Quantifying Inter- and Intra-Subject Variability of Sensorimotor Desynchronization Induced by Median Nerve Stimulation and Motor Imagery for Brain-Computer Interfaces

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Motor Imagery-based Brain-Computer Interfaces (MI-BCIs)

Allow users to control or interact with external devices by interpreting brain activity (e.g. EEG) [1].

PROBLEM: performance **variability both between and within subjects** [2].

30% of users are unable to effectively use a BCI [2]

For a given user: BCI performance might be good one day, poor another day with the same BCI [3]

Technical factors: EEG hardware, electrode positioning, signal processing algorithms [4]

Physiological & psychological factors: age, personality, cognitive state, fatigue, neural plasticity, individual characteristics of neural patterns [5, 6, 7, 8, 9]

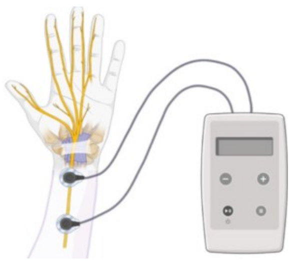
[1] Wolpaw et al, Clin. Neurophy. 2002.
[2] Allison and Neuper, Elsevier, 2010.
[3] Benaroch et al, Front Human Neurosc, 2021.
[4] Oken and Chiappa, Electroenceph Clinl Neuroph, 1988.
[5] Antonakakis et al, NeuroImage, 2020.
[6] Rimbert and Lotte, IEEE EMBC, 2022.
[7] Rimbert et al, Front Human Neurosc, 2019.
[8] Jeunet et al, Elsevier, 2016.
[9] Wriessnegger et al, Front Human Neurosc, 2020.

Median Nerve Stimulation (MNS)-based BCIs

MNS: Painless electrical stimulation, intensity between 8 and 15 mA.

MNS-based BCI : MNS sensorimotor modulations change with concomitant MI [10, 11], leadin

OBJECTIVE: Determine how variable is the EEG induced by MNS vs. the one by MI.



Thomas Hendry, Neuromod, 2024

$$ERD/ERS\% = \frac{\overline{x^2} - \overline{BL^2}}{\overline{BL^2}} \times 100$$

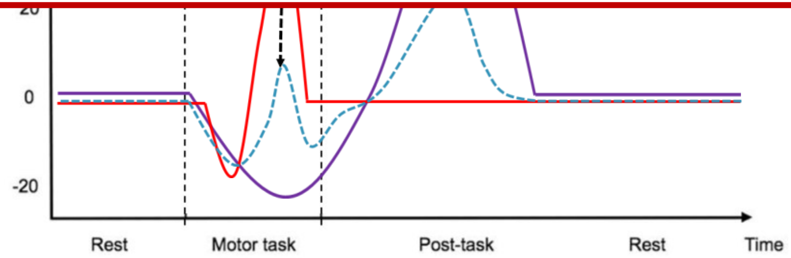
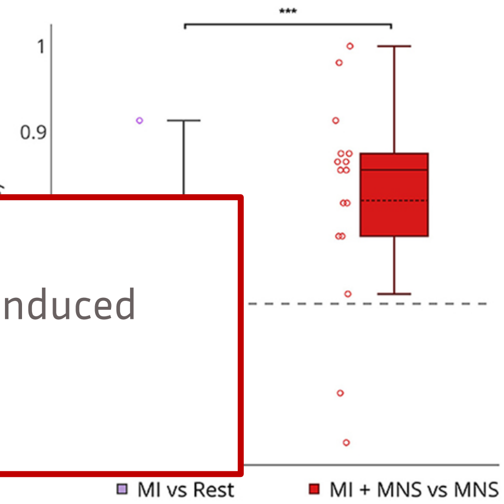


Illustration of ERD/ERS [13] induced by MI, MNS and MNS during MI, in the alpha and beta frequency bands [12]

