

Non-invasive Brain-Computer Interfaces: Enhancing Applicability using Computational Intelligence and Technological Advances

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Presentation outline

- State-of-the-art non-invasive BCI
- R&D challenges
- CI approaches to handling challenges
- Laboratory facilities
- EEG-based Post-stroke rehabilitation
- MEG-based Post-stroke rehabilitation
- Conclusions and further R&D challenges

Background

- Brain-computer Interface a direct communication pathway between a human brain and a computer.
- Mainly useful for patients suffering from motor impairments: world-wide about 10M stroke sufferers; approx. 40k SCI patients in UK alone.
- A broad range of promising applications such as alternative augmentative communication (AAC) systems for environmental control, tele-robotics & mobility, and neuro-rehabilitation systems involving prosthetics and/or orthotics/exoskeletons.
- However because of <u>high brain signal non-stationarity</u> and other <u>practical issues</u>, BCI systems have found limited practical use.

Types of BCI

- Invasive techniques
 - Using micro-electrodes or electro-corticogram (ECoG).
 - Electrodes are implanted directly onto a patient's brain.
 - Need for surgery; may cause scar, and materials issues.
 - Ethical issues; risk of infection.
- Noninvasive techniques
 - Using EEG, MEG, NIRS, and/or fMRI.
 - External sensors for availing brain signals.
 - Susceptible to noise.
 - Most widely used is EEG being easy to use, low cost & portable.

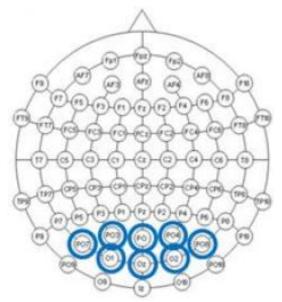


Photo Courtesy: University of Utah Department of Neurosurgery



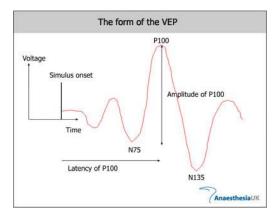
Non-invasive BCI Categorisation based on Mental Tasks

- Visually Evoked Potential (VEP): SSVEP most common
- P300
- Sensorimotor activity



Top View of the brain Electrode placement



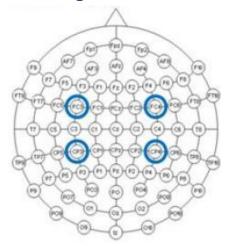


Potential changes of the occipital EEG under stimulation of light

Non-invasive BCI Categorisation....

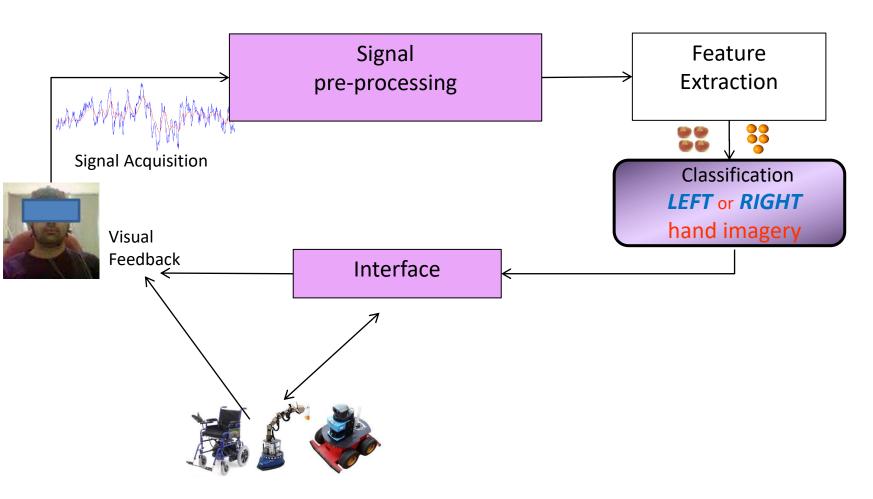
Sensorimotor

Sensorimotor rhythm (SMR) (e.g., mu rhythm) gets modulated when a person imagines to move (i.e. motor imagery by a healthy person), intends to move (e.g., by a disable person), or actually moves his/her right and/or left hand, tongue, or foot.



If we can **decode** the information from brain to <u>display human thinking</u>, we can design a very intuitive and natural communication channel.

Operational Block Diagram of a BCI



Critical Performance Limiting Factors

Human Factors:

Brain signals change due to mood, fatigue, attention, motivation, medications, sensory stimuli, circadian rhythms, progression of disease, and amount of practice.

