Experimental Validation

The Motor Imagery (MI) **BCI FII corpus** is used to validate the Julia implementation of the Riemannian Minimum Distance to mean (MDM) classifier in *PosDefManifold.jl* against the reference implementations in Python (*PyRiemann*). The classification accuracy and the execution time in the two implementations is compared.

Two MI classification tasks are considered:

1) "right hand" vs. "feet",

2) "left hand" vs. "right hand".

Classification Accuracy

The pre-processing and encoding have been carried-out separately in the two languages. For each session in all databases, an 8-fold cross-validation has been performed using the *StratifiedKFold* function of the Python *Scikit-learn* package to extract the training and validation splits, which have been used identically in both languages. This ensures that exactly the same splits are used in the two languages.

Pre-processing

Pass-band 4th-order linear-phase response (forward-backward) Butterworth digital filter in the region 8Hz-32Hz.

Encoding

Sample covariance matrix estimation of the MI trials with a Tikhonov regularization (diagonal loading) with parameter 10e-4.

Model fitting and prediction

Riemannian MDM (nearest centroid).

Table 1: Resources for the implementation in Julia and Python

Implementation	Julia	Python
Pre-processing	DSP.jl (from Eegle.jl)	SciPy
Encoding	Eegle.jl	PyRiemann
Model fitting and prediction	PosDefManifoldML.jl	PyRiemann

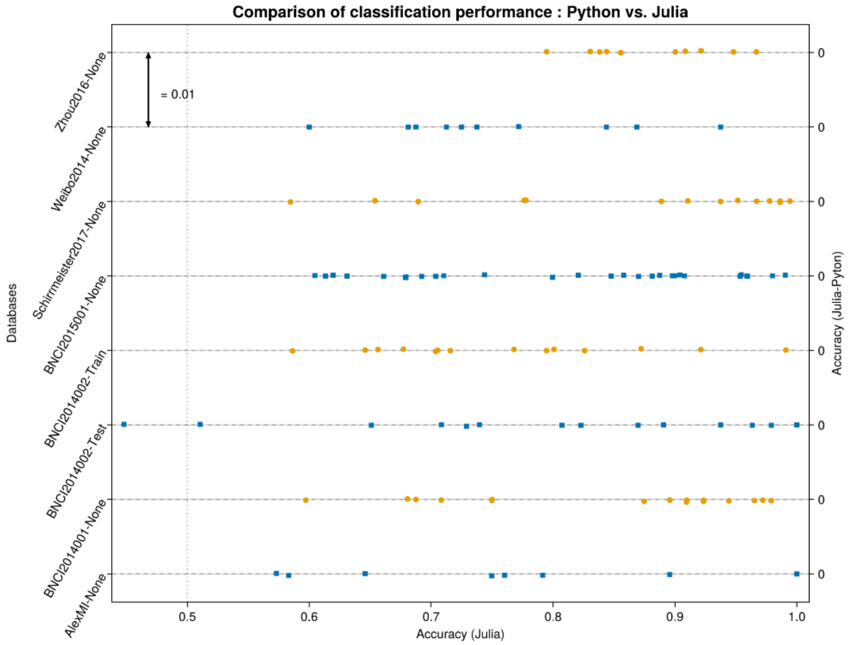
Results

1) “right hand” vs “feet”

Table 2: Classification accuracy for “right hand” vs. “feet” MI

Database	**Julia Mean and Std (%)**	**Python Mean and Std (%)**	**Difference of Means**
AlexMI-None	74.99 ± 14.90871	75.0 ± 14.9092	-0.009375
BNCI2014001-None	84.94 ± 11.90432	84.95 ± 11.9096	-0.011944
BNCI2014002-Test	78.98 ± 17.0275	78.98 ± 17.03021	-0.001179
BNCI2014002-Train	76.18 ± 11.3729	76.17 ± 11.36971	0.005857
BNCI2015001-None	81.11 ± 12.84454	81.1 ± 12.8419	0.001214
Schirrmeister2017-None	86.3 ± 13.98145	86.29 ± 13.98154	0.005071
Weibo2014-None	75.66 ± 10.0781	75.65 ± 10.07801	0.0005
Zhou2016-None	87.85 ± 5.3869	87.84 ± 5.38551	0.009591

Figure 1: Classification accuracies for “right hand” vs. “feet” MI. Each point is a session. Points lying on the horizontal dashed lines indicate a null difference of the accuracy obtained in the two languages.

