One-Class Riemannian EEG Classifier to Detect Anesthesia

Valérie Marissens Cueva

valerie.marissens@loria.fr

Supervisors:
Fabien Lotte, Laurent Bougrain, Sébastien Rimbert

Accidental Awareness during General Anesthesia (AAGA)

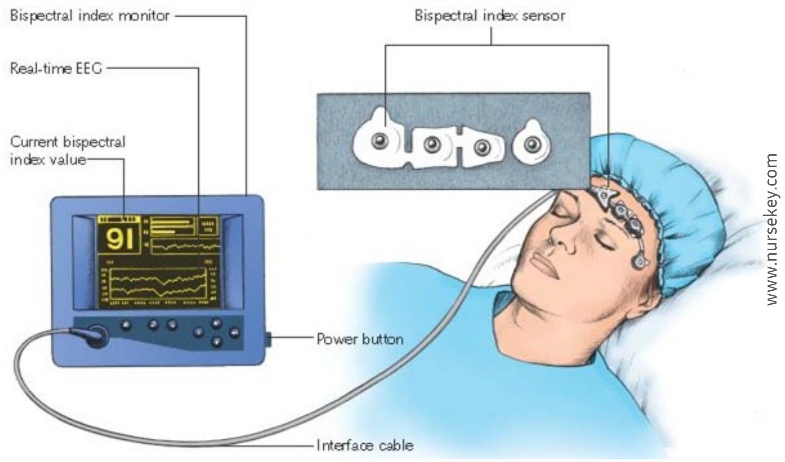
- Unexpected awakening during surgery under general anesthesia [1], which can cause pain and potential psychological sequelae [2].
- During AAGA, patients try to move to alert the anesthetist [3], yet it isn't always possible due to the neuromuscular-blocking agents (NMBAs) which paralyze them.

Heleen Blussé van Oud-Alblas

[1] Pandit et al. British Journal of Anaesthesia, 2014.
[2] Osterman et al. Gen Hosp Psychiatry. 2001.
[3] Sandin et al. The Lancet, 2000.
[4] Bruhn et al. Br. J. Anaesth, 2006.
[5] Myles et al. Lancet, 2004.
[6] Sebel et al. Anesth. Analg. 2004.

Accidental Awareness during General Anesthesia (AAGA)

- Unexpected awakening during surgery under general anesthesia [1], which can cause pain and potential psychological sequelae [2].
- During AAGA, patients try to move to alert the anesthetist [3], yet it isn't always possible due to the neuromuscular-blocking agents (NMBAs) which paralyze them.
- Traditional clinical signs are unreliable indicators of anesthesia depth [4], which leads to the use of brain activity monitors.
- Awareness still occurs with current monitors [5, 6].



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

[1] Pandit et al. British Journal of Anaesthesia, 2014.
[2] Osterman et al. Gen Hosp Psychiatry. 2001.
[3] Sandin et al. The Lancet, 2000.
[4] Bruhn et al. Br. J. Anaesth, 2006.
[5] Myles et al. Lancet, 2004.
[6] Sebel et al. Anesth. Analg. 2004.

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 [7]

feasible with current BCIs, although the MI vs rest classification remains low [8] for a reliable device to be used in a hospital

[7] Rimbert et al. Front. Neurosci, 2019.
[8] 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.

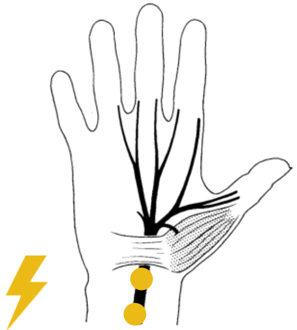


Illustration of the regular branching of the median nerve [9]

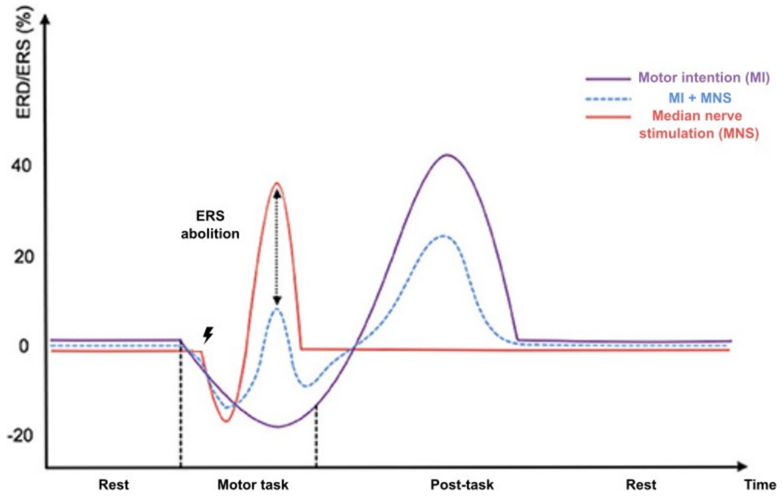


Illustration of ERD/ERS induced by MI, MNS and MNS during MI, in the alpha and beta frequency bands [7].

[7] Rimbert et al. Front. Neurosci, 2019.
[9] 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 [7].

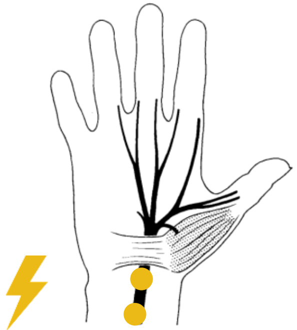
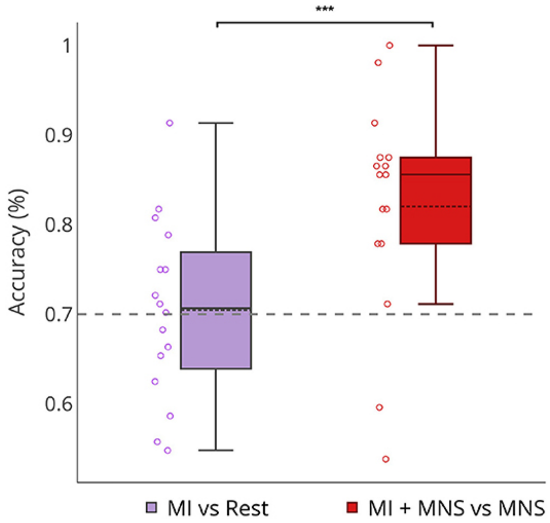


Illustration of the regular branching of the median nerve [9]



Distribution of average classification accuracies (n = 16), obtained by a TS+LR classifier
***p-value < 0.001 [7].

[7] Rimbert et al. Front. Neurosci, 2019.
[9] 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 [7].
- Provides a trigger.

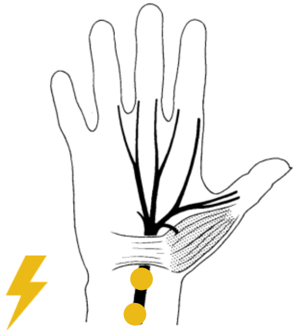
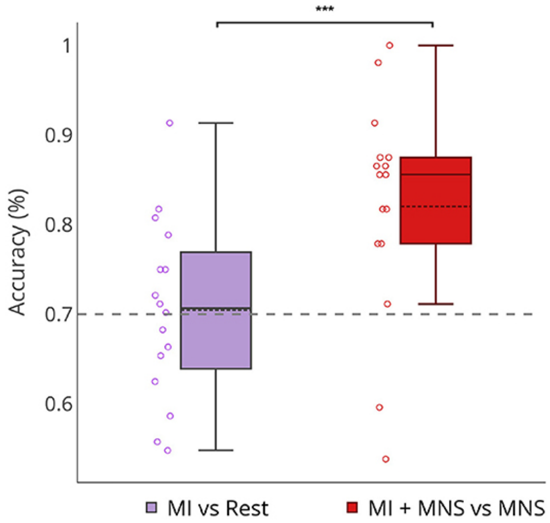


Illustration of the regular branching of the median nerve [9]



Distribution of average classification accuracies (n = 16), obtained by a TS+LR classifier
***p-value < 0.001 [7].

[7] Rimbert et al. Front. Neurosci, 2019.
[9] Lanz, J. of Hand Surgery, 1977.

Problematic

- The MNS pattern is still visible under light sedation (≤1 µg/ml) [10, 11].
- We are still able to detect it at deeper concentrations of anesthesia [12].

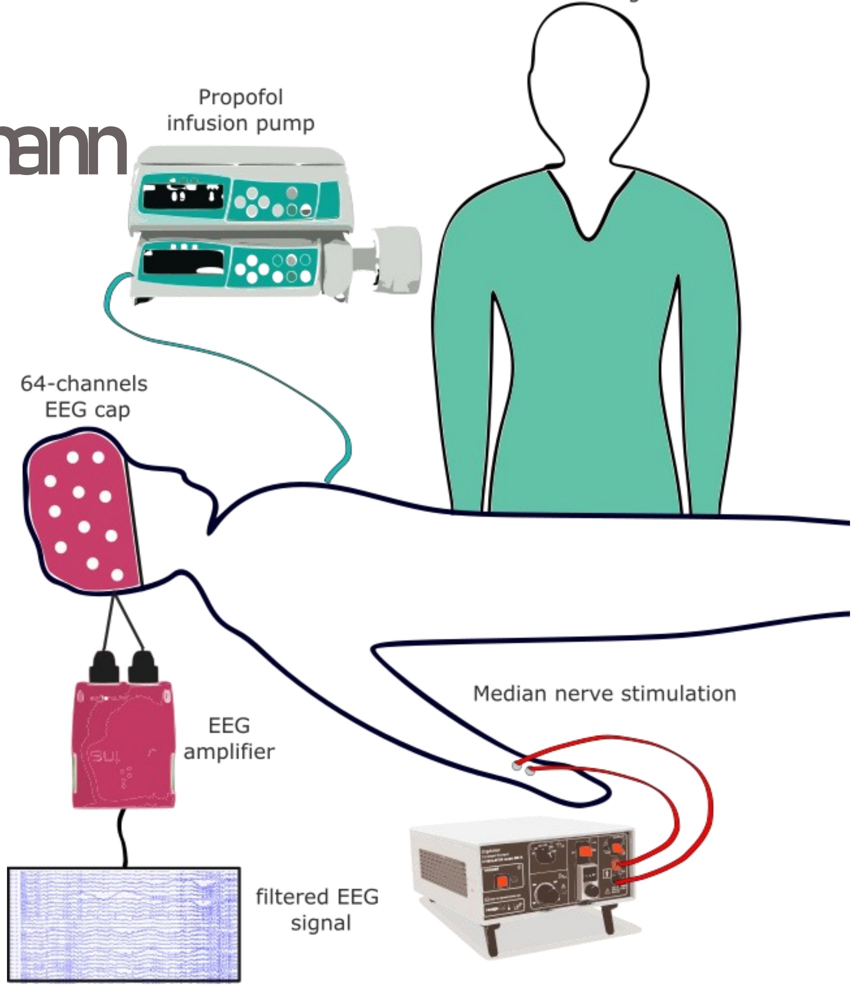
Is it possible to use median nerve stimulation to differentiate states of consciousness under general anesthesia?

