Towards Riemannian EEG classifiers to detect awake and anesthetized states using Median Nerve Stimulation

Valérie Marissens Oueva
valerie.marissens@loria.fr

Supervisors:
Fabien Lotte, Laurent Bougrain, Sébastien Rimbert

Accidental Awareness during General Anesthesia (AAGA)

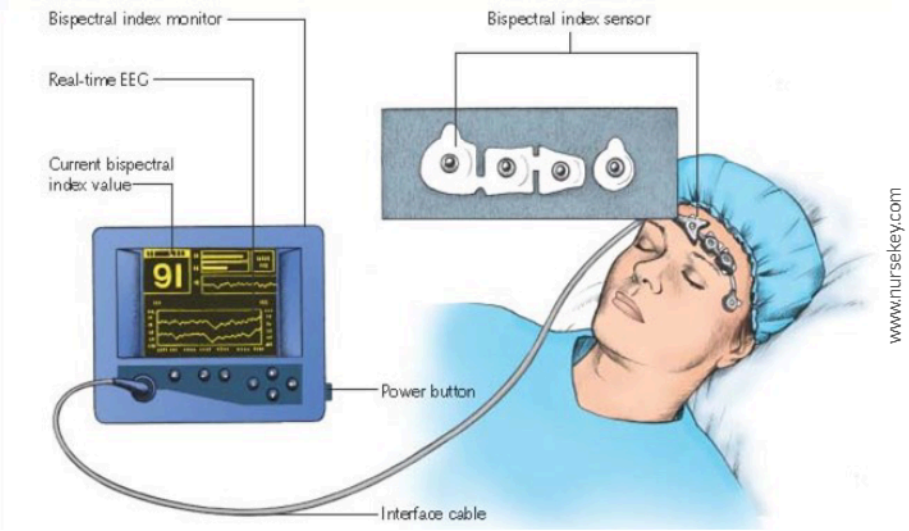
Yuko Shimizu

Monitors to prevent AAGA

- **Awareness still occurs** with current monitors [6, 7, 8, 9, 10].

Reasons:

- Indices were developed from adult cohorts [11]
- Indices might be falsely increased with EMG activity [7, 8] and are less accurate with age [12]



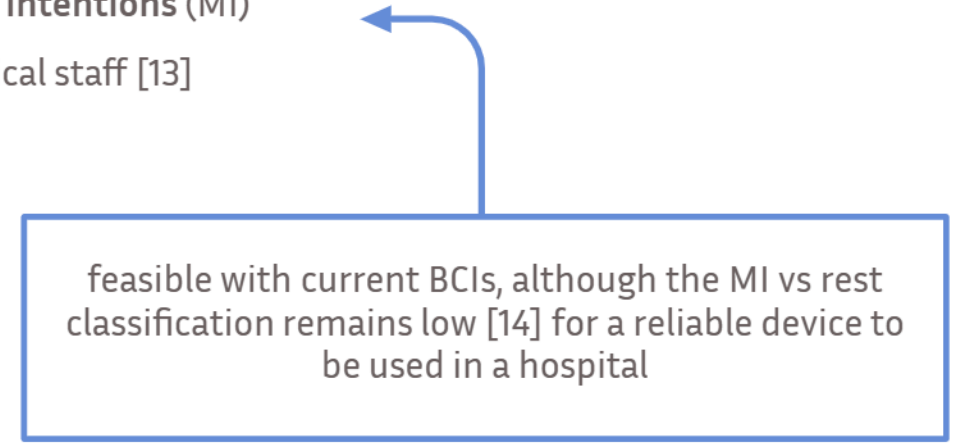
Bispectral Index monitor, Sigl and Chamoun, J Clin Monit, 1994

[6] Myles et al. Lancet, 2004.
[7] Sebel et al. Anesth. Analg. 2004.
[8] Bruhn et al. Anesth, 2000.
[9] Aho et al. Acta Anaesthesiol Scan, 2012.
[10] Schneider et al. Br J Anaesth, 2003.
[11] Bruhn et al. Br J Anaesth, 2006.
[12] Ni et al. Br J Anaesth, 2019.

Long-term objective

Propose a **new Brain-Computer Interface (BCI)** based on motor imagery to:

- monitor the motor cortex with EEG
- **detect movement intentions** (MI)
- and alert the medical staff [13]



[13] **Rimbert** et al, Front. Neurosci, 2019.
[14] Lotte et al, J. Neural Eng, 2018

Median Nerve Stimulation (MNS)-based BCI

- **Painless stimulation** of the median nerve, with an intensity between 8 and 15 mA.

Illustration of the regular branching of the median nerve [15]

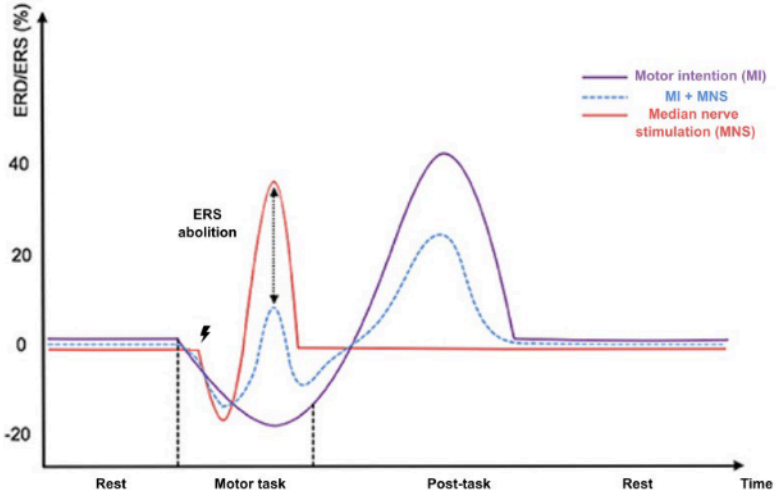


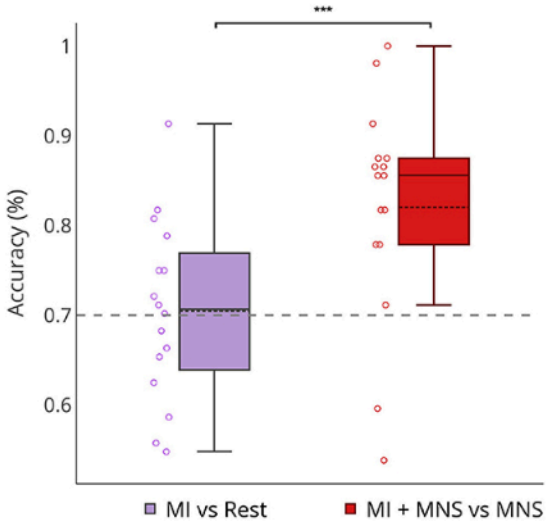
Illustration of ERD/ERS induced by MI, MNS and MNS during MI, in the alpha and beta frequency bands [13].

[13] **Rimbert** et al, Front. Neurosci, 2019.
[15] Lanz, J. of Hand Surgery, 1977.

Median Nerve Stimulation (MNS)-based BCI

- **Painless stimulation** of the median nerve, with an intensity between 8 and 15 mA.
- Combining motor intention (MI) and MNS significantly impacts MNS-generated patterns, leading to **better MI detection accuracy** (+12%) in patients under light sedation [13].
- Provides a trigger.

Illustration of the regular branching of the median nerve [15]



Distribution of average classification accuracies (n = 16), obtained by a Riemannian classifier ***p-value < 0.001 [13].

[13] **Rimbert** et al, Front. Neurosci, 2019.
[15] Lanz, J. of Hand Surgery, 1977.

Problematic

General anesthesia ≥4 µg/ml [19]

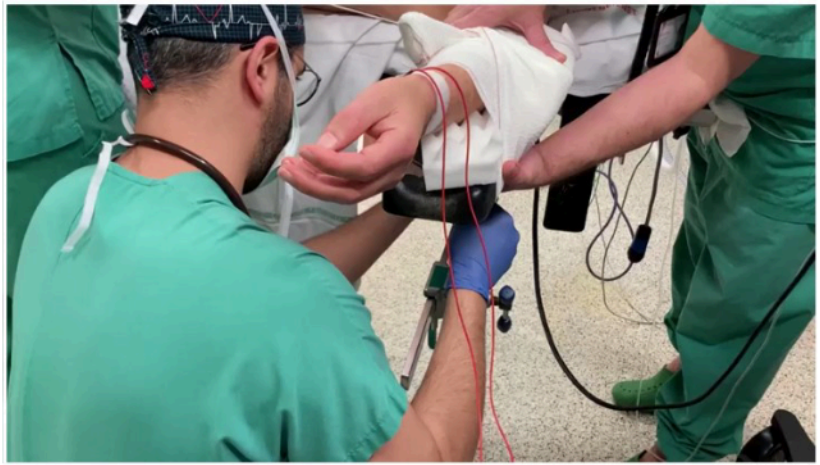
- The MNS pattern is still visible under light sedation (≤1 µg/ml) [16, 17].
- We are still able to detect it at deeper concentrations of anesthesia [18].