Head movements and eye blinking may cause artefacts.

Machine Factors:

Electromagnetic (EM) noise may affect recordings.

For EEGs, impedance changes due to sweating, drying gel, electrode placement variation, surface metal degradation, and lead wear.

Laboratory facilities...

NI Functional Brain Mapping facility

- A joint investment of £5.3M from Invest Northern Ireland (INI) and UU
 equipped with the latest whole head 306 channels Elekta Neuromag MEG
 TRIUX system. First MEG on island of Ireland, about 200 worldwide.
- Magneto-encephalography (MEG) records magnetic field induced by brain activities across the whole scalp while maintaining much higher spatial and temporal resolution.
- Research focus:
 - Improved understanding of dynamics of human brain signal processing;
 - Neurological disorders, stroke, Alzheimer's disease, and epilepsy.
- Outputs:
 - More effective diagnostic tools for early diagnosis;
 - More effective prevention or intervention measures;
 - Collaborative development of Biomarkers;
 - Enhanced software tools for more automated medical image analysis.



Some R&D works addressing challenges

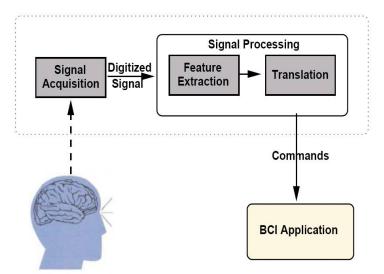
- Rapid selection of user-specific parameters and intelligent pre-processing [e.g. data analytics for optimal channel selection (*Roy et al. (2020), J Neural Eng*); signal pre-processing using SOFNN or recurrent Quantum NN (Gandhi et al. (2013), *IEEE T NN & Learning Sys*)]
- Optimal methods for feature extraction [e.g. PSD (Herman et al. (2008), IEEE T Neural Sys Rehab Eng.) & bi-spectrum (Shahid & Prasad (2011), J Neural Eng)];
- Adaptable and robust classifier design and transfer learning [e.g. Interval Type-2 Fuzzy Logic (Herman et al. (2017), IEEE T Fuzzy Sys); Riemannian geometry based tangent Space (Gaur et al. (2019), IJNS), Deep learning (Roy et al. (2020), Frontiers in Neuroscience].
- Multi-modal BCI through multi-sensor integration combining EMG, ECG, and/or eye-tracker [e.g., EEG-EMG Correlation based feature (*Choudhury et al. (2019), J Neuroscience Methods*)]
- Appropriate user interface (visual and auditory) development for neurofeedback and accomplishing tasks such as text entry, web-page access, wheelchair/mobile robot control, and stroke rehabilitation & related game playing [e.g., Auditory NFB (McCreadie et al. (2014) IEEE T Neural Sys Rehab Eng.)]

Integration of BCI and robotic exoskeleton: A way forward

for neuro-rehabilitation

Robots administer <u>repetitive exercises</u> but may not be sufficiently engaging for neuroplasticity to occur due to:

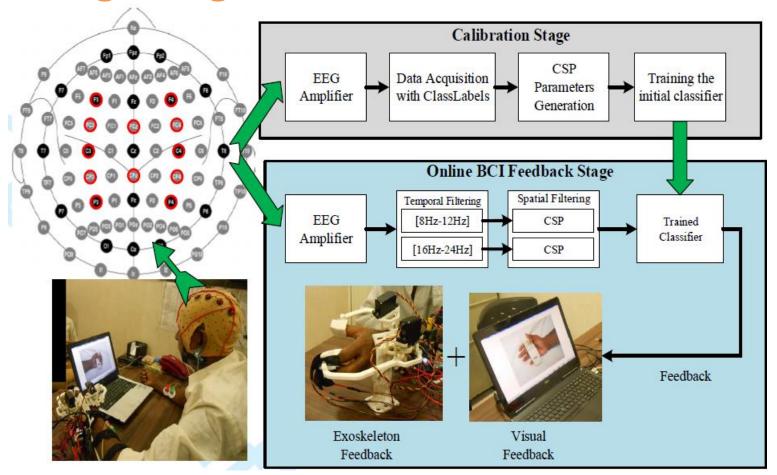
- lack of interactive and engaging user interface.
- A symbiotic fusion of BCI and robot can facilitate:
 - Engaging and natural user interface;
 - Capturing of patient's attention while allowing intense repetition of therapeutic task, causing <u>neuroplasticity</u>;
 - Reliable quantification of patient's performance and recovery process;
 - Applicability to wide range of motor impairments.