General anesthesia ≥4 µg/ml [13]

[10] Guerci et al, SFAR, 2021.
[11] Rimbert at al, IEEE SMC, 2019.
[12] Rimbert et al, ASA Annual Meeting, 2023.
[13] Anderson et al, Anesthesiology, 2019.

Clinical protocol at CHU Brugmann

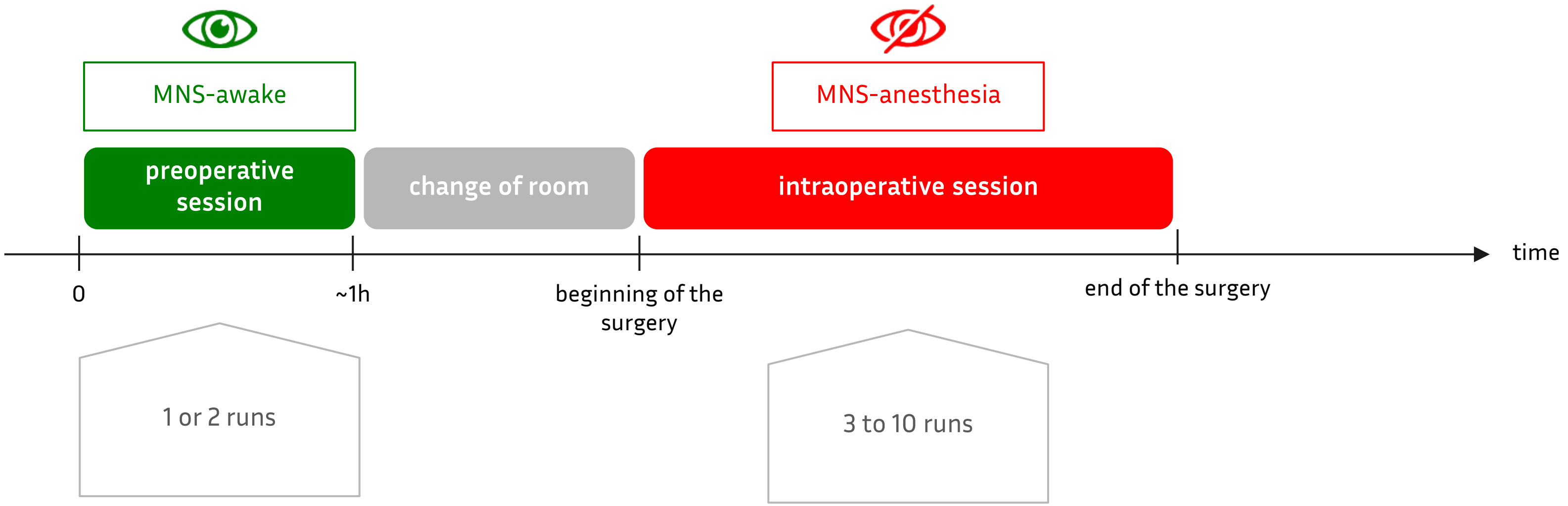
12 patients: 6 females; 50 ± 14.3 years old



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

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

MNS-awake vs MNS-anesthesia

Time-frequency differences

Classification using both classes to train the model

One-class classification

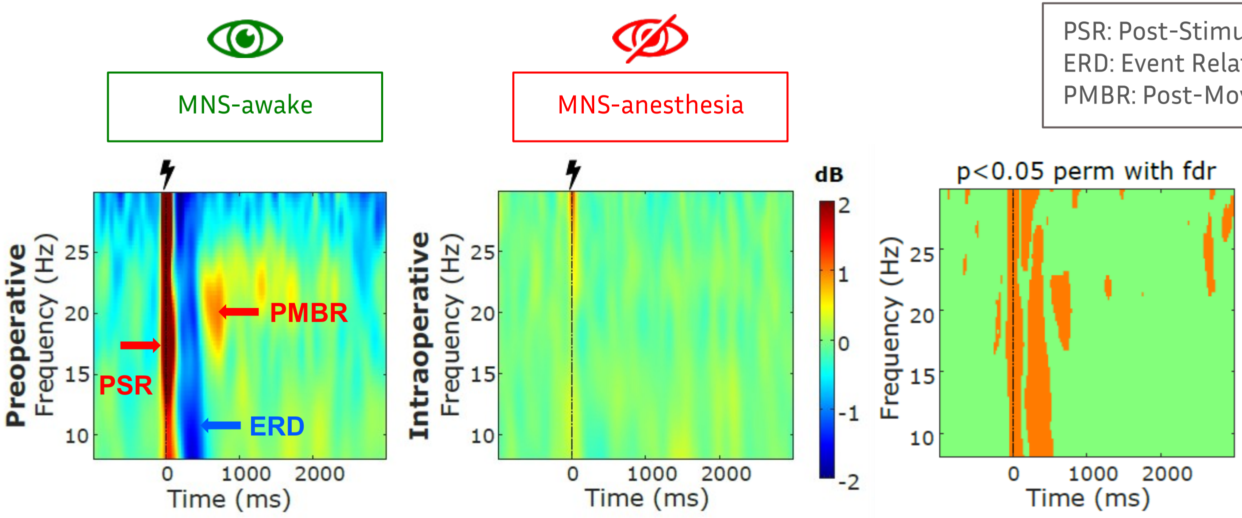
Threshold

Training set

Classifier's evolution throughout the surgery

Impact of GA on the patterns induced by MNS

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 [13] are strongly influenced by general anesthesia: PSR, ERD and PMBR disappear

[15] Rimbert et al. 2th IEEE Intern. Winter Conf. on BCI, 2024.

MNS-awake vs MNS-anesthesia

Time-frequency differences

Classification using both classes to train the model

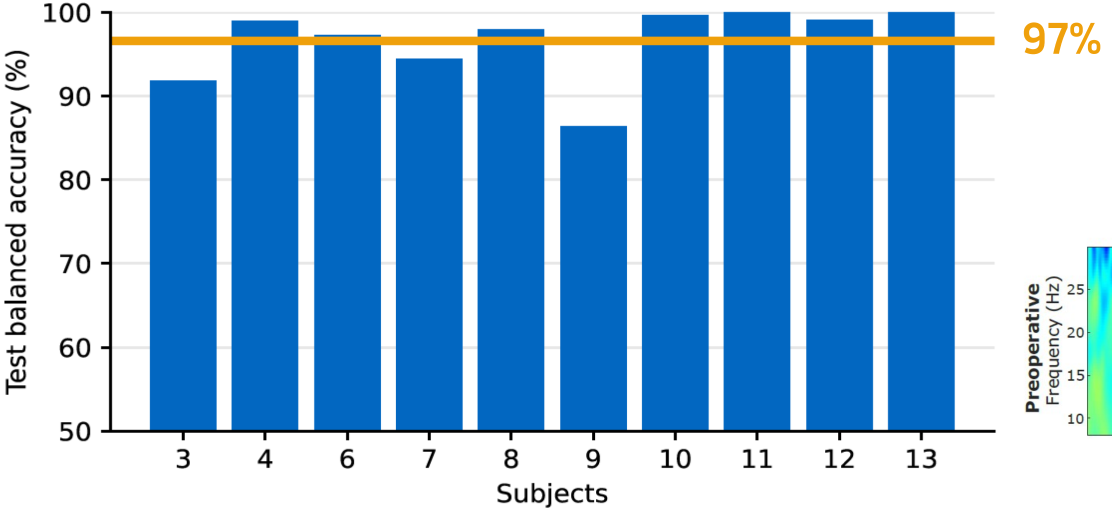
One-class classification

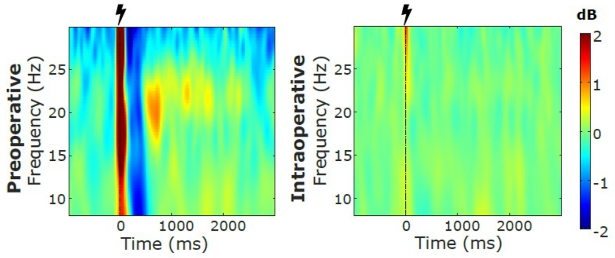
Threshold

Training set

Classifier's evolution throughout the surgery

Offline classification: MNS-awake vs MNS-anesthesia





Test set balanced accuracy of a Riemannian Minimum Distance to the Mean [16, 17] (10 subjects). The yellow line indicates the average test set balanced accuracy (97%).