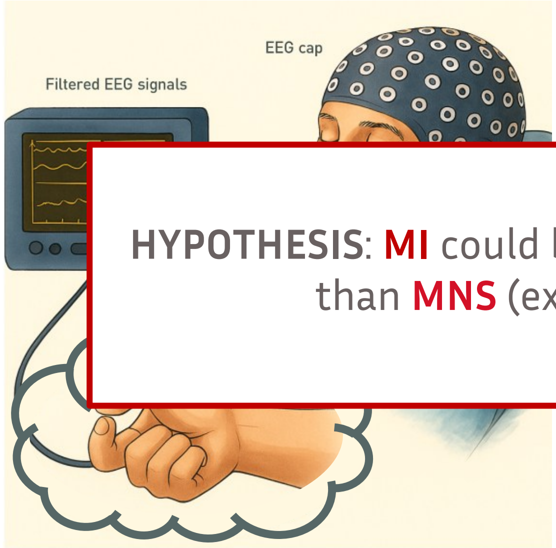


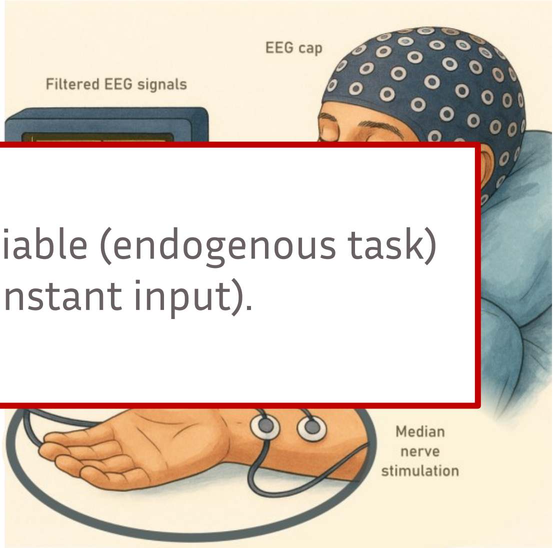
Distribution of average classification accuracies (n = 16), obtained by a Riemannian classifier ***p-value < 0.001 [12]

[10] Cheron et al, Electroenceph. Clin. Neuroph., 1987.
[11] Salenius et al, NeuroImage, 1996.
[12] Rimbert et al, Front. Neurosci, 2019.
[13] Pfurtscheller and Lopes da Silva, Clin Neuroph, 1999.

MI-BCIs vs. MNS-BCIs

Data collection: 31 subjects, 51 trials of MI and 51 trials of MNS in a random order [14].





HYPOTHESIS: **MI** could be more variable (endogenous task) than **MNS** (exogenous constant input).

MOTOR IMAGERY

MEDIAN NERVE STIMULATION

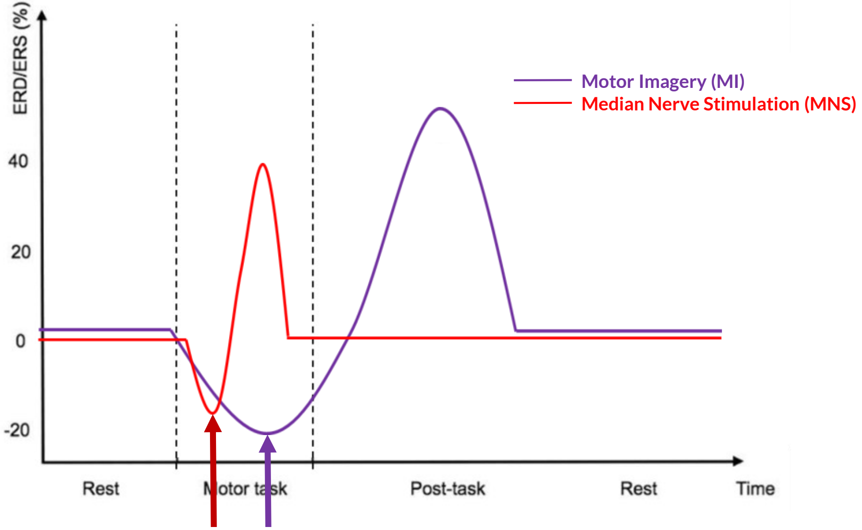
Figures inspired by Sigl and Chamoun, J Clin Monit, 1994

[14] Rimbert et al. Trials, 2019.