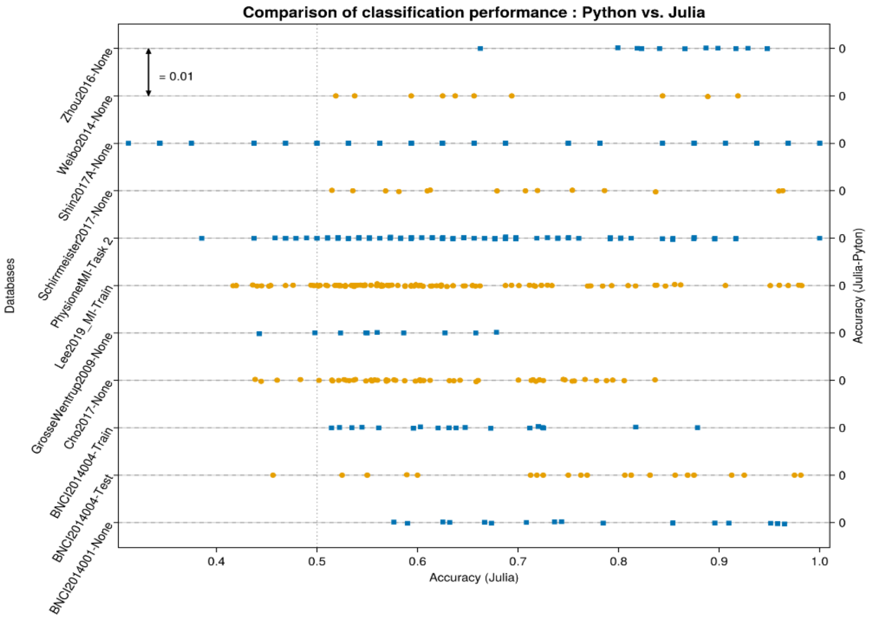


2) “left hand” vs. “right hand”.

Table 3: Classification accuracy for left hand vs. right hand MI

Database	**Julia Mean and Std (%)**	**Python Mean and Std (%)**	**Difference**
BNCI2014001-None	78.24 ± 13.80576	78.24 ± 13.81513	-0.004611
BNCI2014004-Test	76.53 ± 14.12921	76.53 ± 14.12962	0.000315
BNCI2014004-Train	64.8 ± 10.11533	64.8 ± 10.11401	0.002833
Cho2017-None	62.1 ± 10.29322	62.1 ± 10.29349	-3.8e-5
GrosseWentrup2009-None	56.72 ± 7.26641	56.72 ± 7.26111	0.00045
Lee2019_MI-Train	62.0 ± 13.2963	62.0 ± 13.29557	-0.001285
PhysionetMI-Task 2	62.09 ± 12.82857	62.09 ± 12.83081	-0.000216
Schirrmeister2017-None	70.2 ± 14.54348	70.2 ± 14.54554	-0.002179
Shin2017A-None	63.25 ± 16.43238	63.25 ± 16.43238	0.0
Weibo2014-None	69.14 ± 14.35384	69.14 ± 14.35598	-0.0014
Zhou2016-None	85.35 ± 7.97634	85.35 ± 7.97701	0.001682

Figure 2: Classification accuracies for left hand vs. right hand MI. Each point is a session. Points lying on the horizontal dashed lines indicate a null difference of the accuracy obtained in the two languages.



Execution Time

The execution time for performing the above cross-validations has been estimated as the median execution time observed across five repetitions of the whole cross-validation procedure, excluding pre-processing and encoding. Both in the Julia and Python implementation, multithreading has been enabled, allowing four threads to be used in parallel.

Results

1) "right hand" vs "feet"

Table 4: Execution time in milliseconds for "right hand" vs. "feet" MI

Database	Julia Mean and Std (ms)	Python Mean and Std (ms)	Difference (abs)
AlexMI-None	22 ± 6	263 ± 5	241
BNCI2014001-None	123 ± 56	355 ± 19	232
BNCI2014002-Test	23 ± 6	262 ± 3	239
BNCI2014002-Train	43 ± 13	270 ± 8	227
BNCI2015001-None	56 ± 8	271 ± 8	215
Schirrmeister2017-None	13125 ± 15535	42932 ± 14133	29807
Weibo2014-None	1971 ± 1965	3839 ± 2368	1869
Zhou2016-None	40 ± 12	270 ± 5	230