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

MNS-awake vs MNS-anesthesia

Time-frequency differences

Classification using both classes to train the model

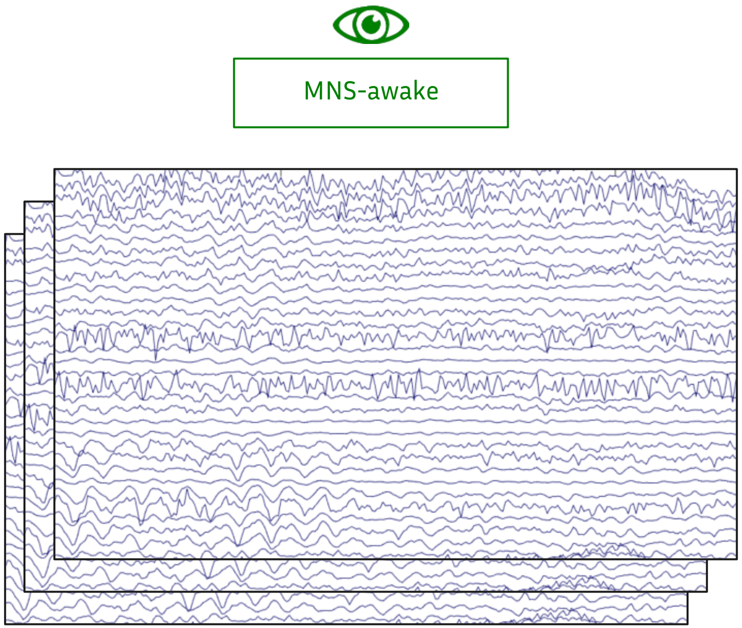
One-class classification

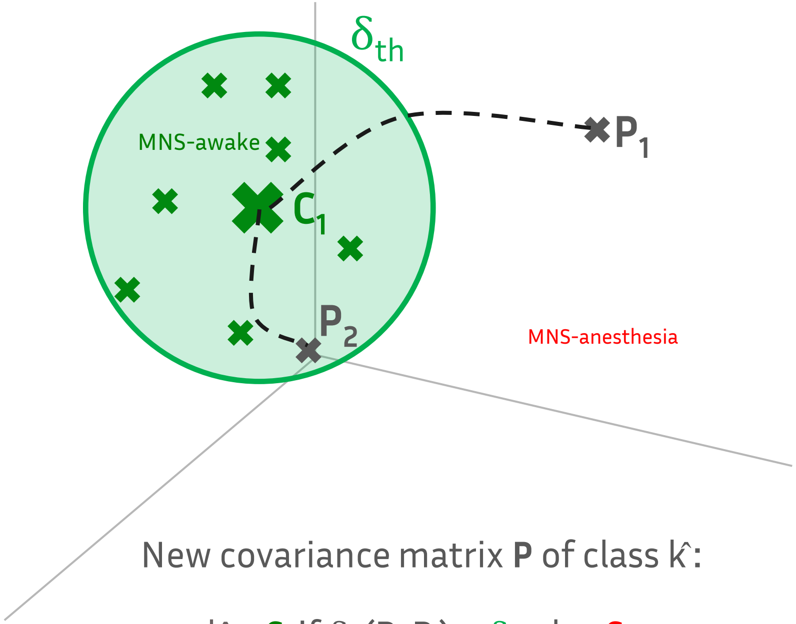
Threshold

Training set

Classifier's evolution throughout the surgery

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

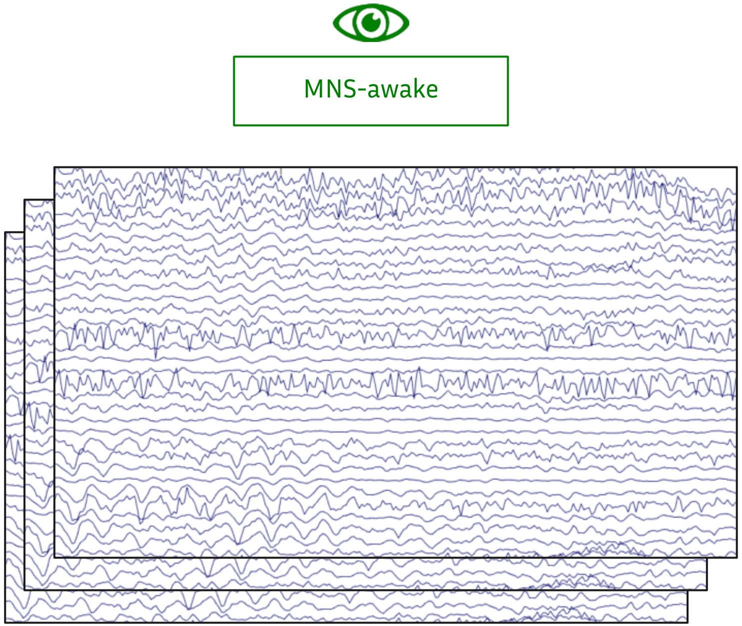


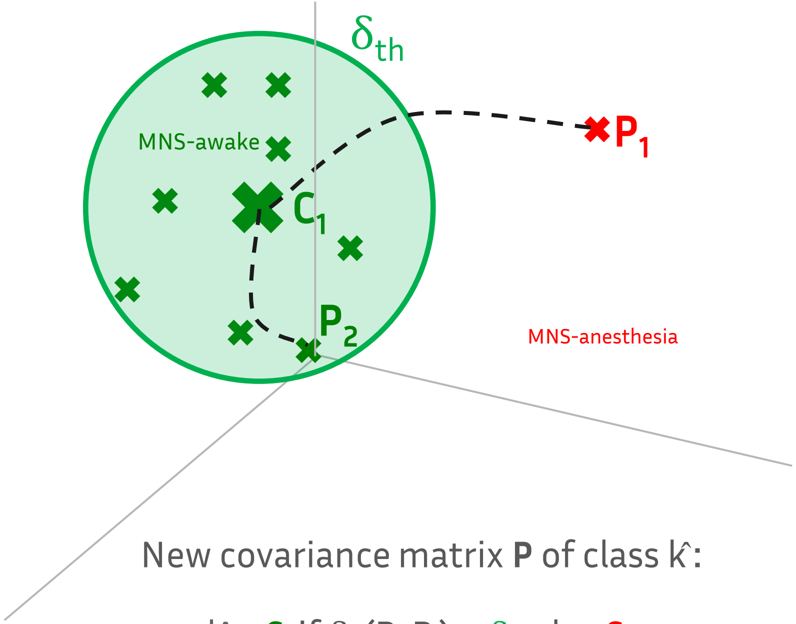


New covariance matrix **P** of class $\hat{k}$:

$\hat{k} = C_1$ if $\delta_R(\mathbf{P}, \mathbf{P}_i) \leq \delta_{th}$ else C_2
with δ_R the Riemannian distance:
$\delta_R(\mathbf{P}, \mathbf{P}_i) = ||\log(\mathbf{P}^{-1/2}\, \mathbf{P}_i\, \mathbf{P}^{-1/2})||_F$

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

MNS-awake vs MNS-anesthesia

Time-frequency differences

Classification using both classes to train the model

One-class classification

Threshold

Training set

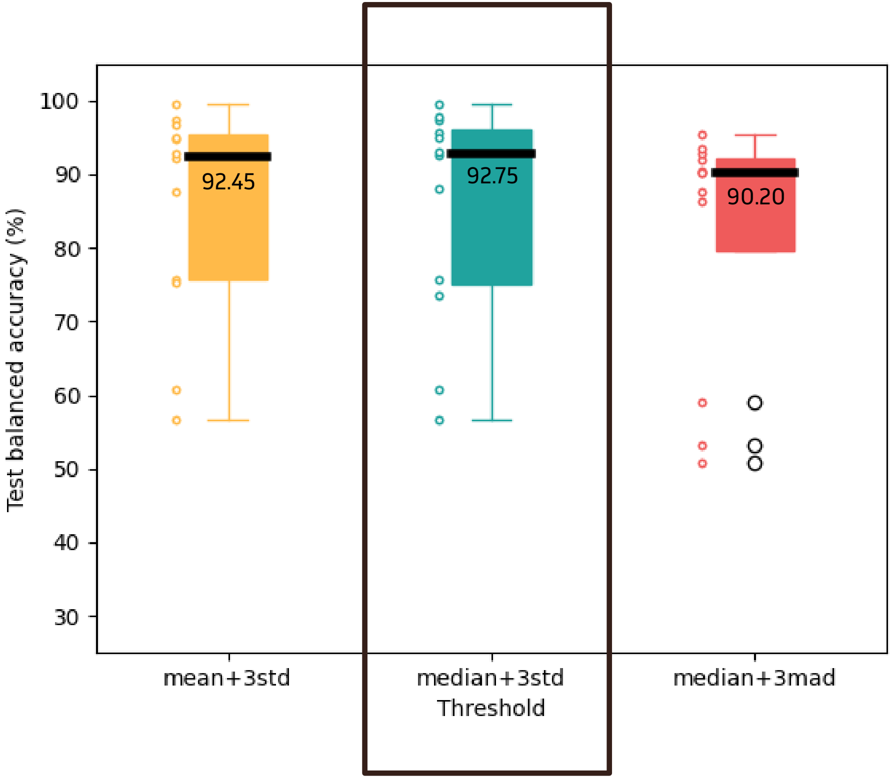
Classifier's evolution throughout the surgery