Quantification of EEG variability

1

Desynchronization pattern: ERD/ERS% at C3 with a small Laplacian filter



minimum ERD value in the 0 to 3 s window

2

Offline BCI performances: motor task vs. resting period, with a Tangent Space Logistic Regression [15]

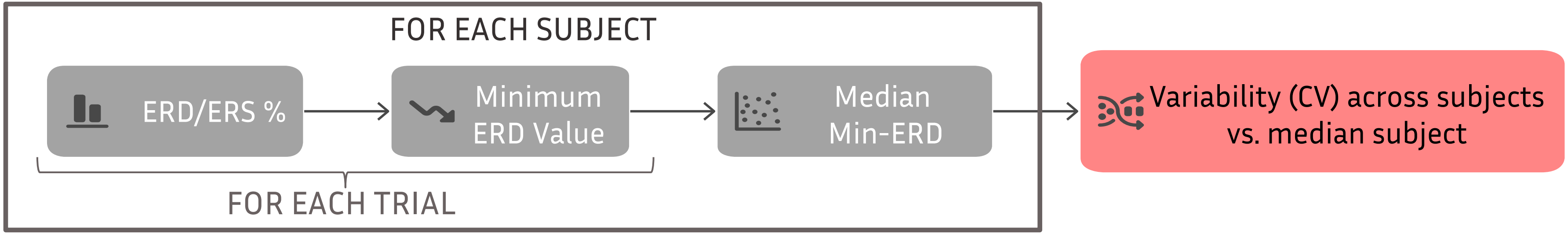
Coefficient of variation (CV) based on the median value and median absolute deviation (MAD) [16]:

$$CV(\mathbf{X}) = \frac{MAD(\mathbf{X})}{|median(\mathbf{X})|} \times 100$$

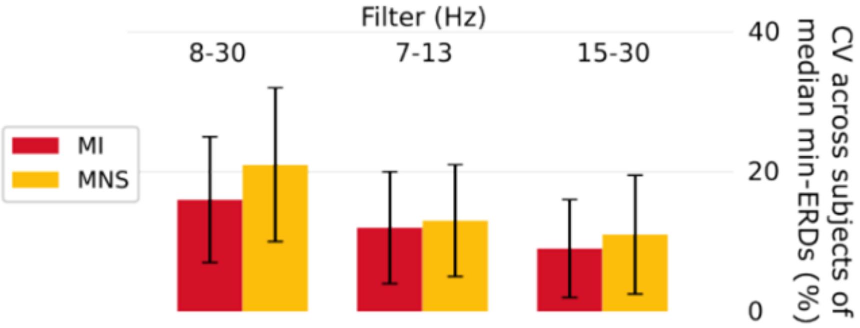
[15] Barachant et al, Springer, 2010.
[16] Arachchige et al, J. of Applied Statistics, 2022.

Between-subjects variability

How EEG patterns (induced by MNS or MI) differ across subjects.



each subject reduced to 1 value



No significant difference between EEG variability induced by MI and by MNS.

Two subjects have similar EEG patterns variability, whether they are induced by MI or MNS.

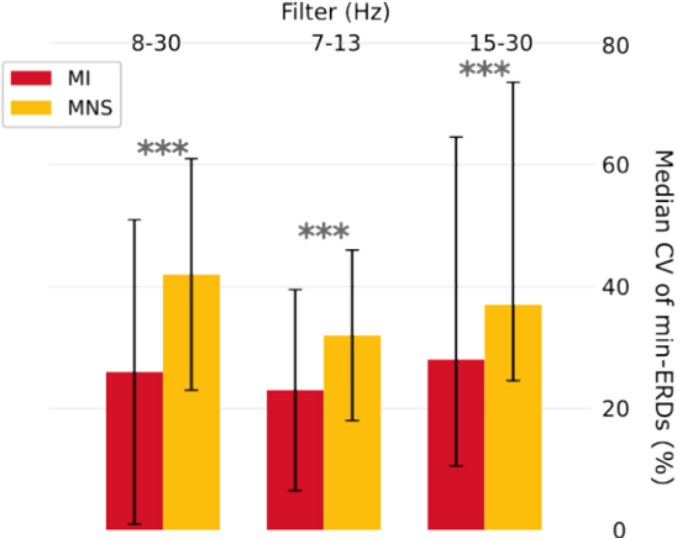
Within-subjects variability

How EEG patterns (induced by MNS or MI) differ across trials, for each subject.