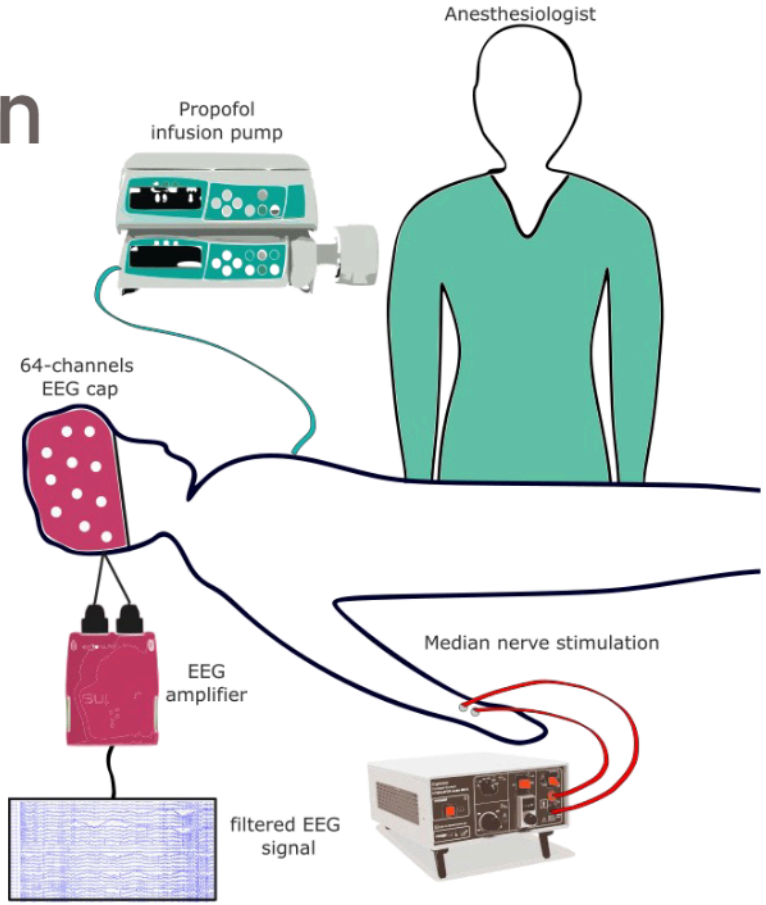
Is it possible to use median nerve stimulation to detect recovery of consciousness under general anesthesia?

[16] Guerci et al, SFAR, 2021.
[17] Rimbert at al, IEEE SMC, 2019.
[18] Rimbert et al, ASA Annual Meeting, 2023.
[19] Anderson et al, Anesthesiology, 2019.

Clinical protocol at CHU Brugmann

12 patients: 6 females; 50 ± 14.3 years old



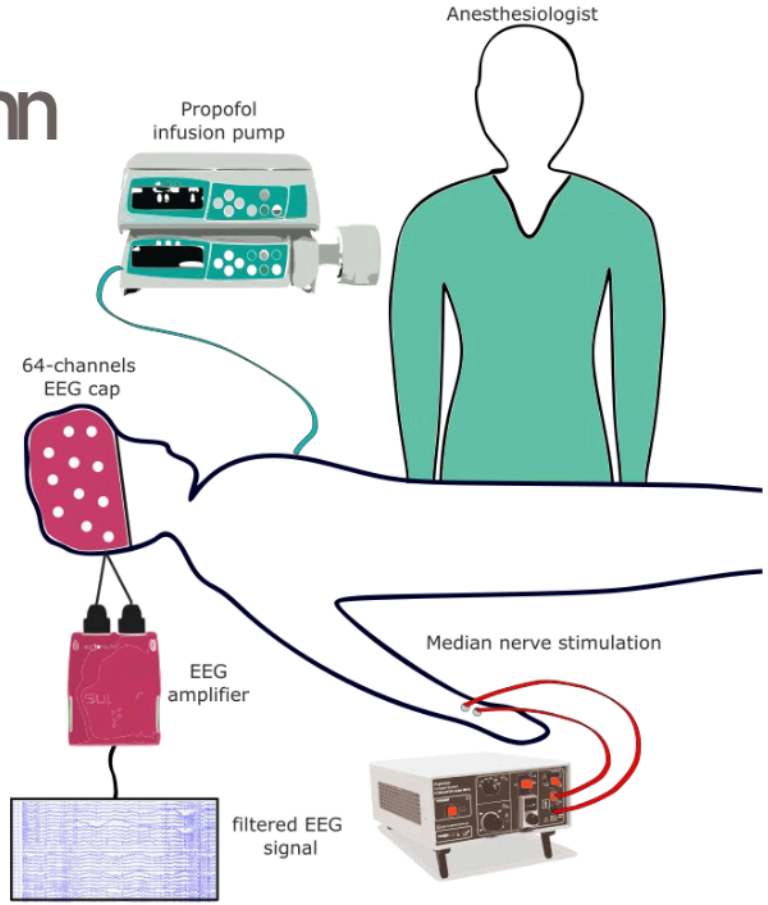


[20] Rimbert et al. JMIR Res. Protoc, 2023.

Clinical protocol at CHU Brugmann

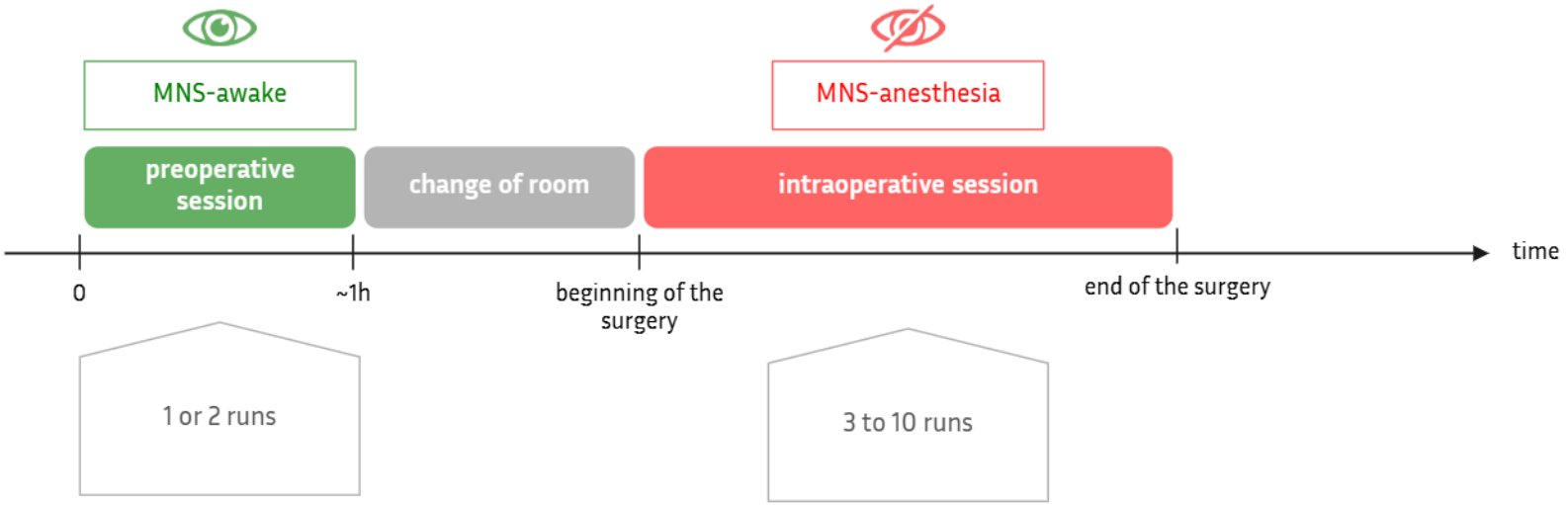
Surgeries:

- Anal fistula (40 min)
- Cholecystectomy (40 min)
- Left laparoscopic salpingo-oophorectomy (1h15)
- Anal sphincteroplasty (1h20)
- Laparoscopy for endometriosis (2h10)
- Transurethral resection of the prostate (1h40)
- Hemorrhoids (40 min)
- Ileostomy closure (1h30)
- Orthopedic plate change (2h20)