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



MNS-awake vs MNS-anesthesia

Time-frequency differences

Classification using both classes to train the model

One-class classification

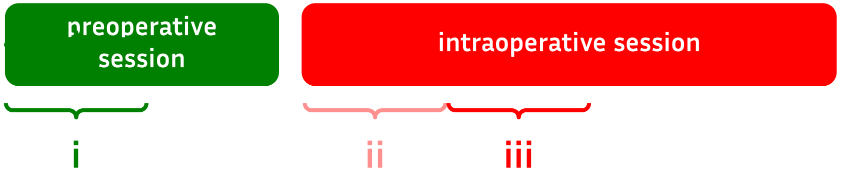
Threshold

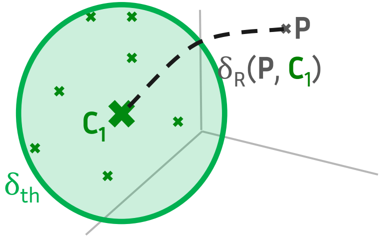
Training set

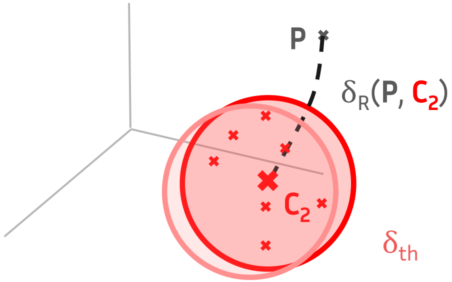
Classifier's evolution throughout the surgery

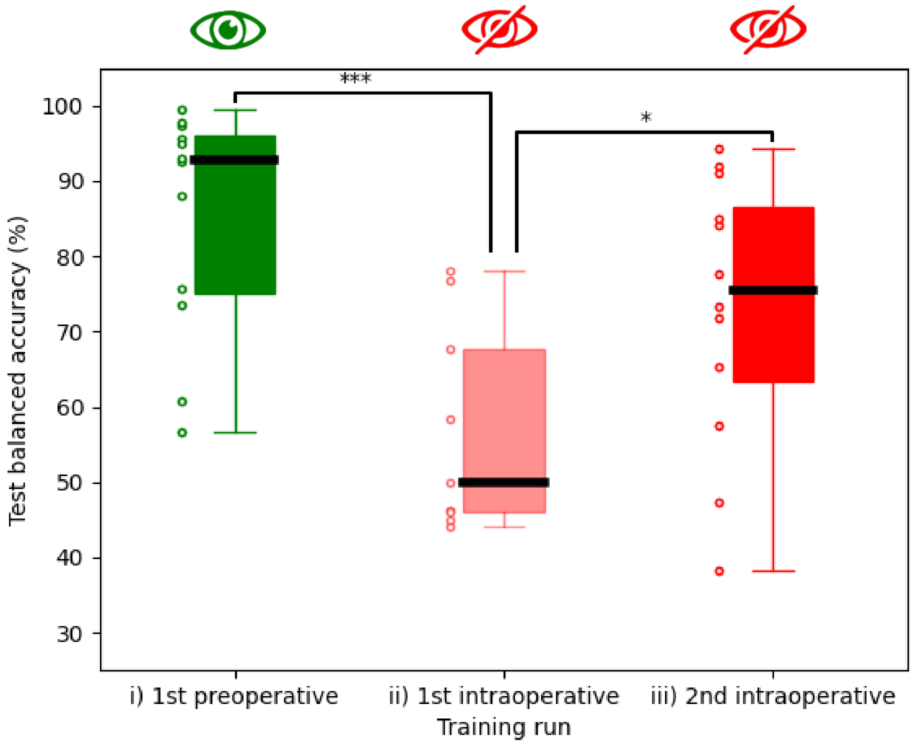
Training set selection

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









MNS-awake vs MNS-anesthesia

Time-frequency differences

Classification using both classes to train the model

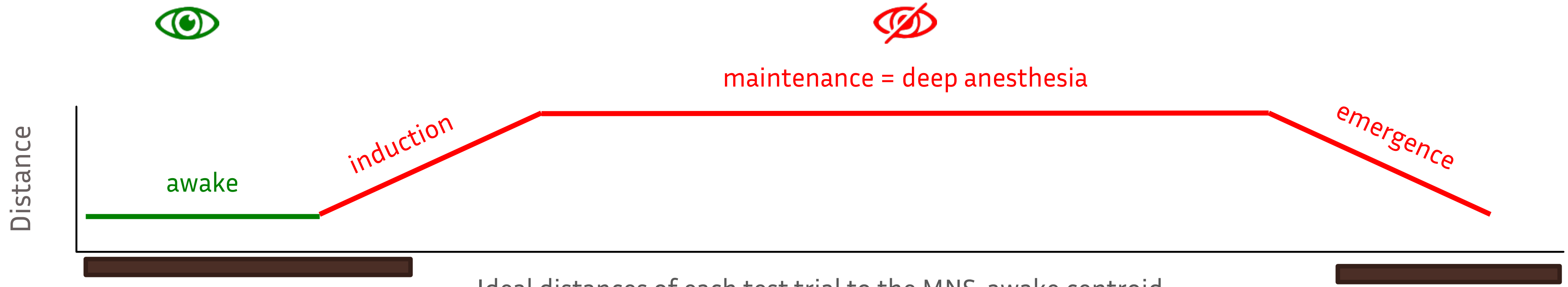
One-class classification

Threshold

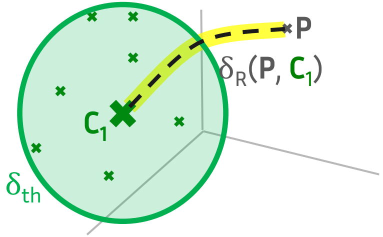
Training set

Classifier's evolution throughout the surgery

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



Ideal distances of each test trial to the MNS-awake centroid

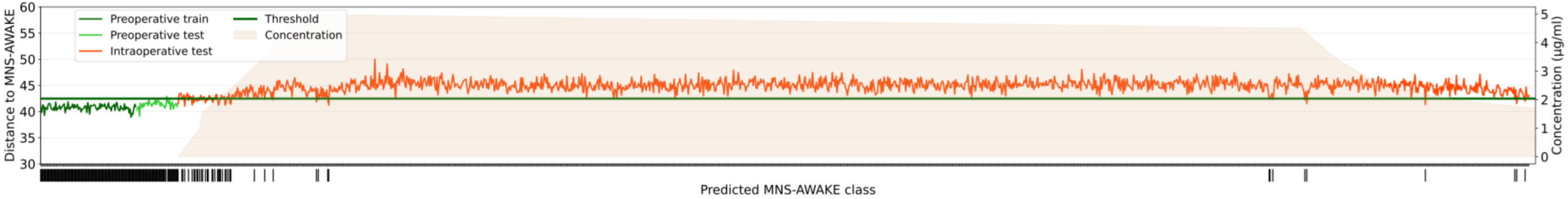


Distance between covariance matrices and the learned centroid: example of subject 8

Calibration:

i) Awake

97%



ii) Induction

45%

ii) Beginning deep anesthesia

85%

Detect Awake and Anesthetized states using the MNS pattern of only one class? If so, which class?

STRENGTHS

Calibrations i and iii:

- Correctly identify the periods when the patient is awake
- Covariance matrices associated to the MNS pattern **evolve consistently with the patient's level of awareness**
- Calibration iii will not be possible in a real-world application, as **deep anesthesia trials will not be available** to calibrate the BCI
  → Train with **preoperative run (i)**

WEAKNESS

Calibration ii:

- Although the 1st intraoperative run would have been advantageous in a real-life setting for quicker calibration, the **centroid is less accurate and the accuracy plummets**

PERSPECTIVES

- Which **one-class algorithm** can better define the MNS-awake class? Which **EEG characteristics**?
- Detect awareness during anesthesia?

Acknowledgments

anr
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

Collaborators:

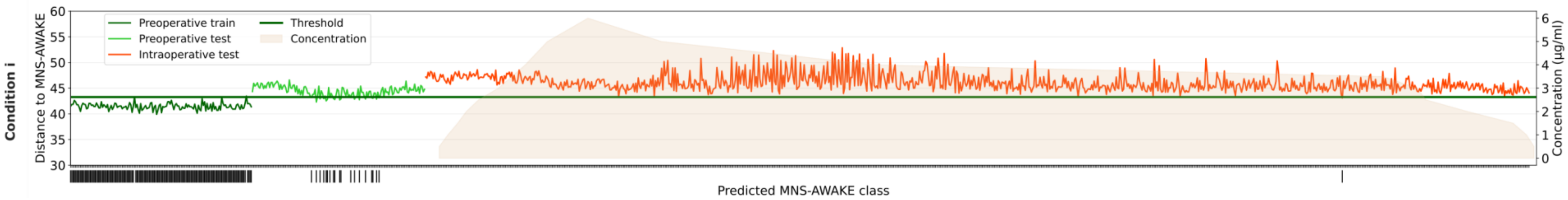
- Ana Maria Cebolla Alvarez
- Mathieu Petieau
- Viktoriya Vitkova
- Iraj Hashemi
- Guy Cheron
- Claude Meistelman
- Denis Schmartz
- Philippe Guerci
- Seyed Javad Bidgoli

BCI4IA project
2022-2026

Thank you for your attention!