FOR EACH TRIAL

ERD/ERS % → Minimum ERD Value → Variability (CV) across trials vs. median trial

each subject has 51 values



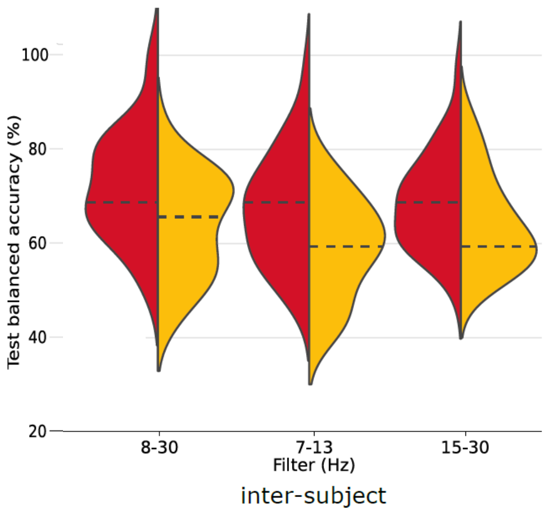
Significantly higher variability in MNS than in MI.

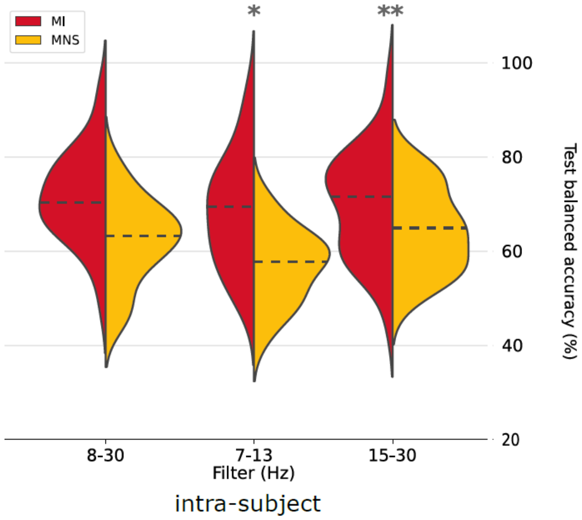
A subject's EEG patterns induced by MNS vary more across trials than the ones induced by MI.

Offline BCI performance results (MI or MNS vs. REST)

Between-subjects: no significant difference in variability of BCI performances across subjects.

Within-subjects: significantly higher variability in MNS vs. REST than in MI vs. REST across trials.





BCI offline test balanced accuracies (distribution over 31 subjects) for MI vs. REST or MNS vs. REST classifications, with a Tangent Space Logistic Regression.

Summary

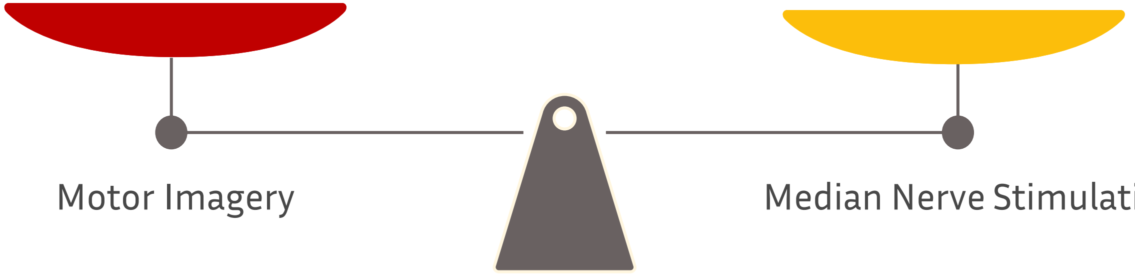
VARIABILITY
Min-ERD
BCI performance

HYPOTHESIS: **MI** could be more variable (endogenous task) than **MNS** (exogenous constant input).

Discussion: Why is EEG induced by MNS more variable than the one induced by MI, within the same subject?