Data collection: protocol

MNS: Median Nerve Stimulation

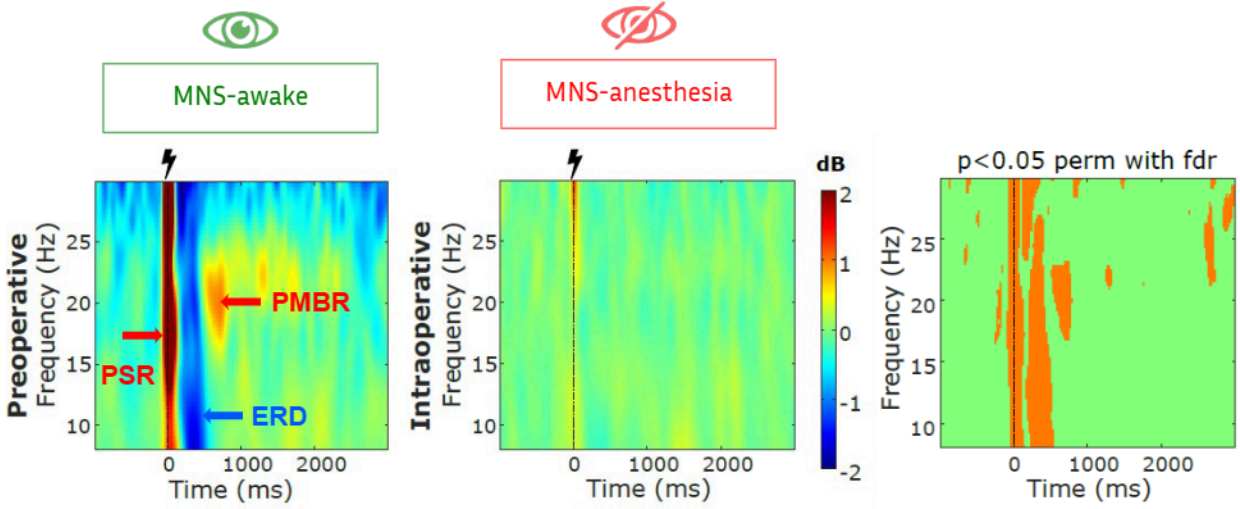


- 1 run = 150 stimulations spaced by 3 to 4 seconds
- the duration and number of runs depended on the length of the surgery

Can we differentiate awake vs anesthetized states?

Impact of GA on the MNS patterns

PSR: Post-Stimulation Rebound
ERD: Event Related Desynchronization
PMBR: Post-Movement Beta Rebound



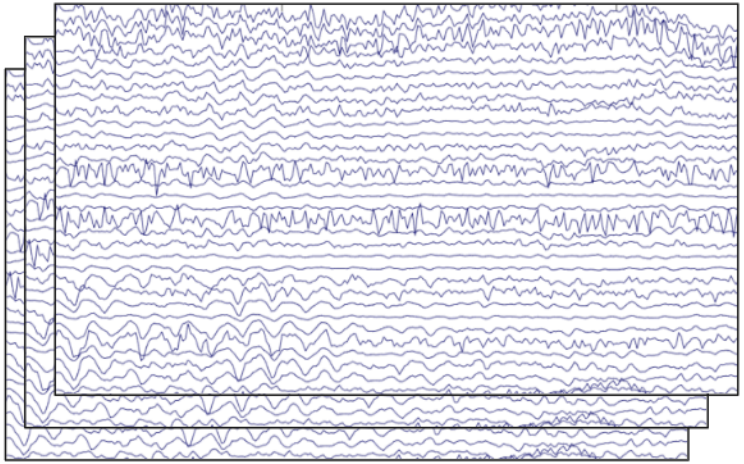
Grand average time frequency analysis across 8 subjects for electrode C4

MNS sensorimotor modulations [21, 22] are strongly **influenced by general anesthesia**: PSR, ERD and PMBR disappear

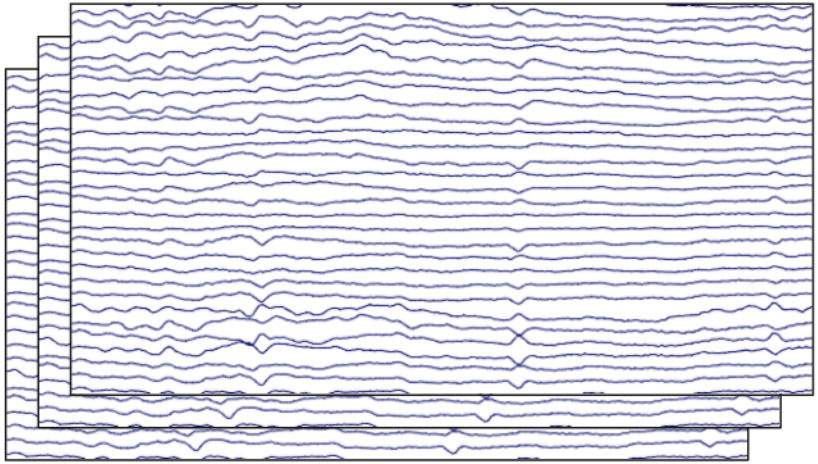
[21] **Rimbert** et al. 2th IEEE Intern. Winter Conf. on BCI, 2024.
[22] **Marissens Cueva** et al. J. Neural Eng, *in submission*, 2024.

Riemannian Minimum Distance to the Mean (MDM)

MNS-awake



MNS-anesthesia



[23] Congedo et al. 8th Inter. BCI Conf. 2019.
[24] Barachant et al. IEEE Trans. Biomed. Eng. 2012.

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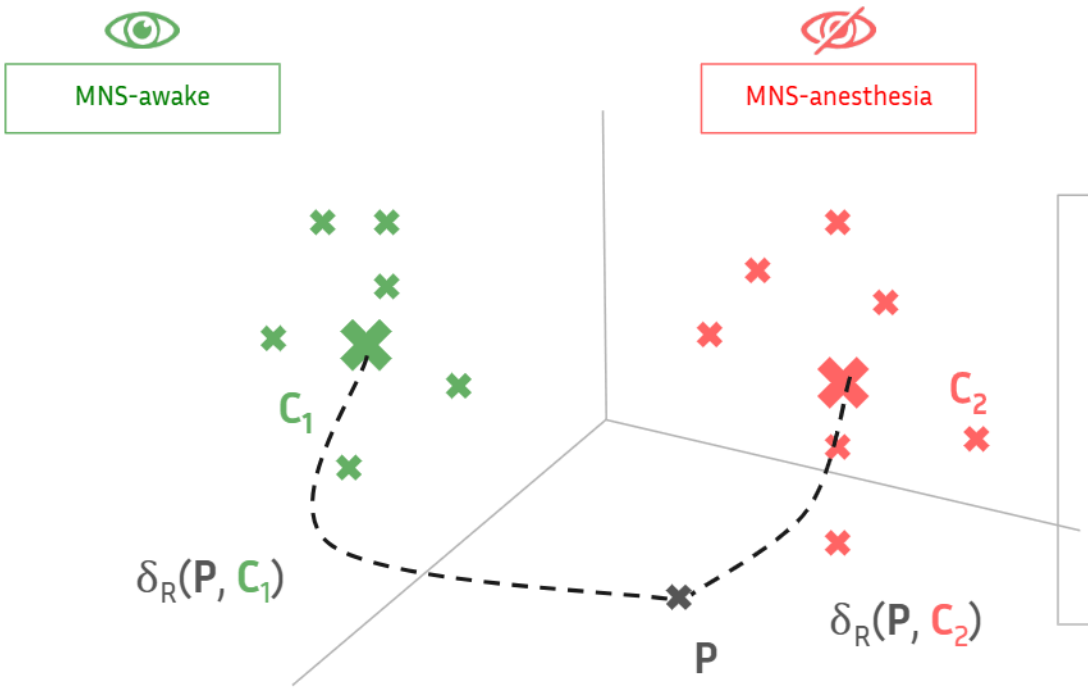

New covariance matrix **P** of class $\hat{k}$:

$$\hat{k} = \text{argmin}_i(\delta_R(\mathbf{P}, \mathbf{P}_i))$$

with δ_R the Riemannian distance:

$$\delta_R(\mathbf{P}, \mathbf{P}_i) = ||\log(\mathbf{P}^{-½}\,\mathbf{P}_i\,\mathbf{P}^{-½})||_F$$

[23] Congedo et al. 8th Inter. BCI Conf. 2019.
[24] Barachant et al. IEEE Trans. Biomed. Eng. 2012.