Contact: valerie.marissens@loria.fr

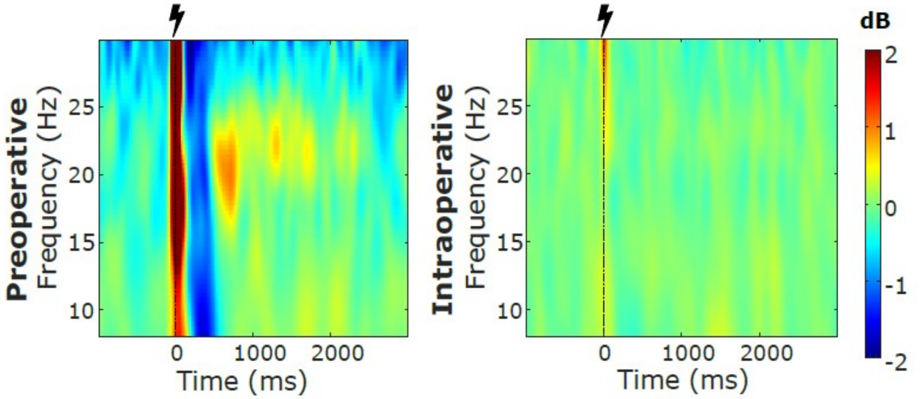
Distance between covariance matrices and MNS-awake class centroid (C_1)



Subject 7

OCMDM

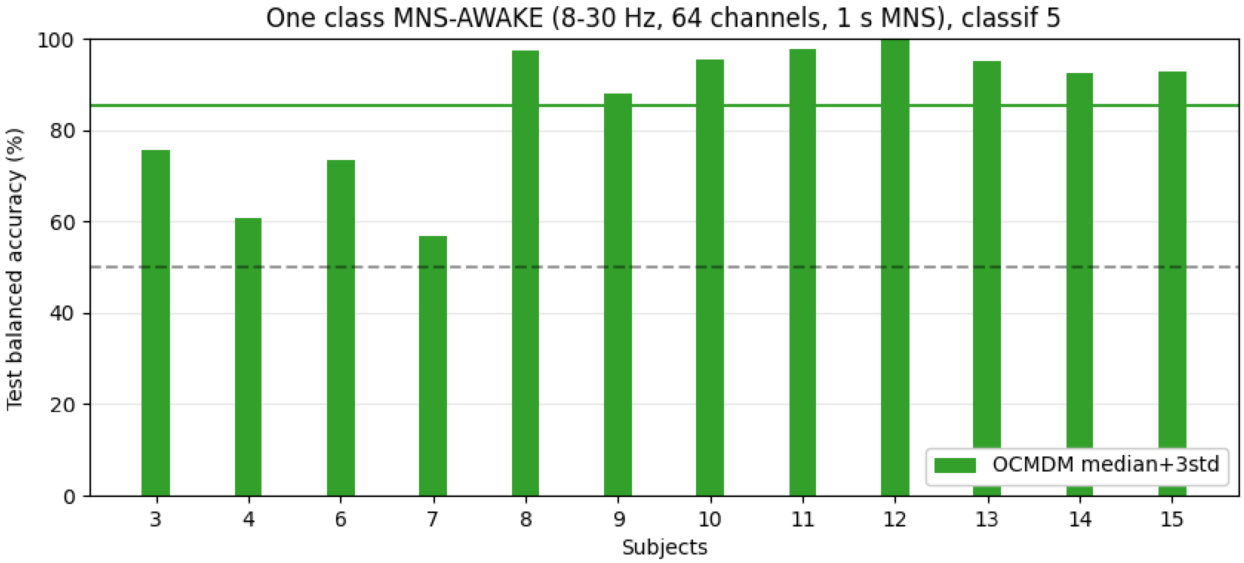
- 250:1000 ms
- mu+beta frequency band
- all 64 electrodes



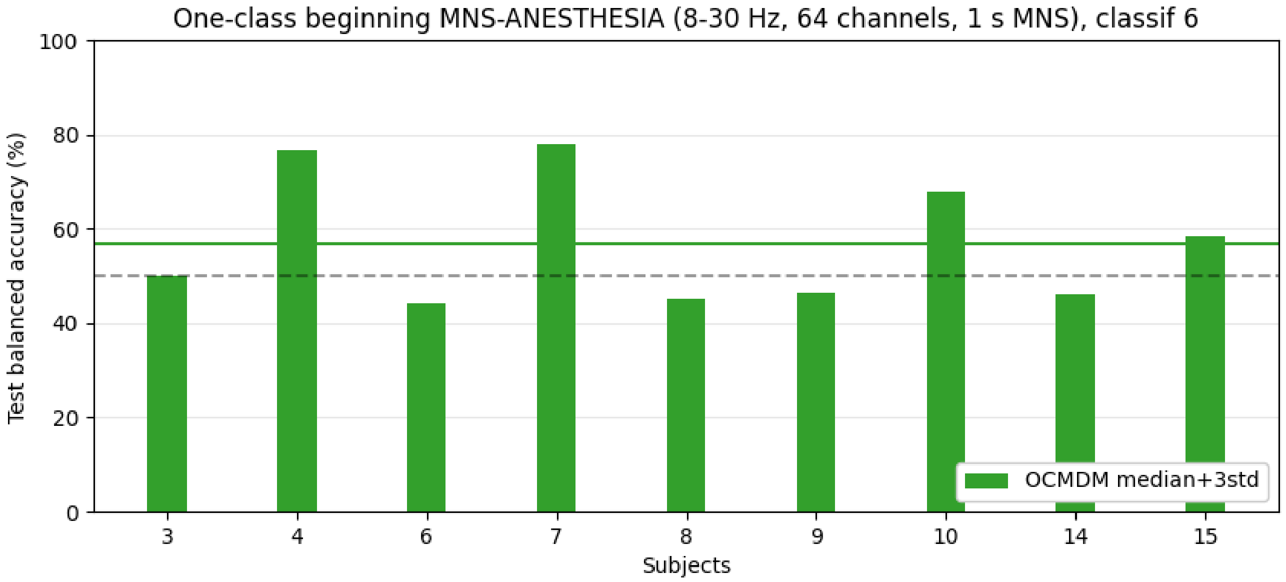
	condition i	condition ii	condition iii
Train	65:296	108:150	70:199
Test intraop	414:1480	306:1288	267:1366
Test preop	28:150	94:445	94:445