- Endogenous task
- Requires attention
- Sustained

- Exogenous input
- Variable attention
- Discrete



Motor Imagery

Median Nerve Stimulation

Fluctuations in cortical excitability: “The amount of ERD or ERS depends on the amplitude of the ongoing activity’” [20].
Spontaneous mu/beta rhythm phase: Cortical responses to MNS depend on the phase of ongoing oscillations [21, 22].

[17] Rimbert et al, Comp Hum Behav, 2023.
[18] Mima et al, J Neurophysiol, 1998.
[19] Backes et al, Clin Neurophy, 2000.
[20] Pfurtscheller, Electroenceph Clin Neurophy, 1992.
[21] Nikouline et al, Neurosc Letters, 2000.
[22] Cheron et al, BMC Neurosci, 2007.

Future directions

Determine the origin of MNS variability?

- Measure baseline mu/beta power and phase before each trial
- Evaluate the variability of EEG induced by MNS+MI
- Add an attention control task
- Evaluate the variability of EEG induced by MNS during sedation or general anesthesia

Multi-dimensional analysis of ERD variability:

- Spatial, spectral, temporal analyses
- Develop a variability index to enable comparison with the scientific literature
- Larger dataset with more trials, across sessions

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Thank you for your attention!

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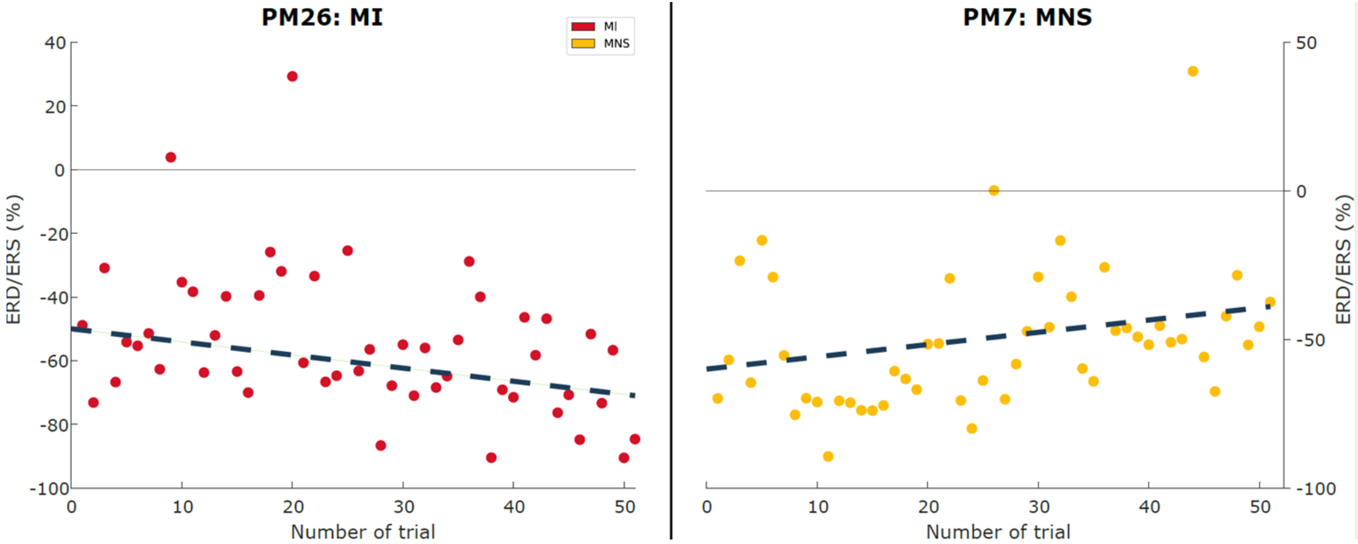
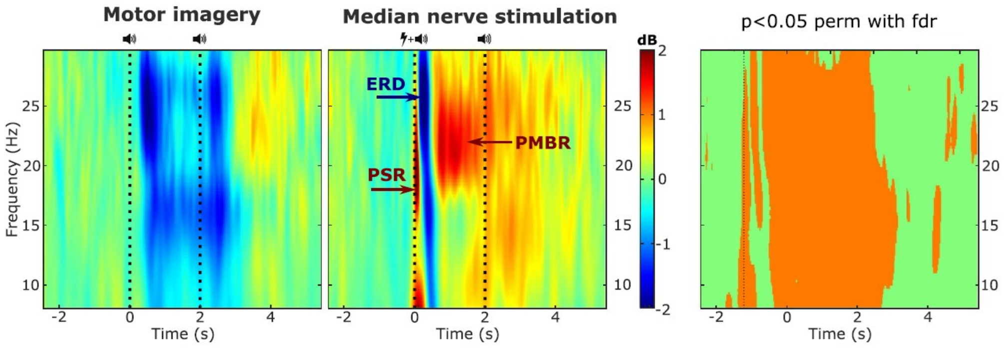
Effect of task repetition