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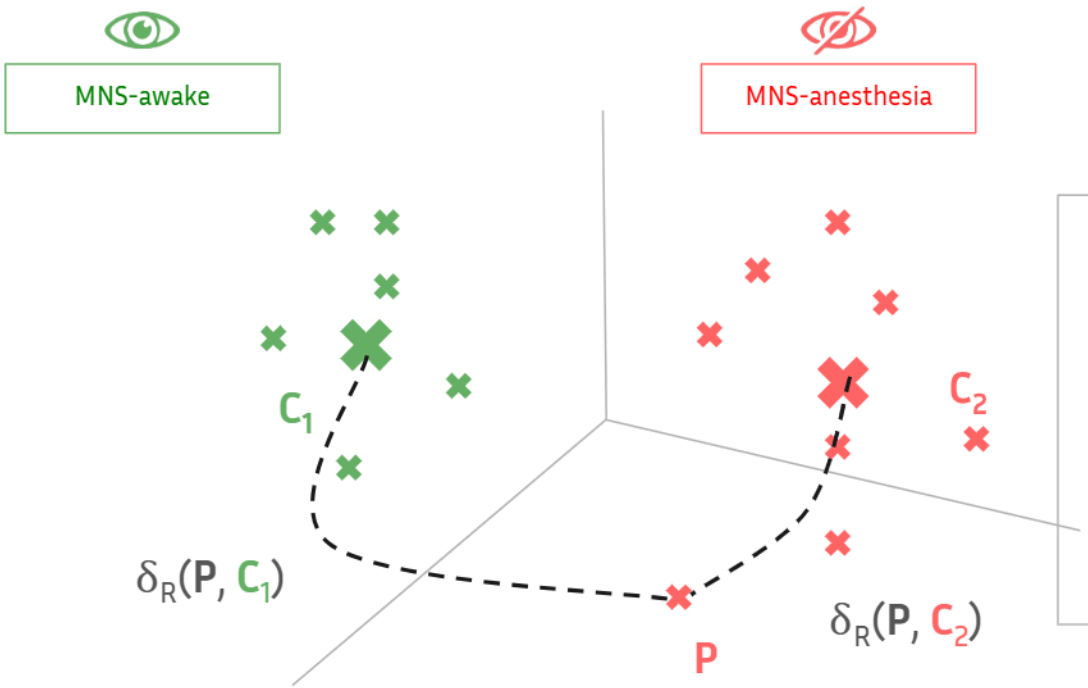

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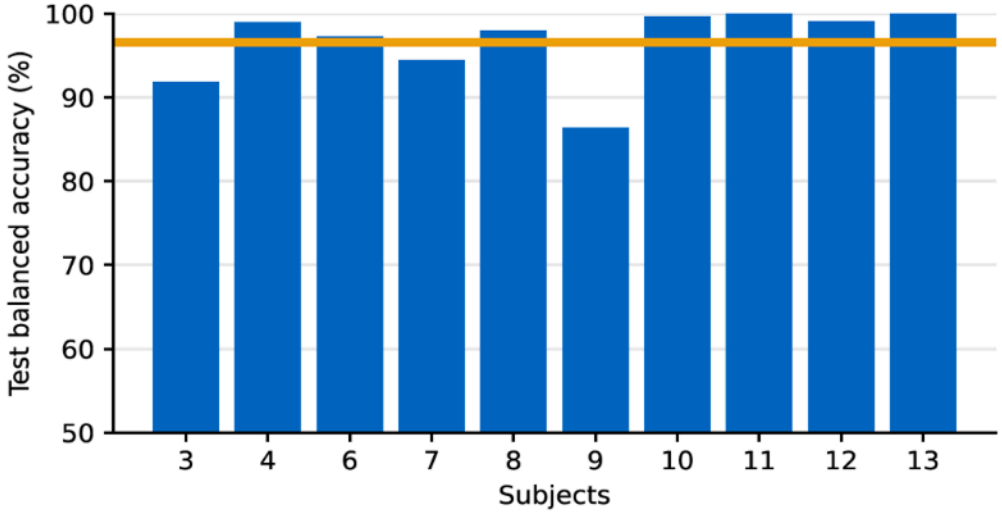
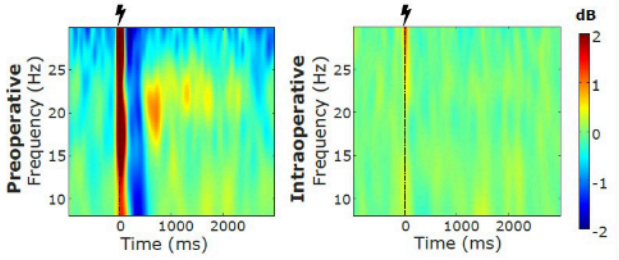
[24] Barachant et al. IEEE Trans. Biomed. Eng. 2012.

Offline classification: MNS-awake vs MNS-anesthesia



97%

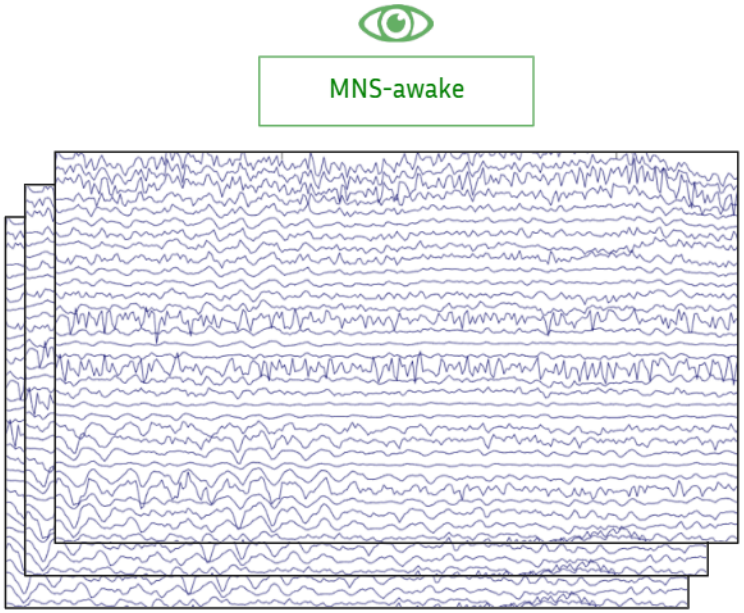


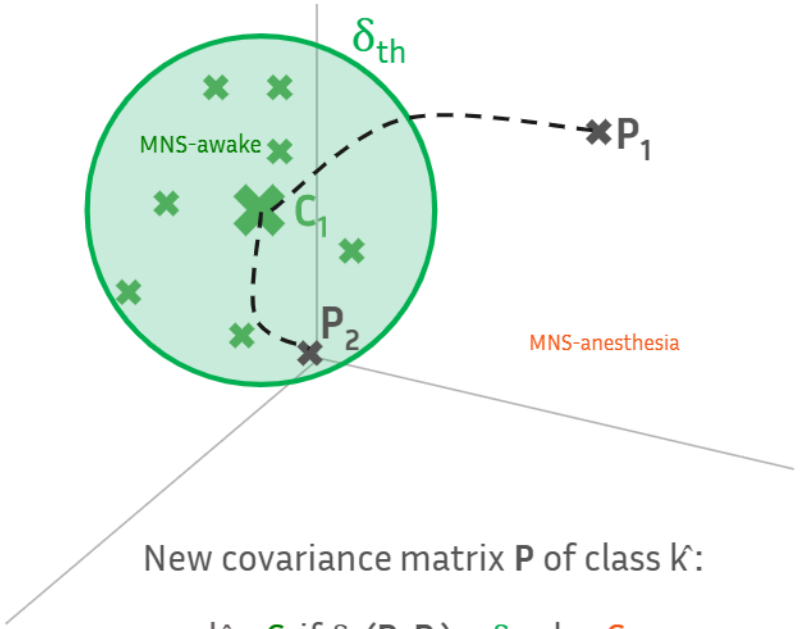
Test set balanced accuracy of a **Riemannian Minimum Distance to the Mean** [23, 24] (10 subjects). The orange line indicates the average test set balanced accuracy (97%).

Problem: Classifier trained with deep anesthesia trials, which are not available before the surgery to calibrate the BCI

[23] Congedo et al. 8th Inter. BCI Conf. 2019.
[24] Barachant et al. IEEE Trans. Biomed. Eng. 2012.