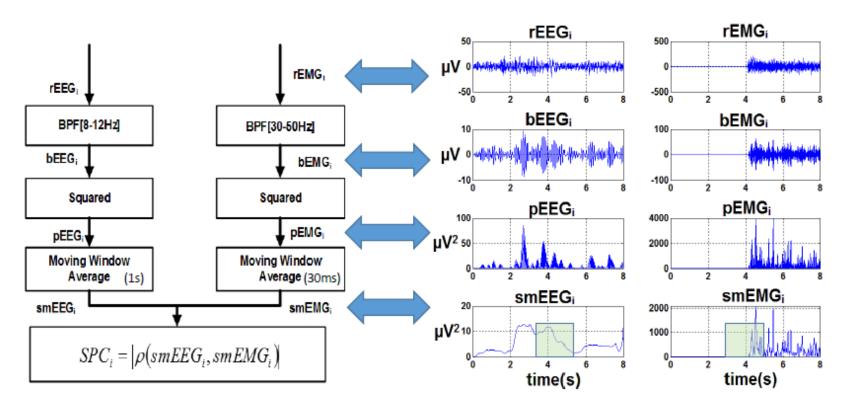
Completed RTD:

Integrating EEG-based BCI and Exoskeleton



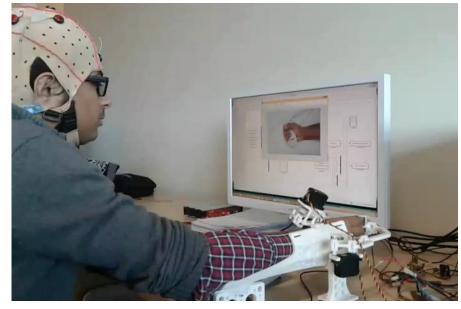
- Features: CSP; Cortico-muscular coherence (CMC) / EEG-EMG band-limited power time-courses (CBPT) Correlation;
- Feature Classifier: SVM

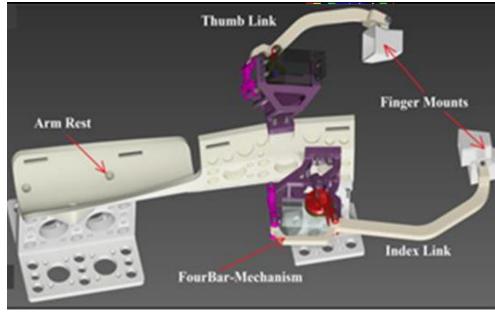
Cortico-Muscular-Coupling...



EMG signal from the flexor-digitorum-superficialis (FDS) muscle

A Participant using the Neuro-rehabilitation System





[Chowdhury et al. (2018), IEEE T Cognitive and Developmental Systems]

Pilot Clinical Trial

- > Participant Selection Criteria
 - Stroke patients with partial or full finger motion disability.
 - Time since stroke not less than 6 months.
 - MMSE score more than 21/30.
- > Experimental Protocol [Prasad et al., 2010]
 - Assist-as-needed Physical Practice (30 min).
 - BCI based Mental Practice (30 min).
 - 2/3 therapy sessions per week; Six week long.
 - Four stroke (ischemic) (1 male, 3 females, mean time after stoke:23(4.6) months, MMSE score:28.34(±1.25)).
 - Recovery outcome measures:
 - Action Research Arm Test (ARAT) (1-57): Grip(1-57),
 Pinch(18), Grip(12), Grasp(18), Gross movement(9).
 - Grip Strength.

Pilot Clinical Trial...

Demographics of the Patients

Sub id	Age (years)	gender	Imp aired side	Domin ant Side	Time Since Stroke (months)	Minimental State Test Score
P01	61	F	R	R	22	30/30
P02	56	M	L	R	28	30/30
P03	69	F	R	R	24	30/30
P04	59	F	L	R	19	30/30

Pilot Clinical Trial...

Physical Practice (PP):

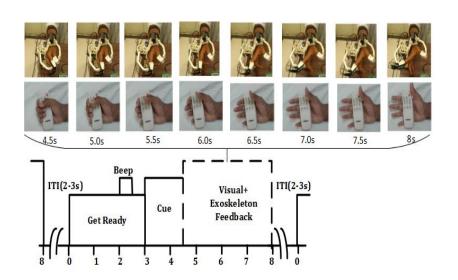
- Repetitive finger flexion and extension exercise in assist-asneeded mode for 30 min
- Strategy implemented by a force threshold based switching between active non-assist and passive assistance mode.
- Participants applied finger-tip force is converted into exoskeleton motion using an impedance model if force is above a certain threshold level (active non-assist mode).
- Switches to passive assistance mode providing full assistance when the applied force is below the threshold.
- The difficulty level of the PP is adjusted by updating the impedance parameters according to the average force generation ability.