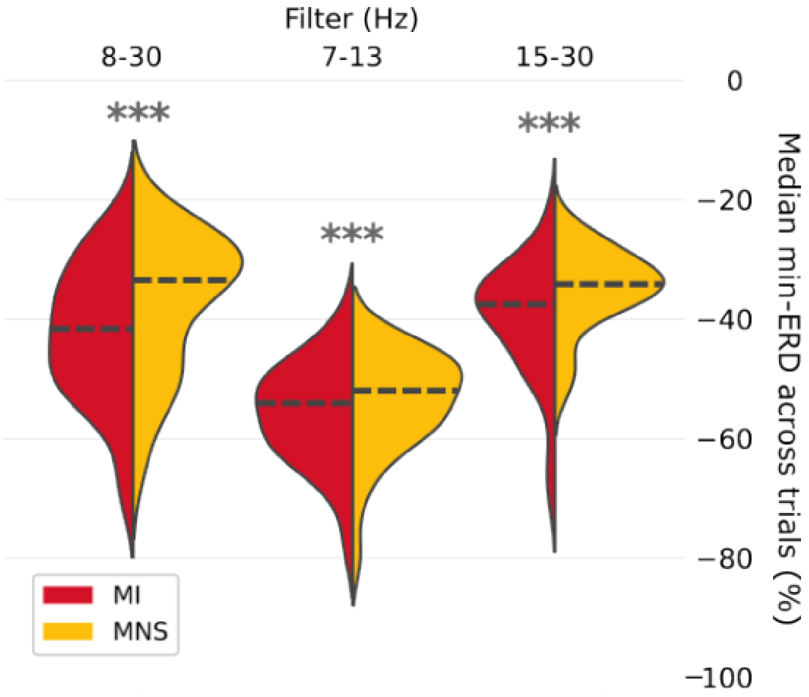
- No global correlation between the number of trials and the min-ERD value.
- In certain subjects:
  - MI stronger desynchronization over time could suggest a training effect
  - MNS decreasing desynchronization may indicate habituation to passive stimulation.



Comparison of MI-ERD and MNS-ERD

The desynchronization (minimum ERD value) was significantly more pronounced during MI compared to MNS (***$p < 0.001$).





More variable attention during MNS than during MI

Variable attention and uncontrolled resting state: Active attention during MNS enhances secondary somatosensory cortex (SII) activity.

Mima et al, J Neurophysiol, 1998: Magnetoencephalography

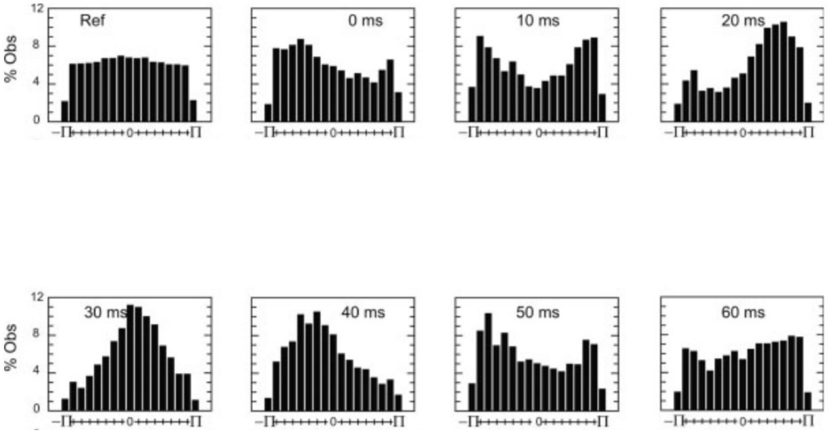
- Two kinds of MNS (strong or weak) with the weak stimulus being infrequent, subjects had to count these rare stimuli.
- In terms of somatosensory evoked magnetic fields, **active attention increased SII but not SI activity**.