One-Class Riemannian Minimum Distance to the Mean (MDM)





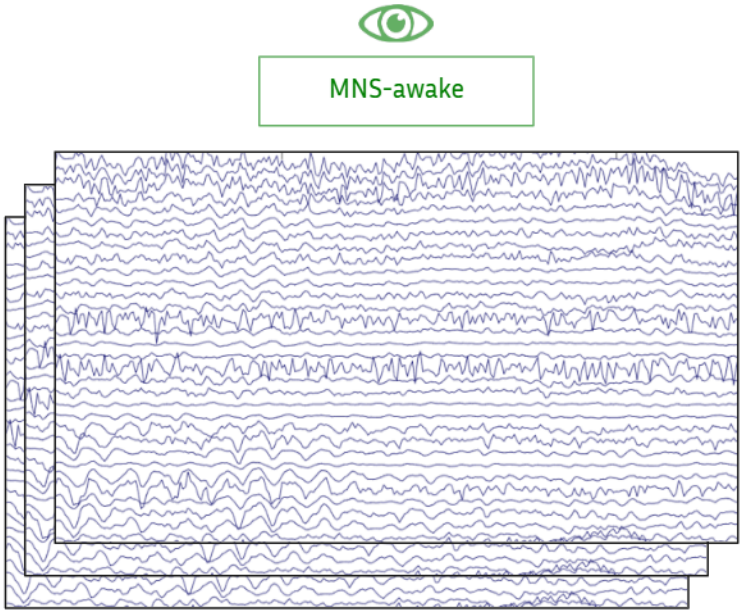
New covariance matrix **P** of class $\hat{k}$:

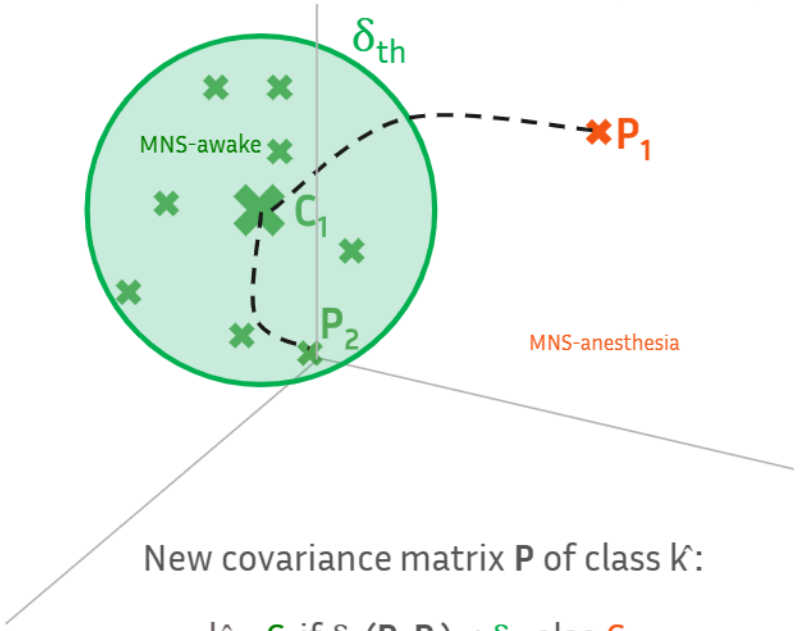
$\hat{k} = C_1$ if $\delta_R(\mathbf{P}, \mathbf{P}_i) \leq \delta_{th}$ else C_2

with δ_R the Riemannian distance:

$\delta_R(\mathbf{P}, \mathbf{P}_i) = ||\log(\mathbf{P}^{-½}\, \mathbf{P}_i\, \mathbf{P}^{-½})||_F$

One-Class Riemannian Minimum Distance to the Mean (MDM)





New covariance matrix **P** of class k:

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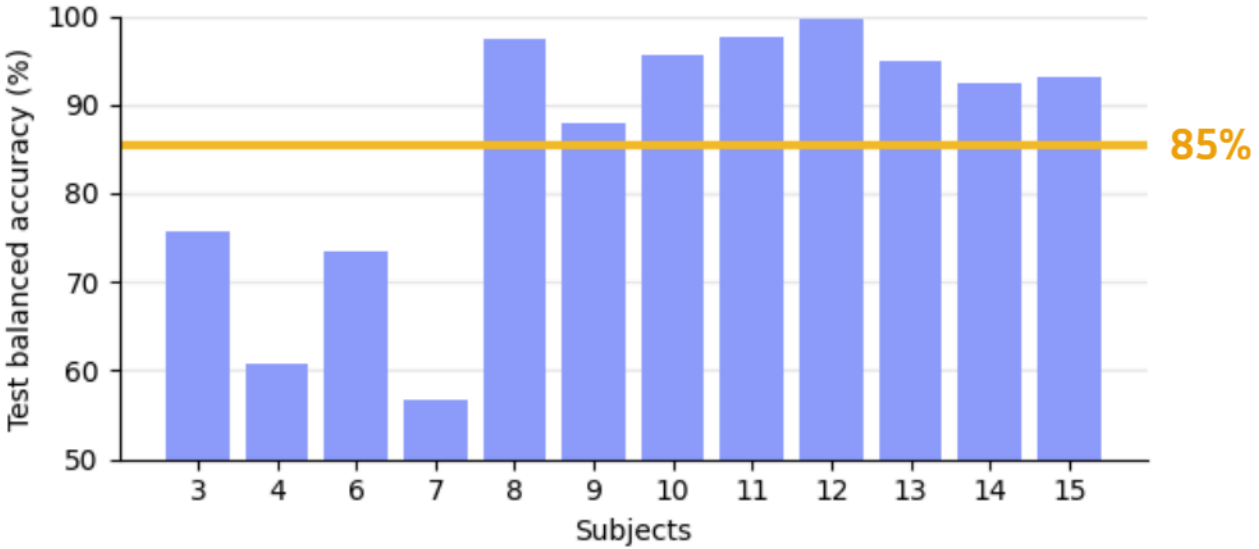
with δ_R the Riemannian distance:

$\delta_R(\mathbf{P}, \mathbf{P}_i) = ||\log(\mathbf{P}^{-½}\, \mathbf{P}_i\, \mathbf{P}^{-½})||_F$

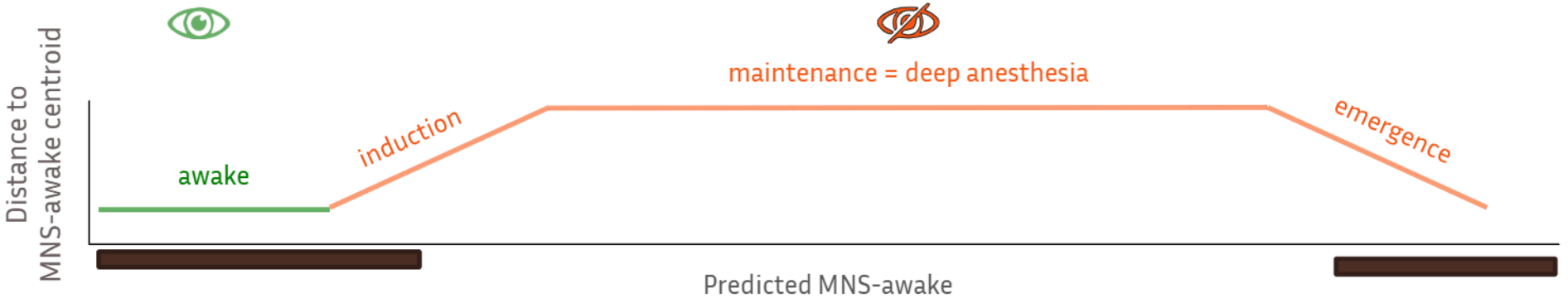
One-Class classification trained on MNS-awake

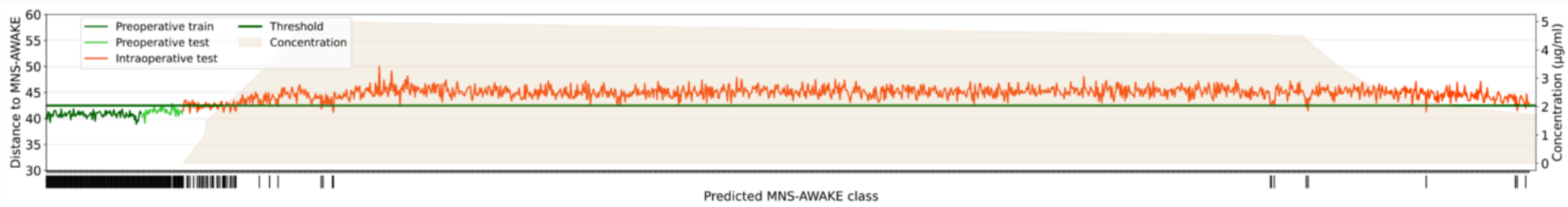


Test set balanced accuracy of a **One-Class Riemannian Minimum Distance to the Mean** [25] (12 subjects). The orange line indicates the average test set balanced accuracy (85%).