Pilot Clinical Trial...

≻Mental Practice

BCI system 16 channel EEG/EMG g.USBamp system from

g.tec

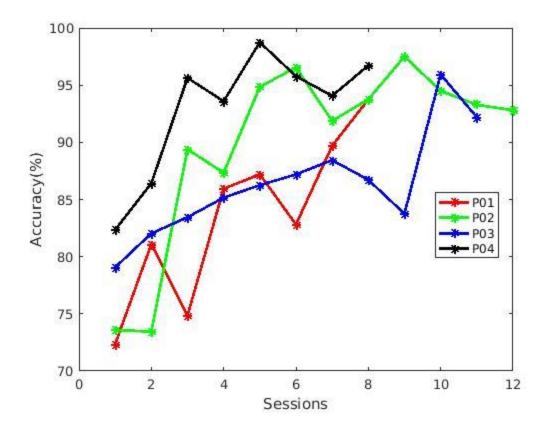


Visual neurofeedback along with paradigm timing diagram.

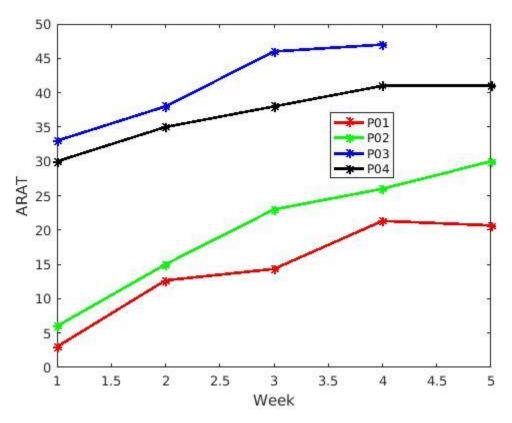


A Patient undergoing the trial

Change in BCI Classification Accuracy

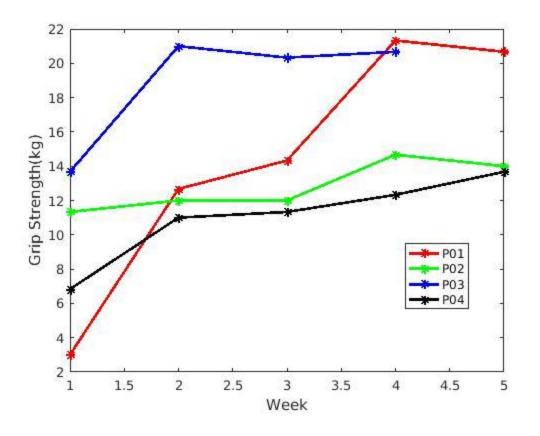


Clinical Outcome Measure: Action Research Arm Test (ARAT)

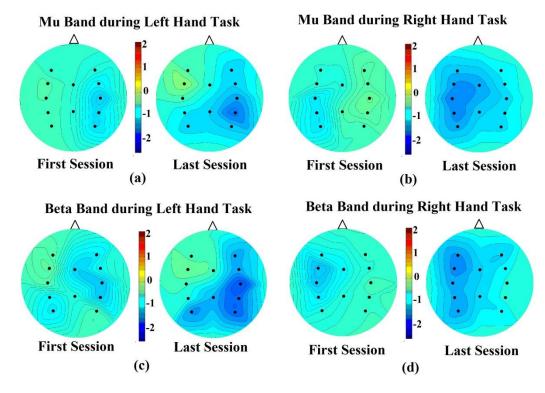


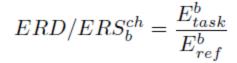
All the participants achieved Minimal clinically important difference (MCID) in their ARAT.

Clinical Outcome Measure: Grip Strength



Scalp Topoplots for ERD/ERS Changes



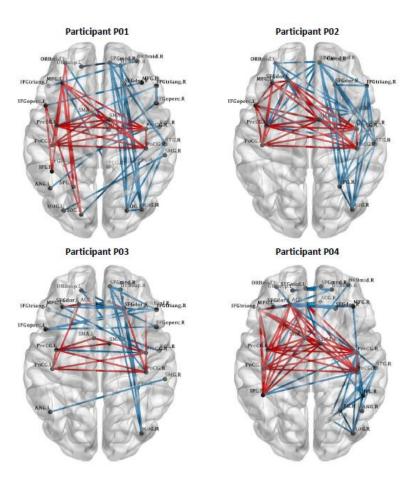


- Both mu and beta band ERD increased from first to the last session
- Significant pre vs post ERD changes in EEG :