Figure 3: Execution Time in milliseconds (log$_{10}$) for "right hand" vs. "feet" MI

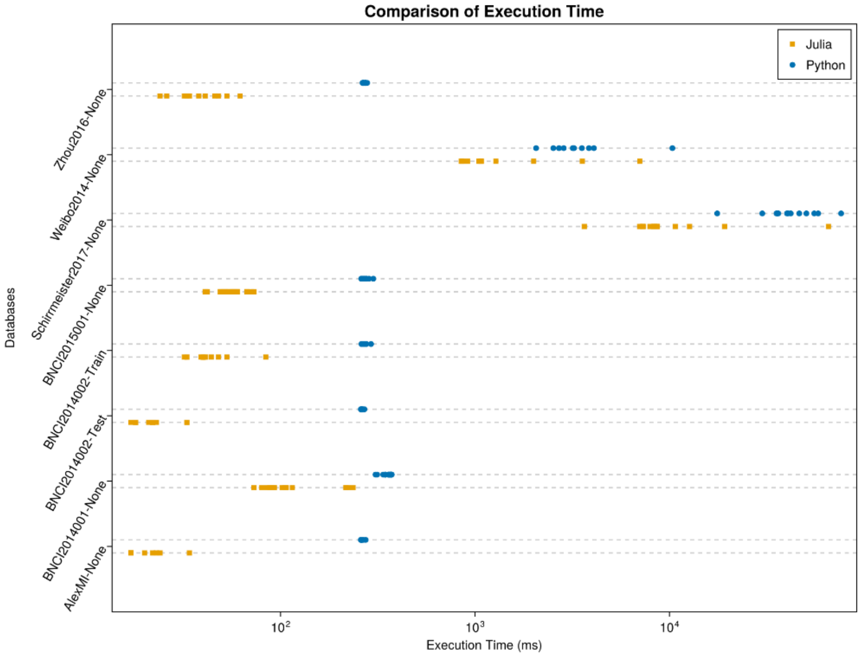
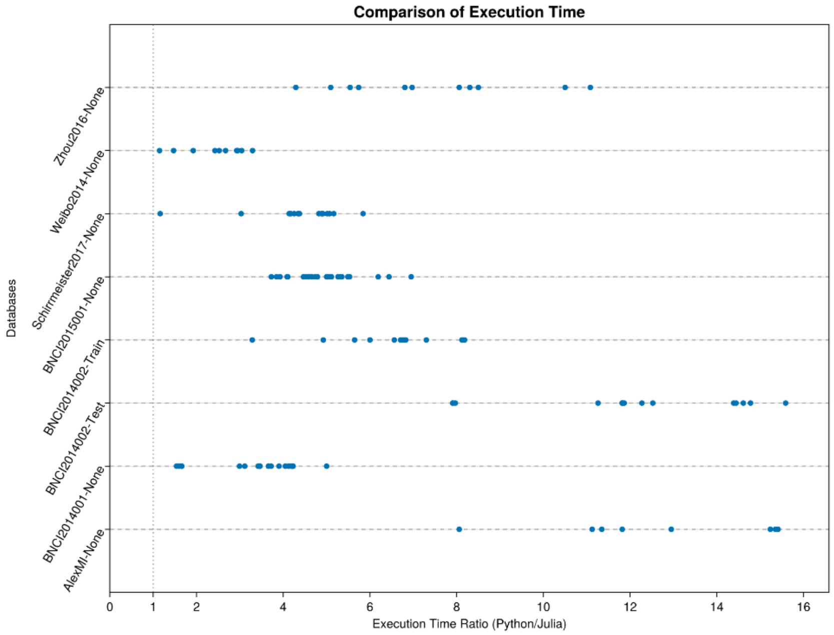


Figure 4: Execution Time (Ratio Python/Julia) for “right hand” vs. “feet” MI



2) “left hand” vs. “right hand”.