[25] Marissens Cueva et al. 5th Inter. Neuroerg. Conf. 2024

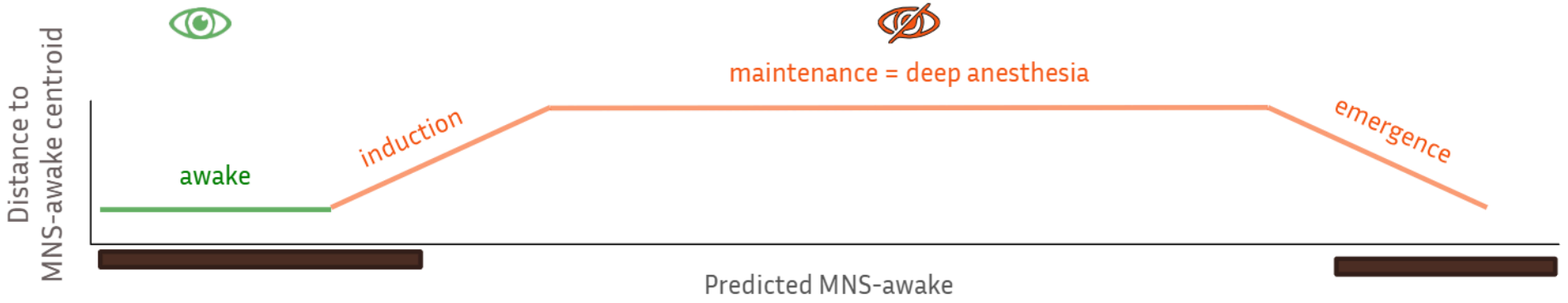
Distance between covariance matrices and MNS-awake class centroid (C$_1$)

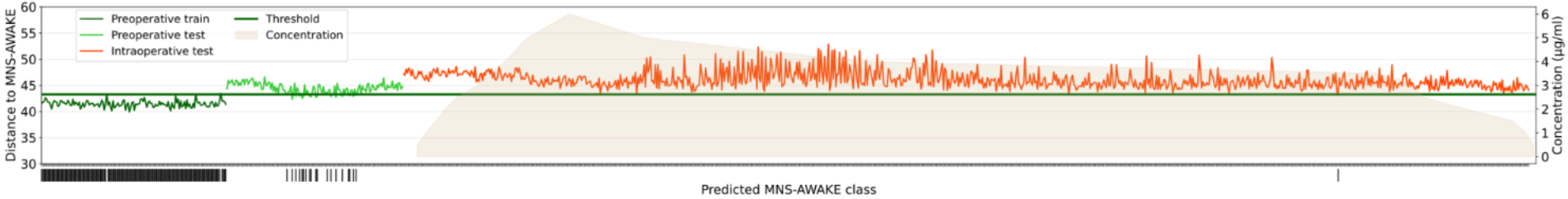




Subject 8 (97.3 %)

Distance between covariance matrices and MNS-awake class centroid (C_1)





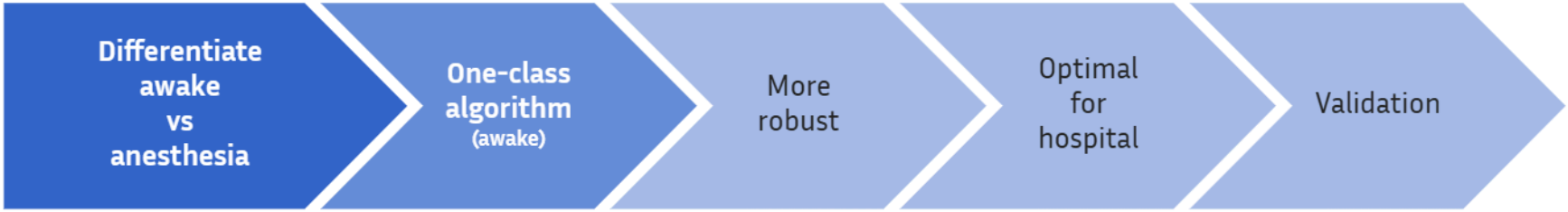
Subject 7 (56.7 %)

Conclusions

- It is indeed possible to use **median nerve stimulation** to detect the recovery of consciousness under general anesthesia

- A One-Class Riemannian Minimum Distance to the Mean algorithm **trained with only the awake data** correctly differentiates between MNS-awake and MNS-anesthesia (test balanced accuracy of **85.44 %**)

Perspectives for a new MNS-based BCI to detect AAGA



Acknowledgments

BCI4IA project
2022-2026

Fabien Lotte
Research Director
Inria Center at the University of Bordeaux

Laurent Bougrain
Associate Professor
Université de Lorraine

Sébastien Rimbert
Inria Starting Faculty Position
Inria Center at the University of Bordeaux

ANR BCI4IA

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BCI4IA project
2022-2026

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Thank you for your attention!

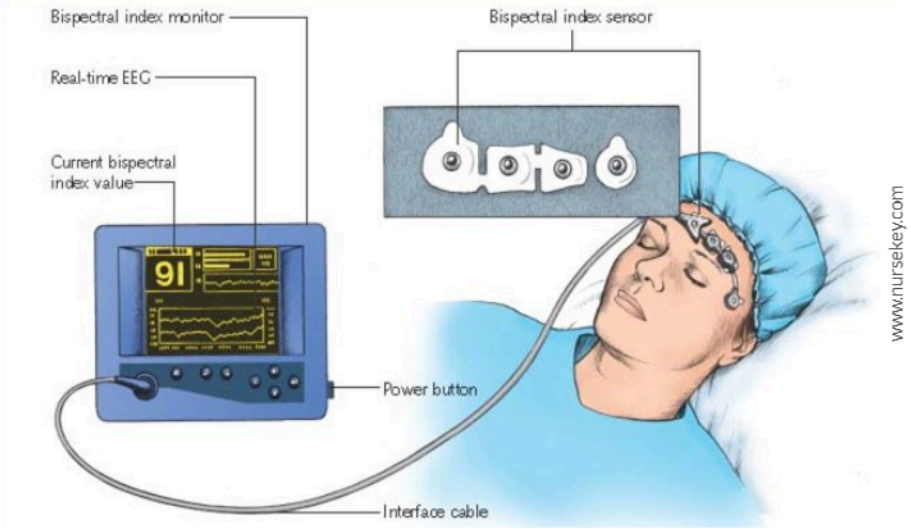
Contact: valerie.marissens@loria.fr

Monitors to prevent AAGA

NeuroSENSE monitor

SedLine monitor

Narcotrend monitor



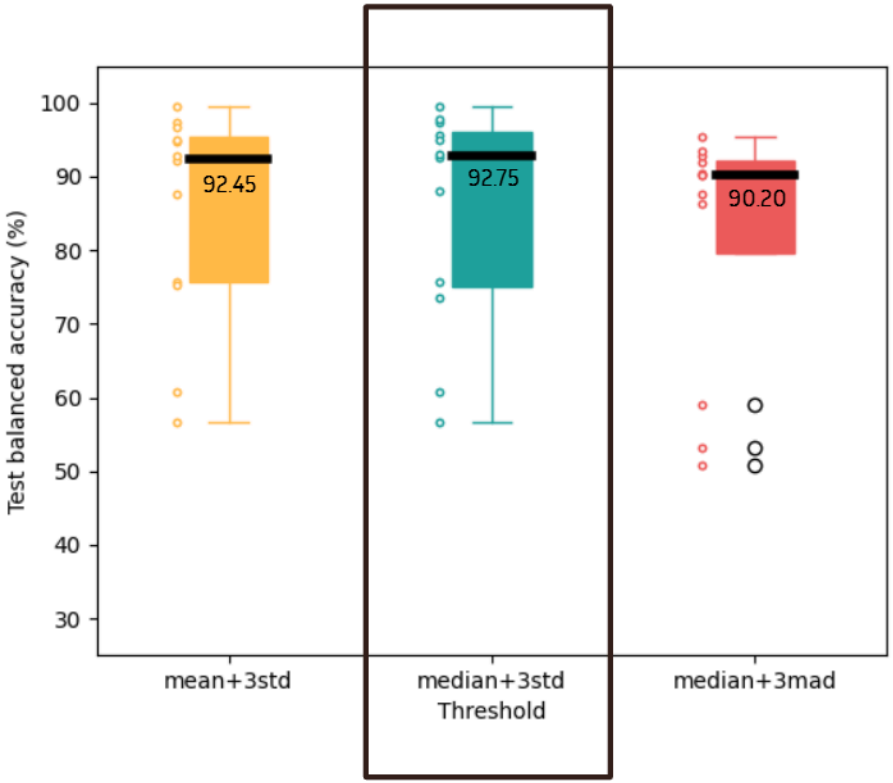
Bispectral Index monitor, Sigl and Chamoun, J Clin Monit, 1994

Threshold selection

Δ : distances between training MNS-awake set covariance matrices and MNS-awake centroid

