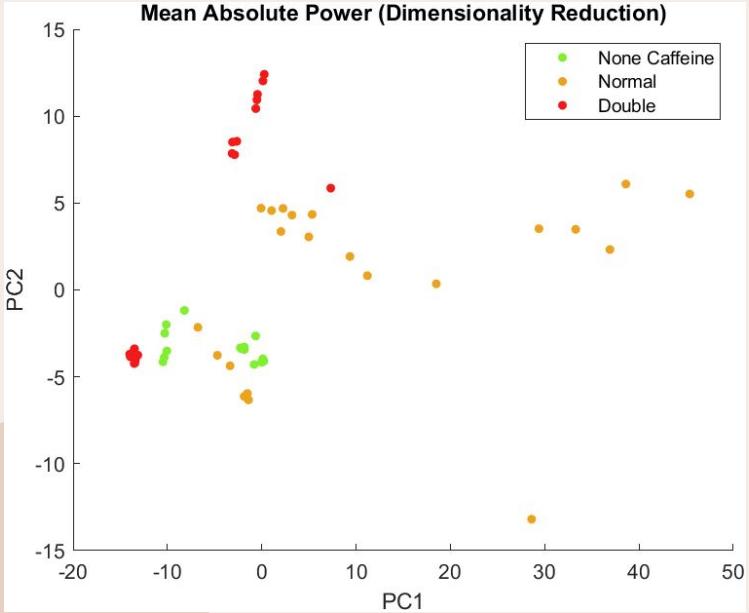
Classification Accuracies with approach 3

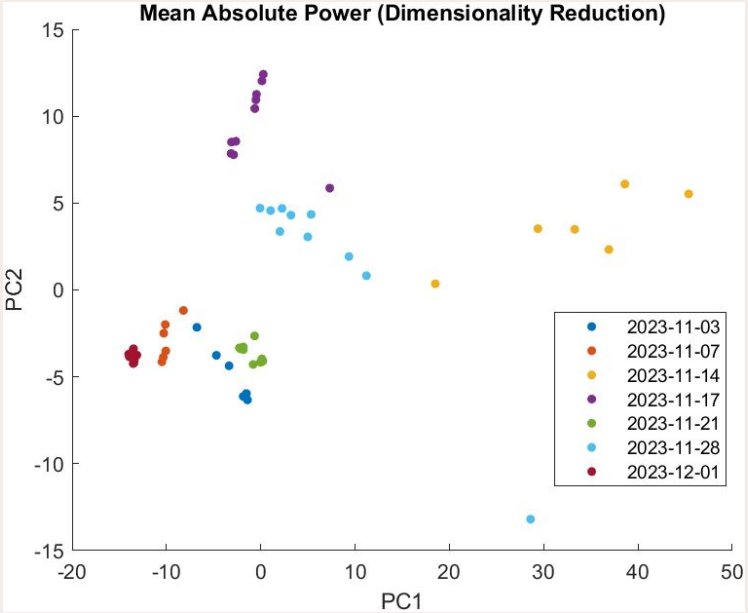
Parameters: X dataset without scores (EEG only), DWT signal processing





High Accuracy is probably due to day-to-day variability





05

Discussion and Future Work

Discussion

- Direct opposite HR and HRV results between participants

- More caffeine intake does not improve memory overall, but can possibly improve memory in Nback (experience)

- XGB Model for filtered signal and all features had the overall best accuracy (91.7%) and F1 Score (90.0%)
- With only EEG data, the RF model (84.0% acc, 75.0% F1) performed much better than the XGB model (68.0% acc, 53.3% F1)
- DWT Signal with only EEG data had the overall poorest performance in both models, but the RF F1-score was the highest (93.3%)

Future Work

- *Collect more data* (only 152 data points)
  - more participants
  - more & longer trials & different tasks
  - dosage curve vs. three subjective levels
- Improve denoising
- Use new feature extraction methods to minimize loss
- More electrodes spread across scalp (EEG Cap)
- Deep neural network models that takes raw/processed data as input
- Real-time classification during cognitive tasks

Questions?

References

[1] City of Vienna Council, “History of Viennese coffee house culture”. Nov. 2013 https://www.wien.gv.at/english/culture-history/viennese-coffee-culture.html

[2] A. Ajjimaporn, P. Noppongsakit, P. Ramyarangsi, V. Siripornpanich, and R. Chaunchaiyakul, “A low-dose of caffeine suppresses EEG alpha power and improves working memory in healthy University males,” Physiol. Behav., vol. 256, p.113955, Nov. 2022, doi: 10.1016/j.physbeh.2022.113955.

[3] J. Y. Jung, H.-W. Lee, I.-S. Jang, K. Suk, and M.-G. Lee, “Caffeine Maintains Arousal Level and Prevents Change of Electroencephalogram Spectral Powers with Time at Rest,” J. Korean Sleep Res. Soc., vol. 11, no. 1, pp. 5–10, Jun. 2014, doi: 10.13078/jksrs.14002.

[4] K. Rodak, I. Kokot, and E. M. Kratz, “Caffeine as a Factor Influencing the Functioning of the Human Body—Friend or Foe?,” Nutrients, vol. 13, no. 9, p. 3088, Sep. 2021, doi: 10.3390/nu13093088.

[5] B. K. Pradhan, M. Jarzębski, A. Gramza-Michałowska, and K. Pal, “Automated Detection of Caffeinated Coffee-Induced Short-Term Effects on ECG Signals Using EMD, DWT, and WPD,” Nutrients, vol. 14, no. 4, p. 885, Feb. 2022, doi: 10.3390/nu14040885.

[6] M. A. Keane and J. E. James, “Effects of dietary caffeine on EEG, performance and mood when rested and sleep restricted,” Hum. Psychopharmacol. Clin. Exp., vol. 23, no. 8, pp. 669–680, Dec. 2008, doi: 10.1002/hup.987.

[7] “Heartbeats in Your Project, Lickety-Split ❤️ – World Famous Electronics llc.” Accessed: Nov. 08, 2023. [Online]. Available: https://pulsesensor.com/

[8] “Brain Game: N Back - Improve your Working Memory,” BrainGymmer. Accessed: Nov. 08, 2023. [Online]. Available: https://www.braingymmer.com/en/brain-games/n_back/play/

[9] “Digit Span Memory Test - MemoryHealthCheck.” Accessed: Nov. 08, 2023. [Online]. Available: https://www.memorylosstest.com/digit-span/

[10] R. Cassani, A. Tiwari, and T. H. Falk, “Optimal filter characterization for photoplethysmography-based pulse rate and pulse power spectrum estimation,” in 2020 42nd Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC), Montreal, QC, Canada: IEEE, Jul. 2020, pp. 914–917. doi: 10.1109/EMBC44109.2020.9175396.

[11] Pradhan, B.K.; Jarz ̨ebski, M.; Gramza-Michałowska, A.; Pal, K. Automated Detection of Caffeinated Coffee-Induced Short-Term Effects on ECG Signals Using EMD, DWT, and WPD. Nutrients 2022, 14, 885. https://doi.org/10.3390/nu14040885