Table 5: Execution time in milliseconds for “left hand” vs. “right hand” MI

Database	**Julia Mean and Std (ms)**	**Python Mean and Std (ms)**	**Difference (abs)**
BNCI2014001-None	149 ± 65	356 ± 23	207
BNCI2014004-Test	14 ± 3	264 ± 3	249
BNCI2014004-Train	15 ± 2	265 ± 3	250
Cho2017-None	1045 ± 61	3101 ± 252	2056
GrosseWentrup2009-None	4021 ± 398	20416 ± 2577	16395
Lee2019_MI-Train	613 ± 138	2103 ± 256	1489
PhysionetMI-Task	351 ± 279	931 ± 204	580
Schirrmeister2017-None	12789 ± 14878	42223 ± 13491	29435
Shin2017A-None	25 ± 8	269 ± 5	243
Weibo2014-None	1954 ± 1963	3791 ± 2301	1837
Zhou2016-None	37 ± 7	272 ± 6	234

Figure 5: Execution Time in milliseconds (log_{10}) for "left hand" vs. "right hand" MI

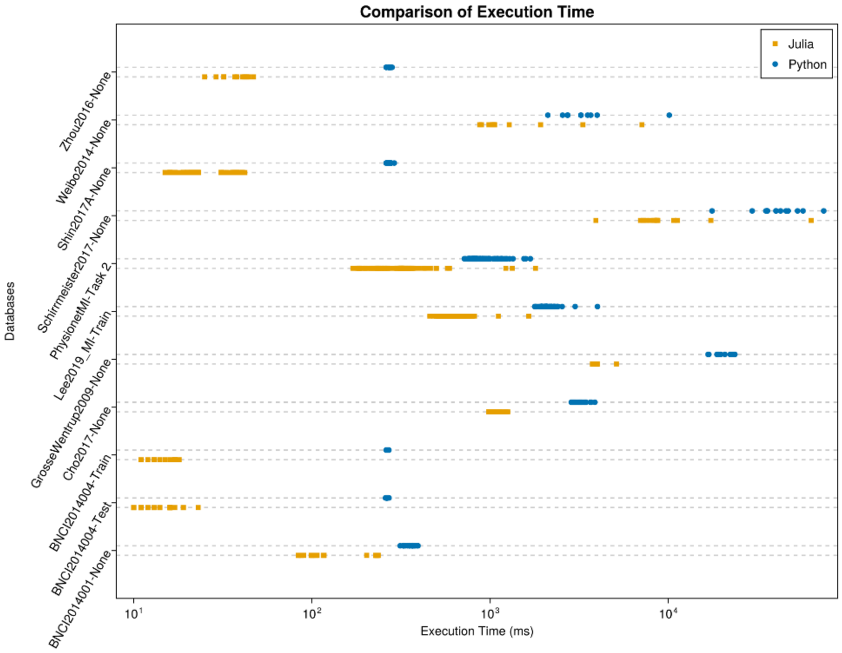
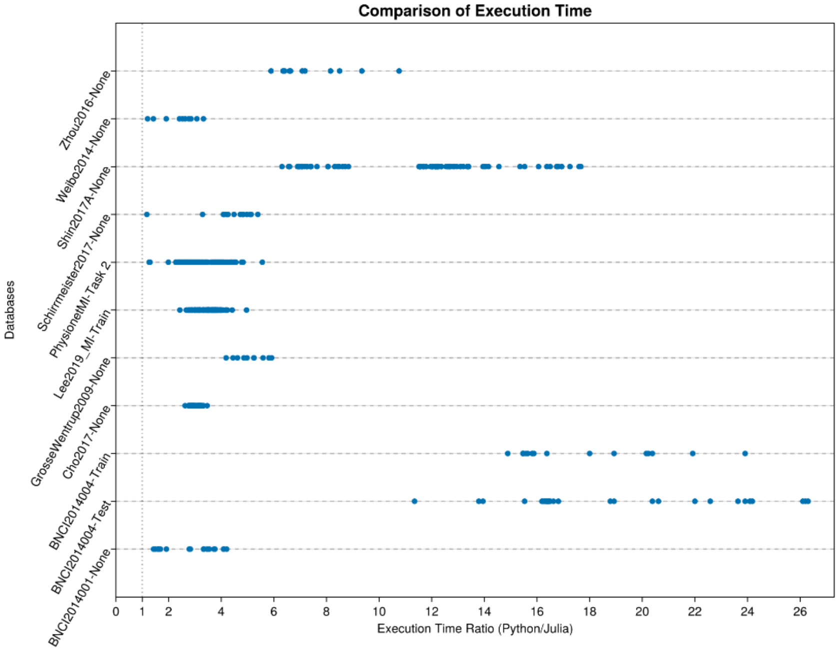


Figure 6: Execution Time (Ratio Python/Julia) for left hand vs. right hand MI



Conclusions

The Julia and Python implementations allows the same accuracy. Typically, the Julia implementation is a few times faster. The speed-up factor with the analyzed data is up to ≈ 25.