Backes et al, Clin Neurophy, 2000: Functional magnetic resonance imaging

- Subjects had to count the total number of interruptions in one fMRI session, where MNS was interrupted at random intervals for 1 s.
- **Only SII exhibited a significant increase** in fMRI activity with selective attention, in agreement with its role in higher-order processing of somatosensory stimuli.

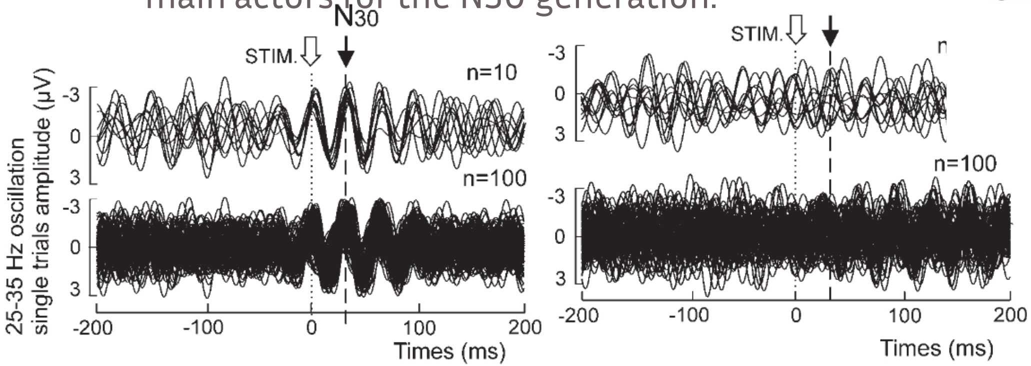
MNS is more sensitive to mu/beta rhythms phase at stimulus onset

Spontaneous mu/beta rhythm phase:
Cortical responses to MNS depend on the phase of ongoing oscillations.



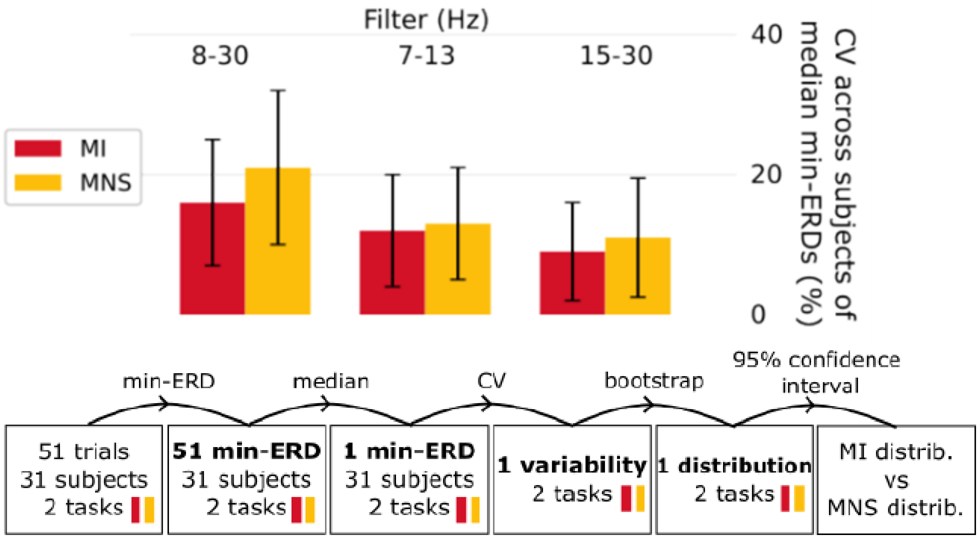
Cebolla et al, Human Brain Mapp, 2009: EEG, N30 somatosensory evoked potential

- Phase-locking phenomenon is one of the main actors for the N30 generation.



Desynchronization and BCI performance results

Between-subjects: no significant differences in variability



Within-subject variability: significantly higher in MNS than in MI