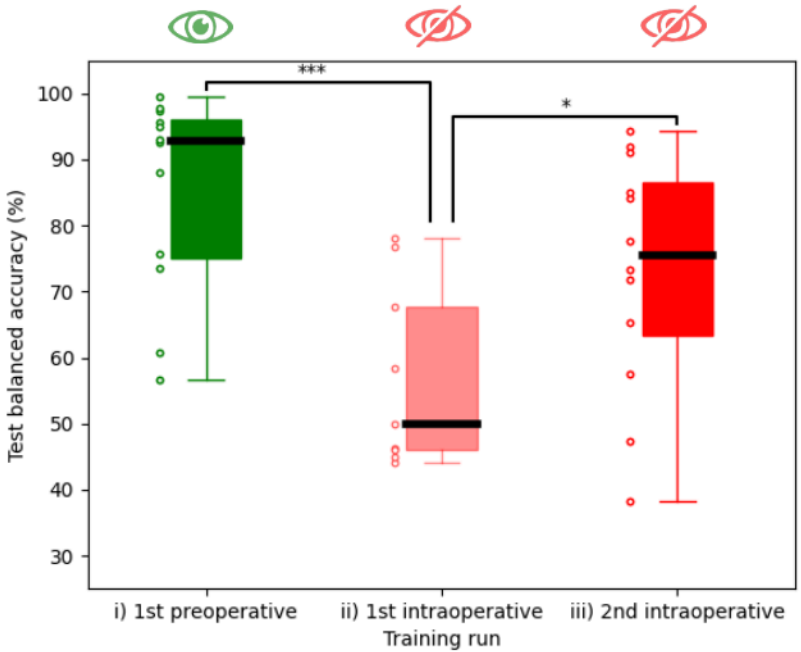
1. $mean_{\Delta} + 3std_{\Delta}$
2. $median_{\Delta} + 3std_{\Delta}$
3. $median_{\Delta} + 3mad_{\Delta}$

with std: standard deviation and mad: median absolute deviation

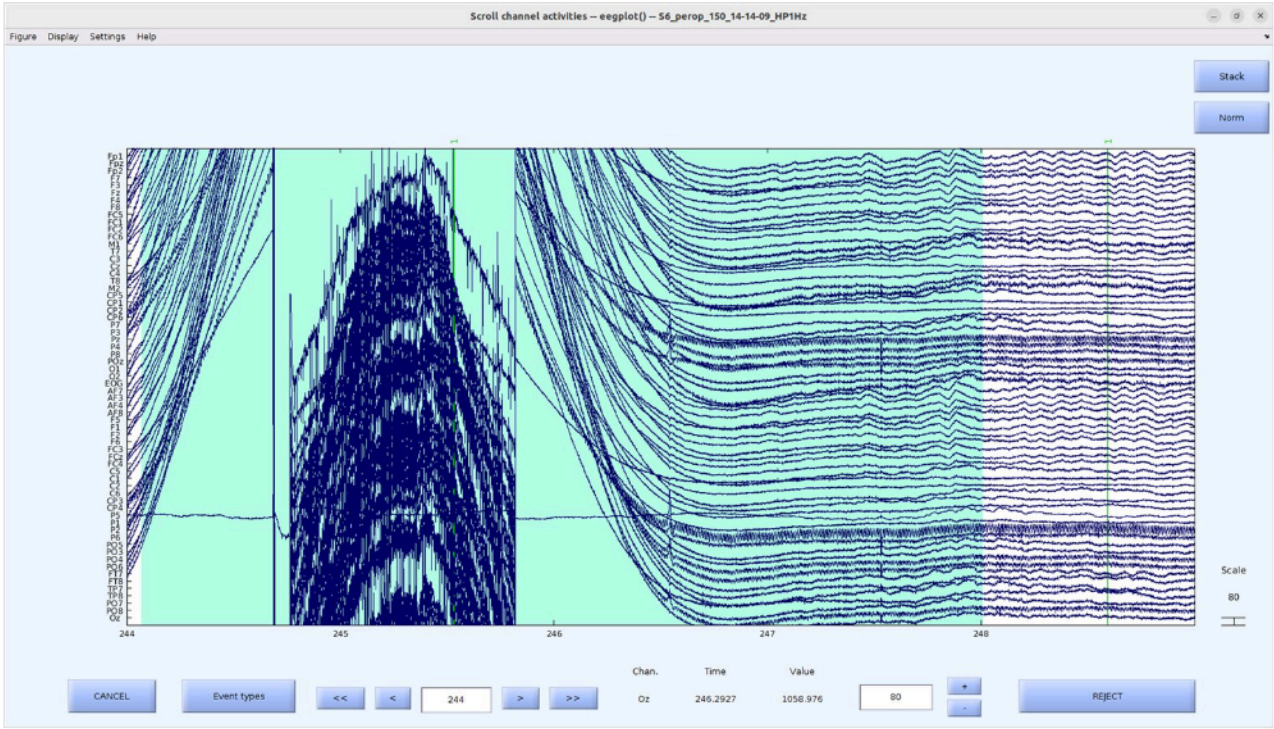


Which training class?

i. 1st preoperative run
ii. 1st intraoperative run
iii. 2nd intraoperative run

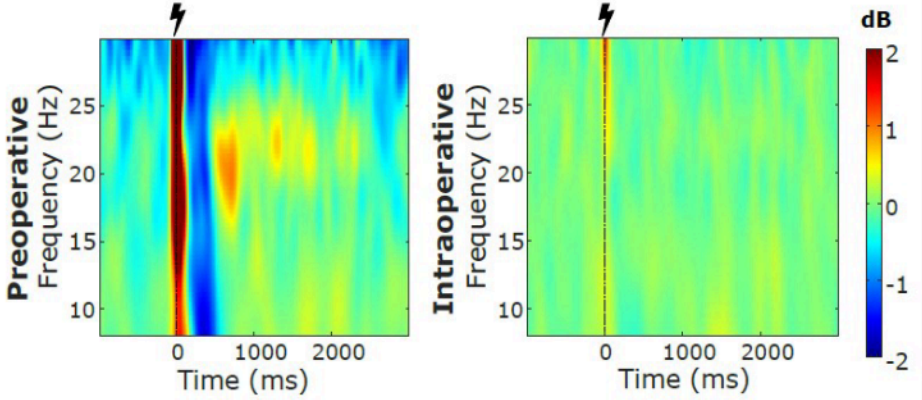


Electrocautery-related EEG artifacts



CCMDM

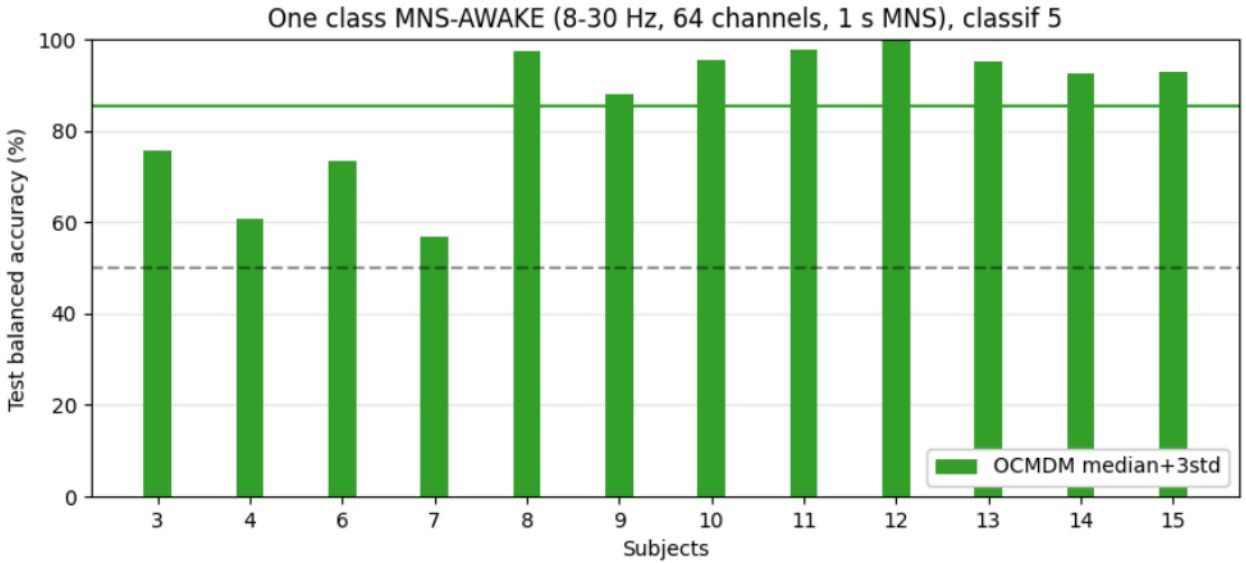
- 250:1000 ms
- mu+beta frequency band
- all 64 electrodes



	condition i	condition ii	condition iii
Train	65:296	108:150	70:199
Test intraop	414:1480	306:1288	267:1366
Test preop	28:150	94:445	94:445