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

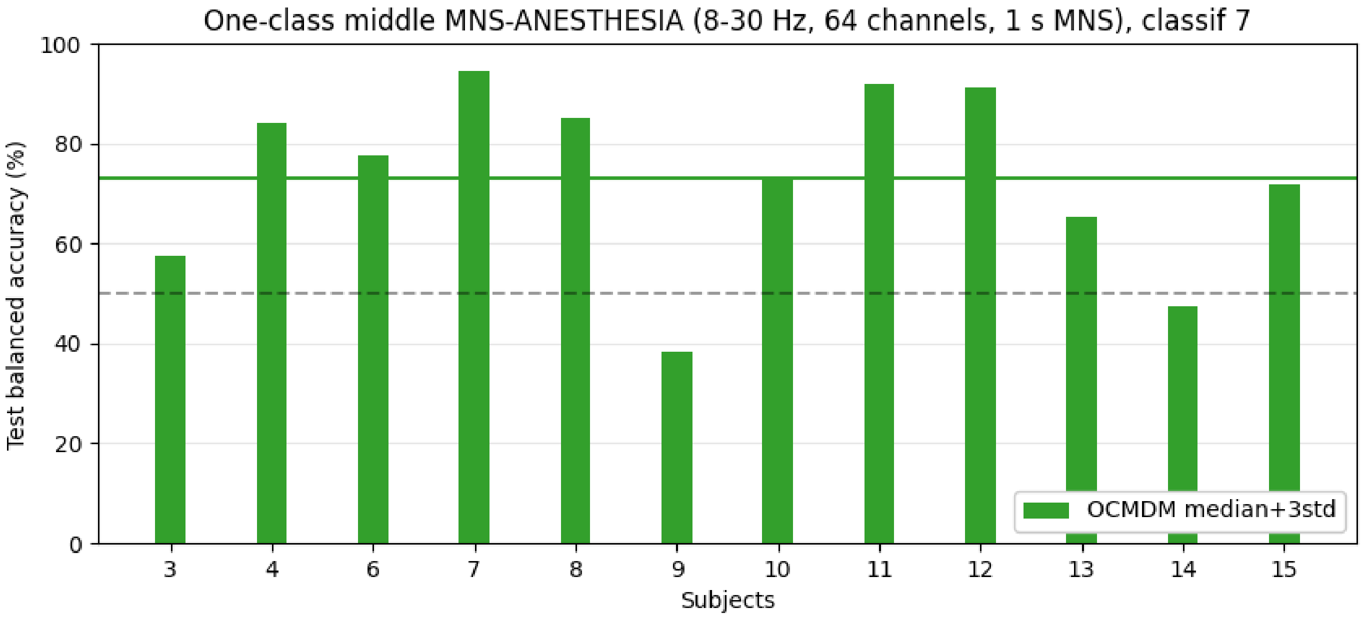
Classification results per subject



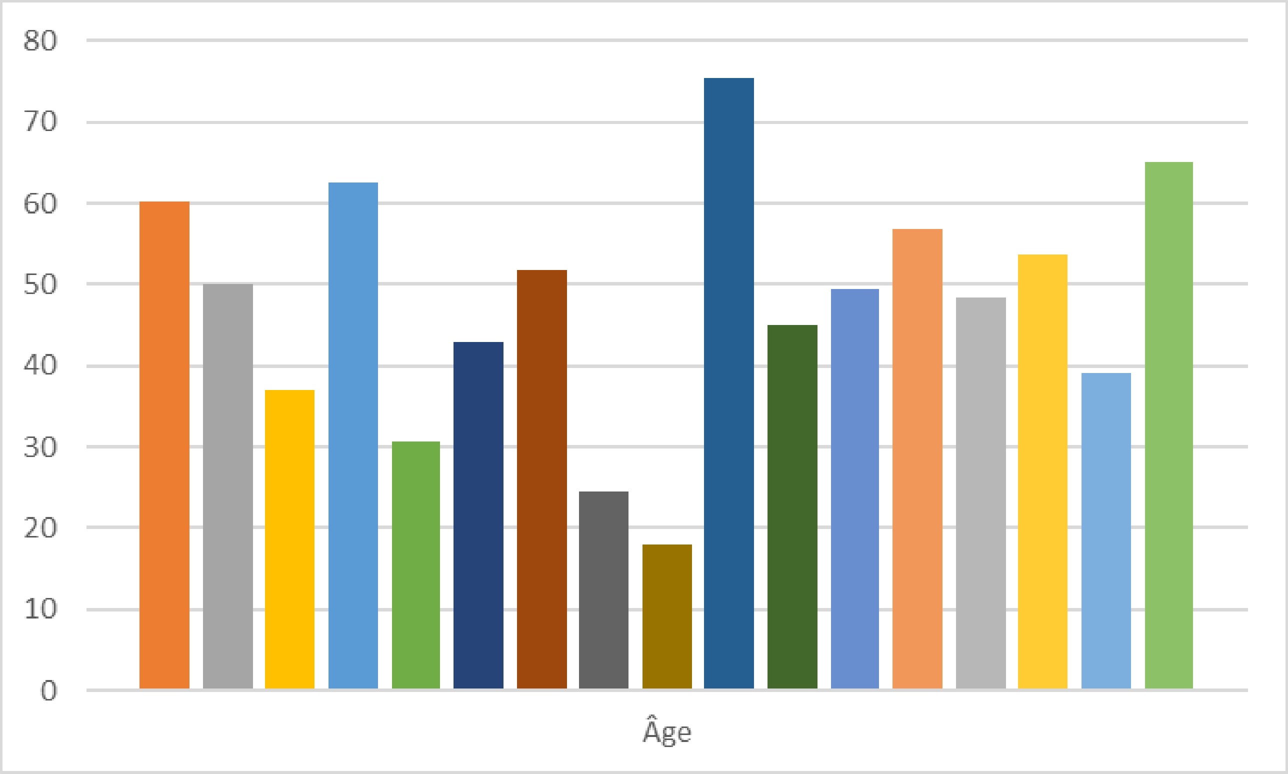
Classification results per subject



Classification results per subject



Informations des patients



Interventions

Fistule anale	40 min
Cholecystectomie	40 min
Annexectomie coelio Gauche	1h15
Sphinteroplastie anale	1h20
Coelioscopie pour endométriose	2h10
TURP	1h40
Hemmoroides	40 min
Fermeture d'Ileostomie	1h30
Changement de plaque orthopédique	2h20

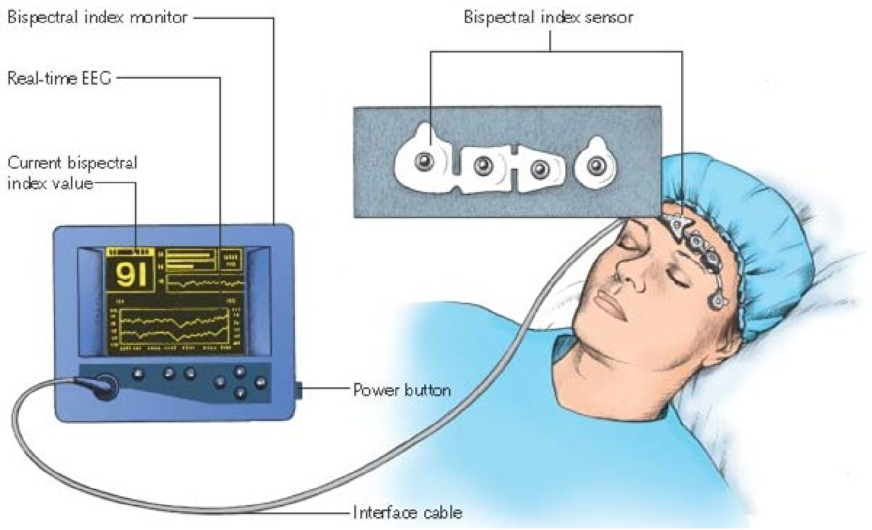
Monitors to prevent AAGA

www.narcotrend.de

Narcotrend monitor


www.maasimo.fr

SedLine monitor



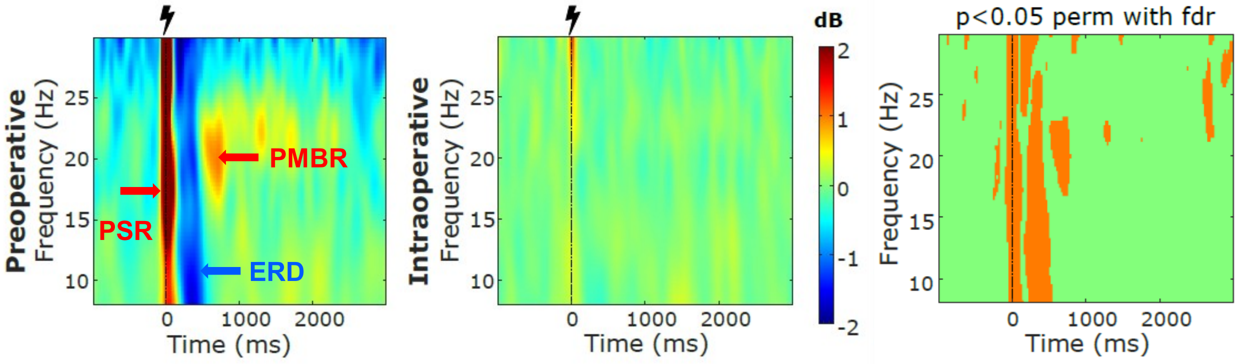
www.nursekey.com

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

Future analysis

- Other EEG features (entropy, functional connectivity, somatosensory evoked potentials) will be investigated
- Identification of the specific frequency band and most relevant electrodes to detect changes in the MNS pattern when a patient is anesthetized
- Validation: a protocol will be carefully conceived to try to simulate an AAGA and observe if the BCI will indeed be able to detect it.

Impact of GA on the patterns induced by MNS



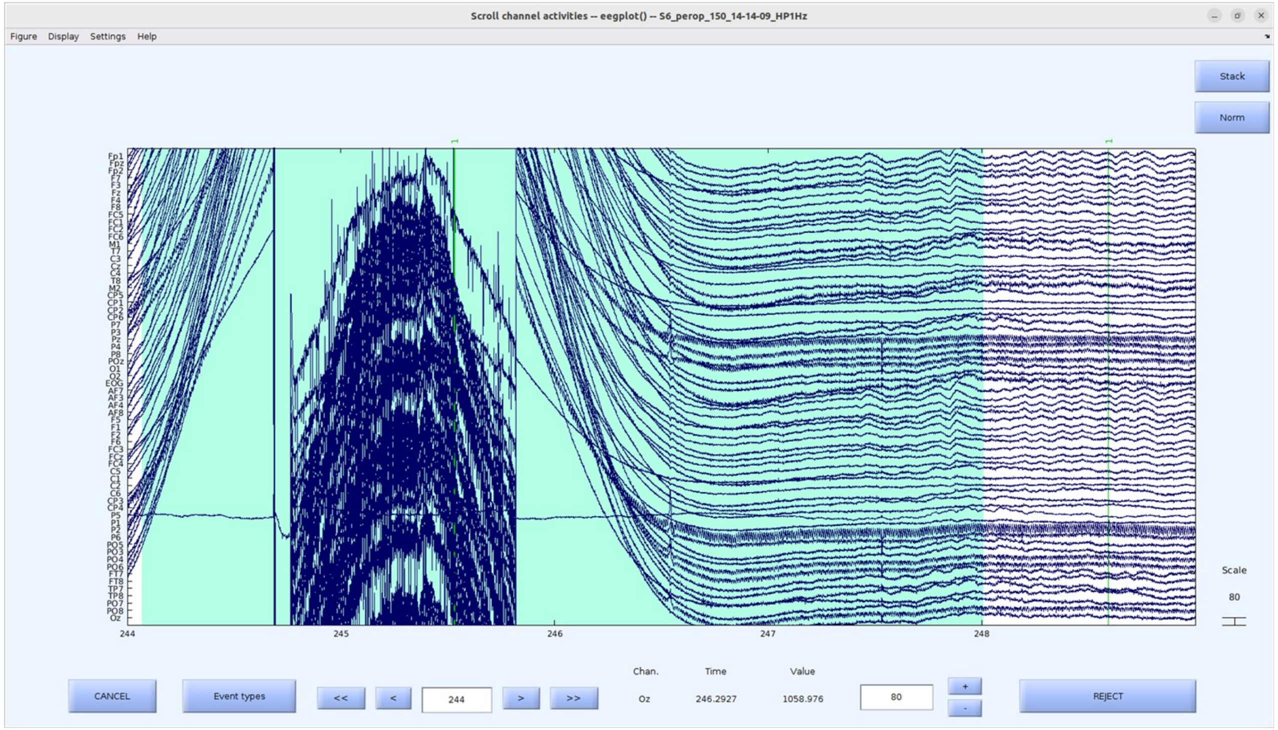
Grand average time frequency analysis across 8 subjects for electrode C4

- Electrical artifact is also modified: other possible factors are changes in skin conductance, environment, patient's arm position between the two sessions

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

Electrocautery-related EEG artifacts



ANR BCI4IA: protocols

BCI4IA project
2022-2026

MOTANA:

- CHRU de Nancy
- 0, 0.5 and 1 μg/ml propofol
- healthy volunteers

STIM-MOTANA:

- CHU de Brugmann
- before and during surgery under GA

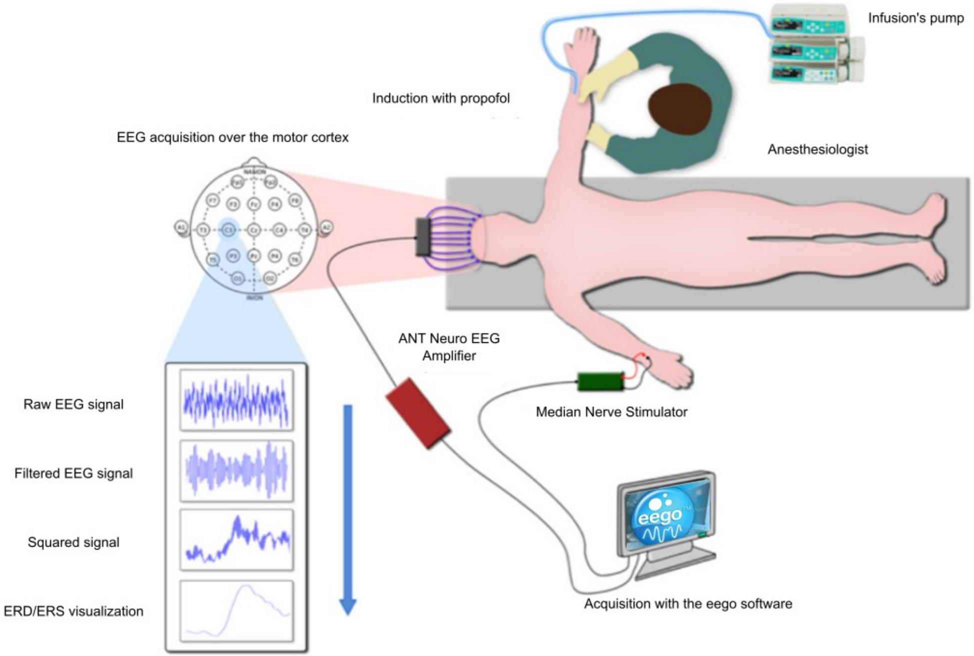
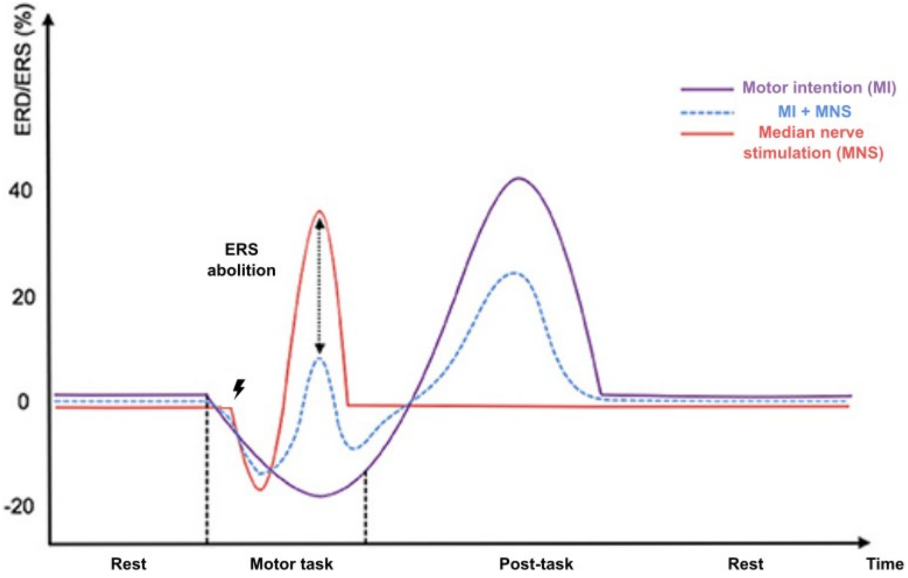


Diagram of the experiment (adapted from S. Rimbert et al., Trials, 2019)

Illustration of ERD/ERS induced by MI, MNS and MNS during MI, in the alpha and beta frequency bands [4]

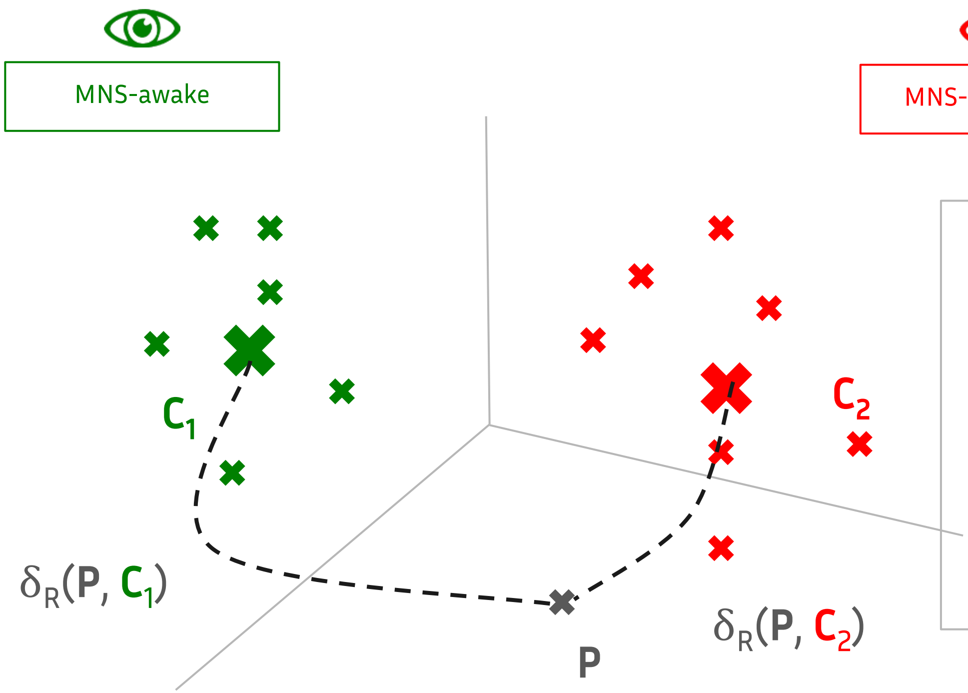


[4] S. Rimbert et al. Front. Neurosci, 2019.
[5] Schnitzler et al. Neuroimage, 1997.

States of consciousness under general anesthesia

awake	anesthetized	
conscious	conscious	unconscious

Riemannian Minimum Distance to the Mean (MDM)



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

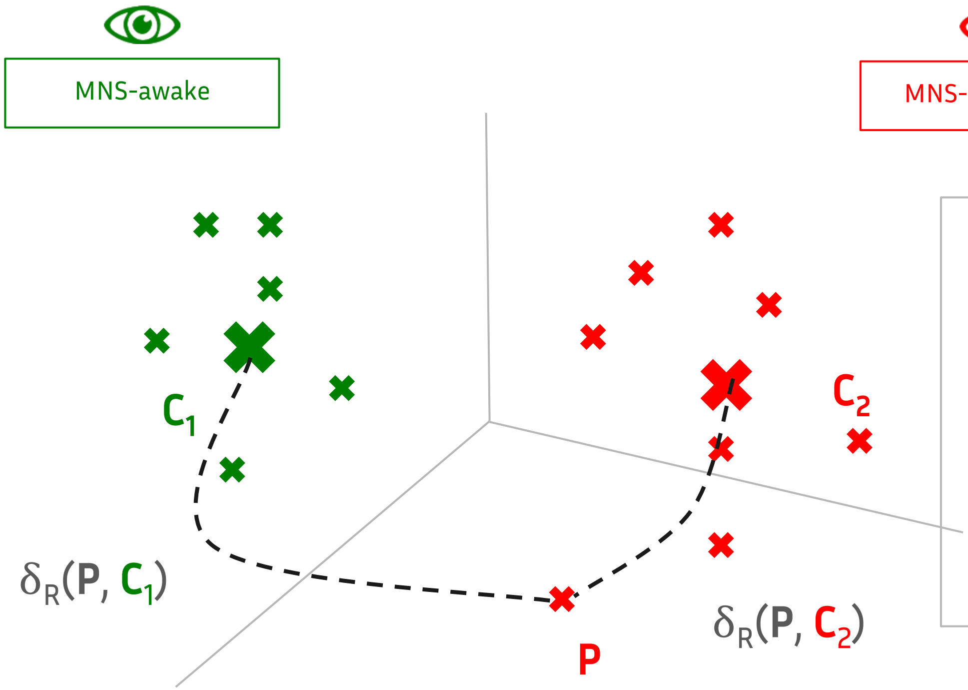
$$\hat{k} = \mathrm{argmin}_i(\delta_R(\mathbf{P}, \mathbf{P}_i))$$

with δ_R the Riemannian distance:

$$\delta_R(\mathbf{P}, \mathbf{P}_i) = ||\log(\mathbf{P}^{-1/2}\, \mathbf{P}_i \mathbf{P}^{-1/2})||_F$$

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

Riemannian Minimum Distance to the Mean (MDM)



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

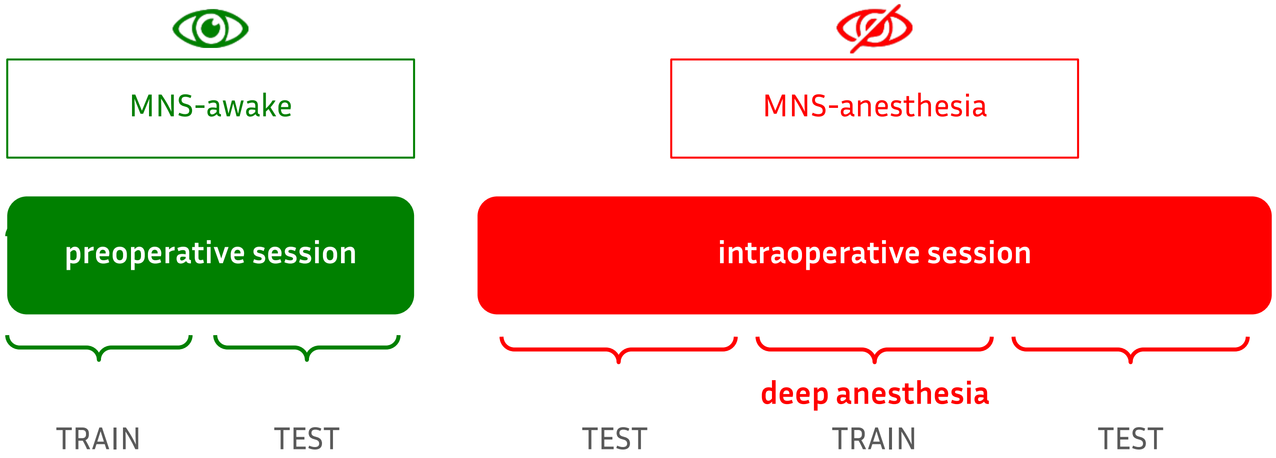
$$\hat{k} = \operatorname{argmin}_i(\delta_R(\mathbf{P}, \mathbf{P}_i))$$

with δ_R the Riemannian distance:

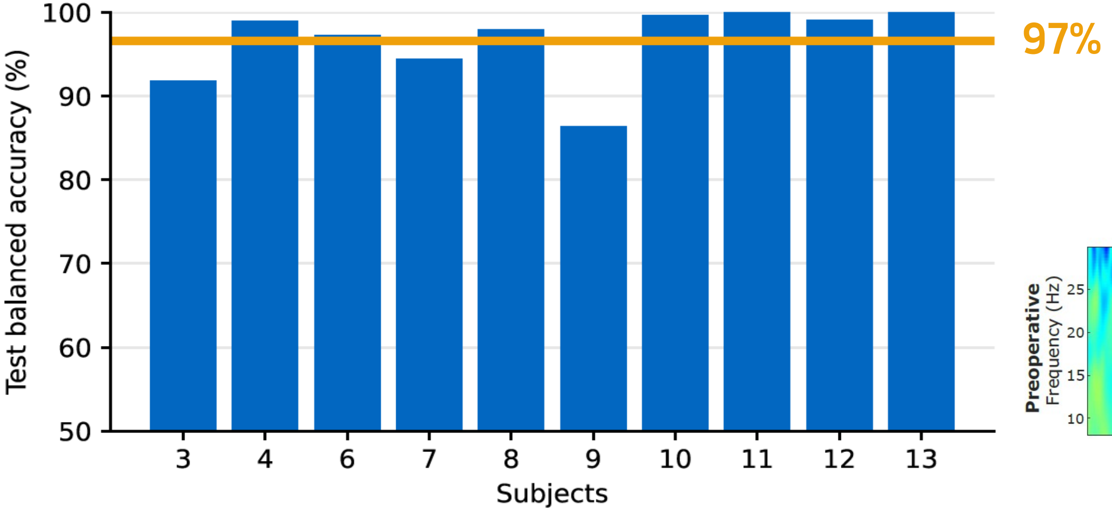
$$\delta_R(\mathbf{P}, \mathbf{P}_i) = \|\log(\mathbf{P}^{-½}\, \mathbf{P}_i\, \mathbf{P}^{-½})\|_F$$

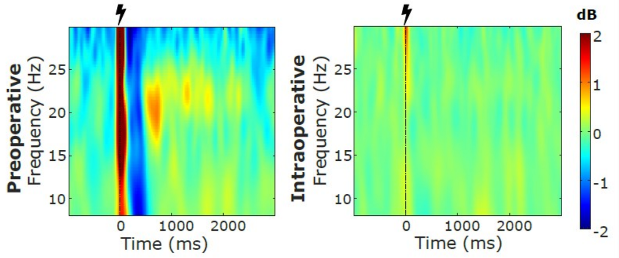
[14] Congedo et al. 8th Inter. BCI Conf. 2019.
[15] Barachant et al. IEEE Trans. Biomed. Eng. 2012.

Offline classification: MNS-awake vs MNS-anesthesia



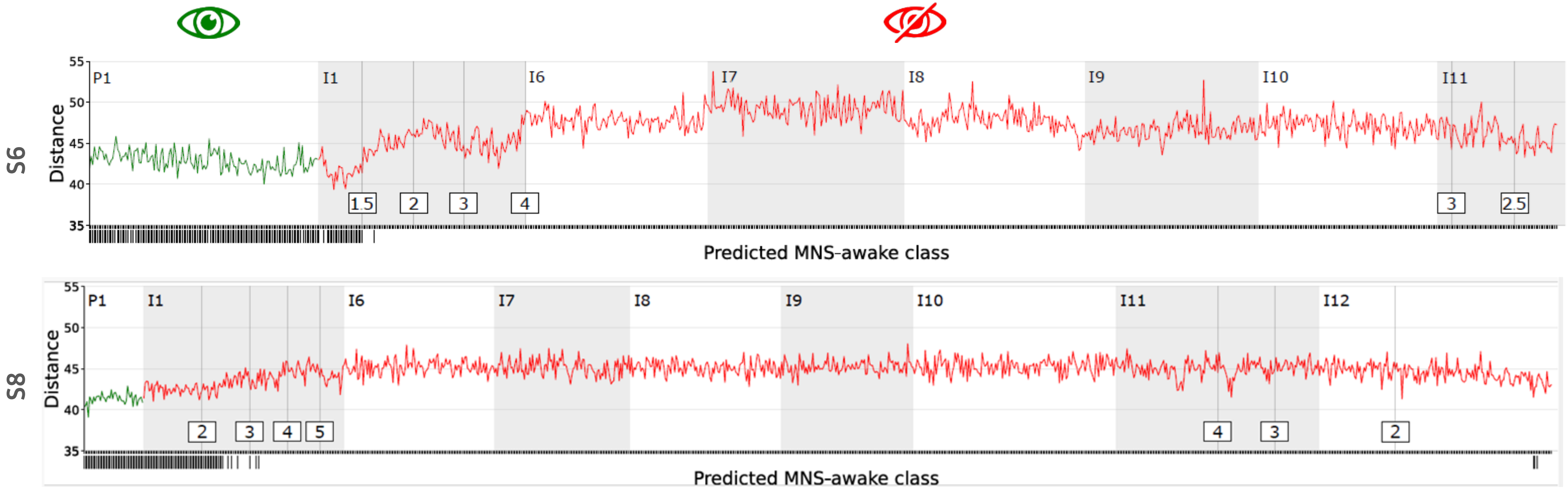
Offline classification: MNS-awake vs MNS-anesthesia





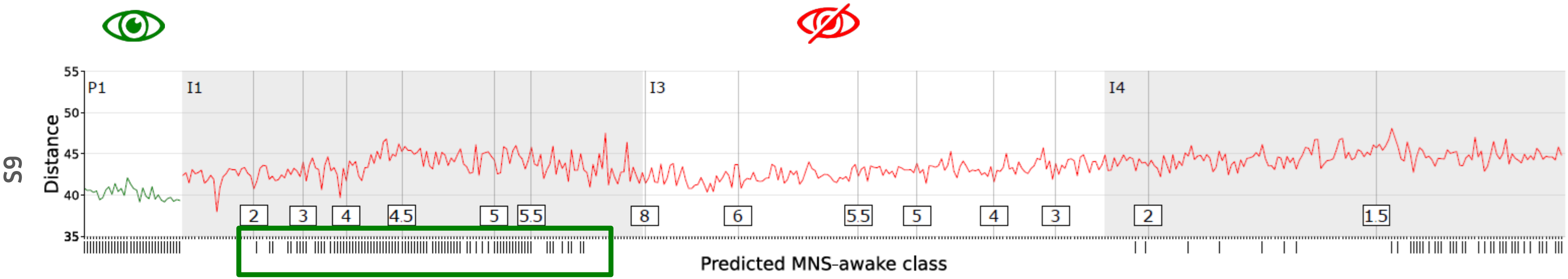
Test set balanced accuracy of the 10 subjects.
The yellow line indicates the average test set balanced accuracy (97%).

Distance between test covariance matrices and the MNS-awake class centroid



Distances of each test trial to the MNS-awake centroid, for subjects 6 and 8.

Distance between test covariance matrices and the MNS-awake class centroid



Distances of each test trial to the MNS-awake centroid, for subject 9

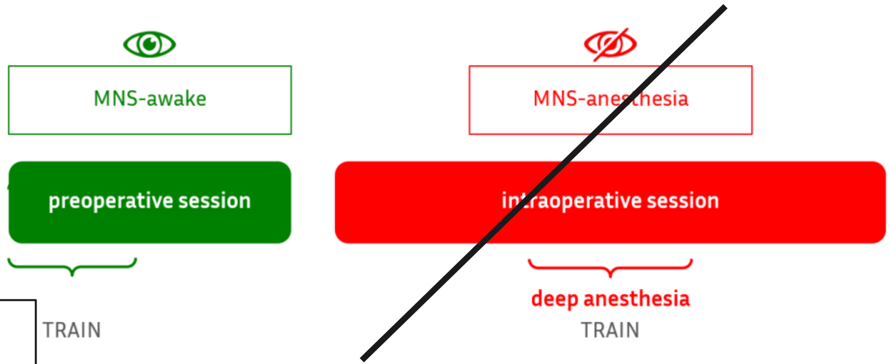
- External elements polluted the signal (repositioning electrodes, the operating table, intubation...)
- Age of 75 vs average of 50 years old [14]
- Fewer training trials (although no correlation between the number of trials and accuracies)

[16] Purdon et al. Br. J. Anaesth, 2015

Detect Awake and Anesthetized states following the Median Nerve Stimulation pattern with a Riemannian MDM classifier ?

- Correctly identifies the periods when the patient is awake
- **Covariance matrices associated to the MNS pattern seem to evolve consistently with the patient's level of awareness.**

- In a real-world application, deep anesthesia trials will not be available to calibrate the BCI. Thus, a one class approach will be required.



Neuroergonomics
THE BRAIN AT WORK AND IN EVERYDAY LIFE

One-Class Riemannian EEG Classifier to Detect Anesthesia

Valérie Marissens Cueva[1,2], Sébastien Rimbert[2], Ana Maria Cebolla Alvarez[3], Mathieu Petieau[3], Iraj Hashemi[3], Viktoriya Vitkova[3], Guy Cheron[3], Claude Meistelman[4], Philippe Guerci[4], Denis Schmartz[5], Seyed Javad Bidgoli[6], Laurent Bougrain[2], Fabien Lotte[1]