Number of trials used for the 13 subjects (9 for condition ii) (min:max)

Classification results per subject



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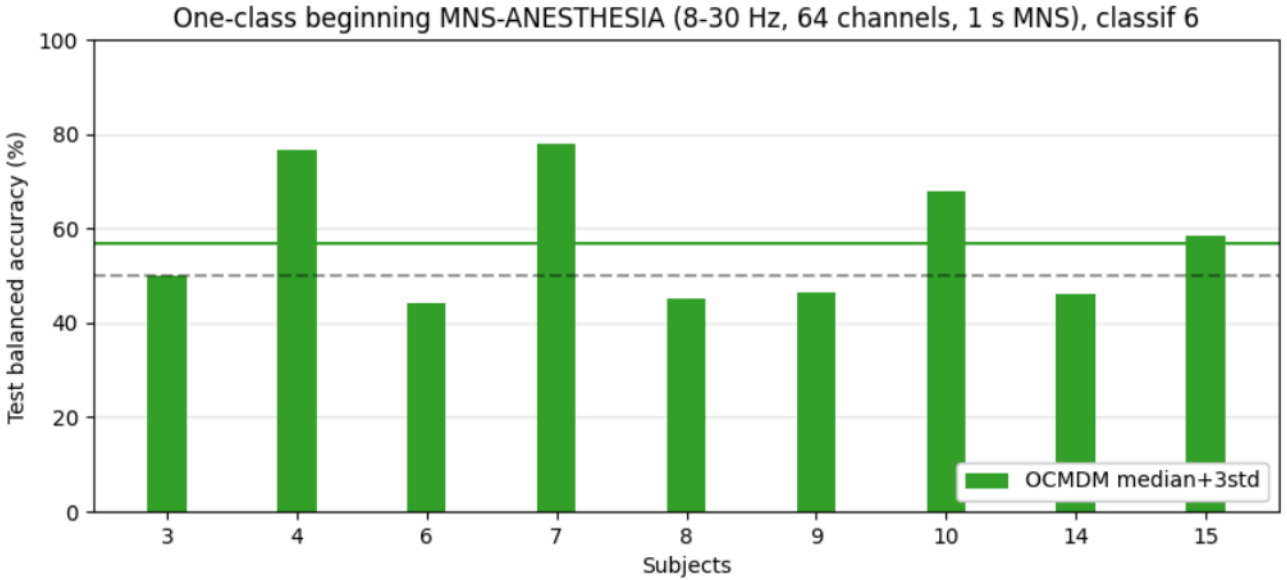

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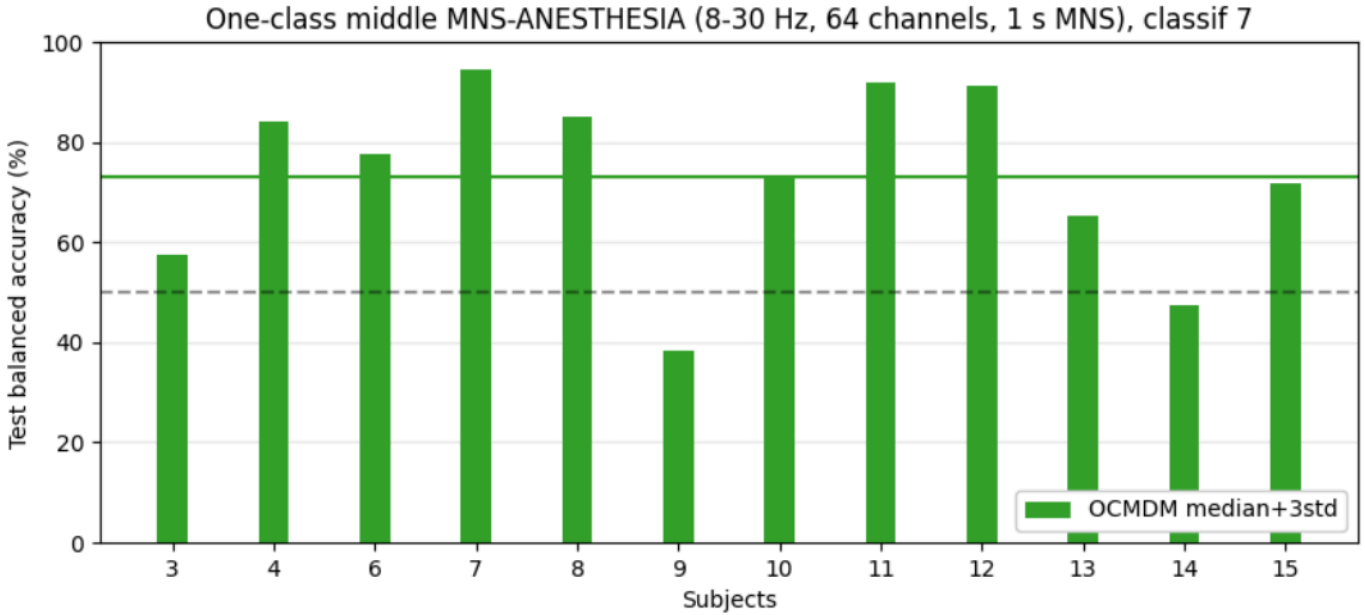
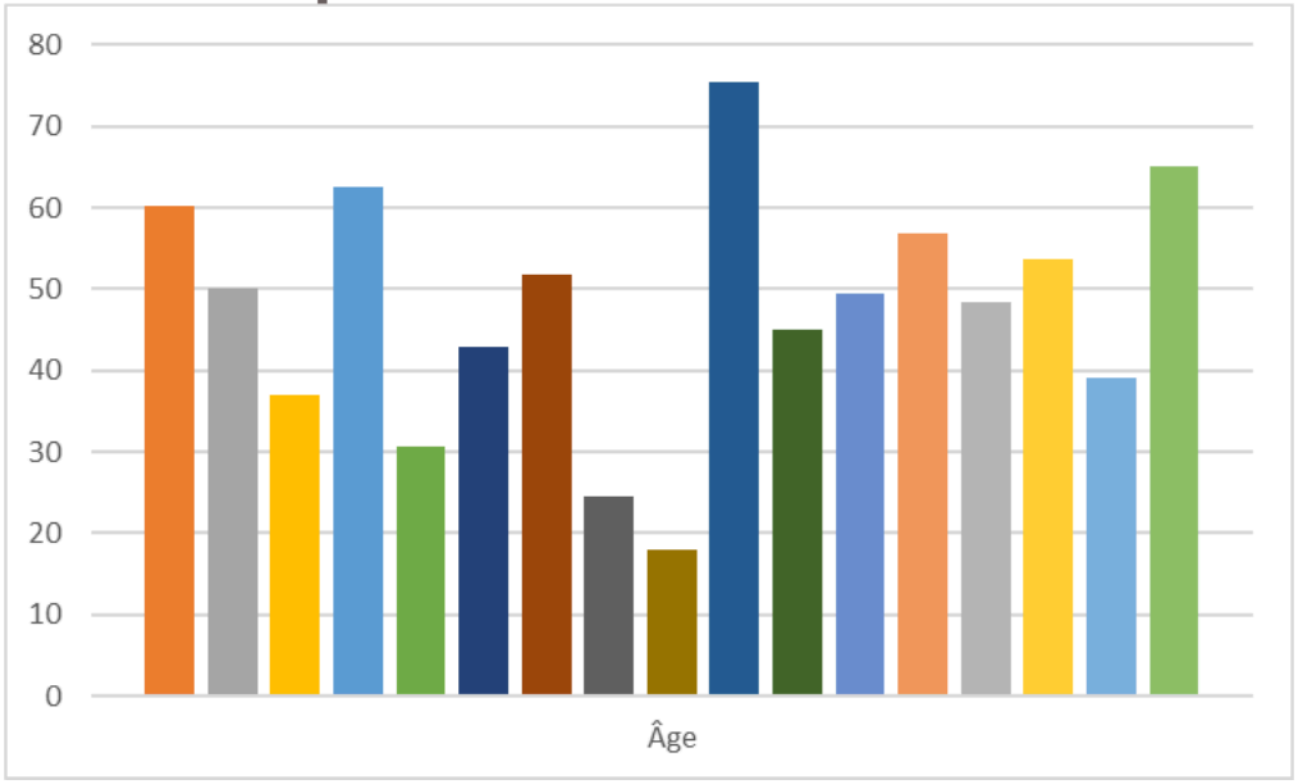


Informations des patients



Offline classification: MNS-awake vs MNS-anesthesia

- Classifier: Riemannian Minimum Distance to the Mean
- 64 electrodes
- Preprocessing :
  - downsampling 128 Hz
  - 8-30 Hz band pass filter
  - epochs : 250 to 1000 ms