Mu band Left Task: CP4; Mu band Right Task: C3, CP3

Beta band Left Task: C4; Beta band Right Task: F3 and FC3

Resting State beta band connectivity change in MEG – A Neuroplasticity Analysis



- Functional connectivity (FC) clusters correlated positively (Red) and negatively (Blue) with the hand functional recovery index for all four participants in beta frequency band (15-26 Hz).
- ➤ The intra-hemispherical FC values in M1, S1, and SMA within both ipsilesional and contralesional hemispheres increase with UL functional recovery.
- ➤ The ipsilesional hemisphere possesses larger number of positively correlated clusters.
- ➤ The inter-hemispherical FC analysis showed a stable pattern of positively correlated connections within the motor cortical regions whereas the inter-hemispheric negative cluster is variable across the participants.

Left -> Ipsilesional hemisphere

Rathee, Chowdhury, Meena, Dutta, McDonough, and Prasad, "Brain-machine interface driven post-stroke upper limb functional recovery correlates with beta-band mediated cortical naturals." IEEE Trans. on Noural Systems & Bobabilitation Eng., 2010.

Advancing MEG-based BCI Supported Neurorehabilitation

-MEG Issues:

- Highest spatiotemporal resolution (204 gradiometer & 102 magnetometer channels, Neuromag® TRIUX, recorded at 1k Hz) of all neuroimaging modalities.
- Sensors in a dedicated helmet rather than physically placed on subjects' scalps resulting in significant signal attenuation and channel displacements due to head movements.
- Low decoding accuracy, despite using large number of channels.
- For MEG-based BCI no systematic channel selection methodology.

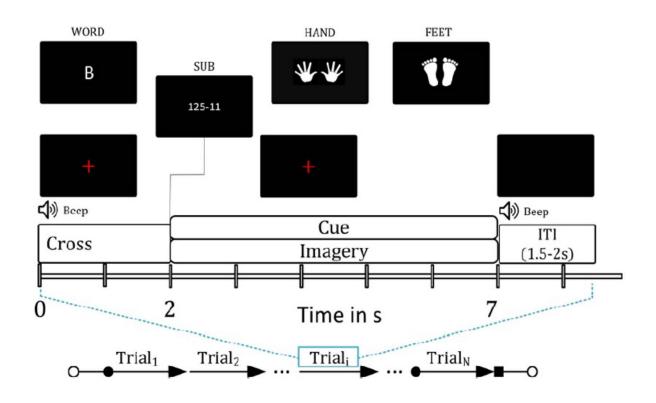
➤ UKIERI phase-3 project: Advancing MEG-based Brain-Computer Interface Supported Upper Limb Post-Stroke Rehabilitation (DST UKIERI 2016 -17 -128, PI, £145k, 2017 – 21).

Channel Selection using Computational Intelligence (CI)

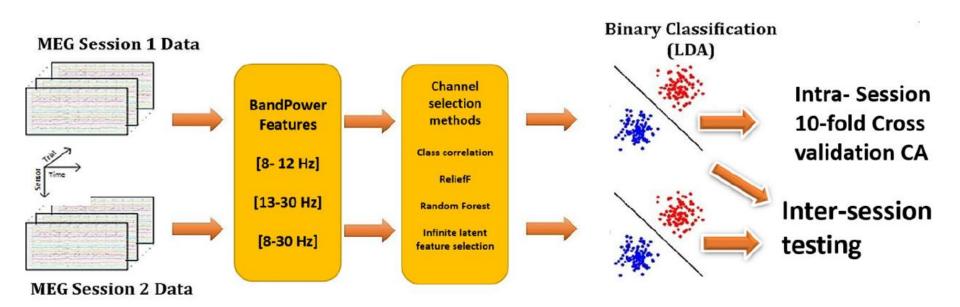
- Timing paradigm design for data recording;
- MEG data recorded for two sessions from 17 healthy participants performing mixed imagery (motor imagery and cognitive imagery) tasks;
- Data pre-processing bad channels removed.
- Channel selection methods: Class-Correlation, ReliefF, Random Forest, and Infinite Latent Feature Selection were applied across six binary tasks in three different frequency bands;
- Features: Band power and common spatial pattern (CSP)
- Feature classification using Linear Discriminant Analysis (LDA) classifier.

Roy, Rathee, Chowdhury, McCreadie, & Prasad (2020). Assessing impact of channel selection on decoding of motor and cognitive imagery from MEG data. Journal of Neural Engineering, 17(5).

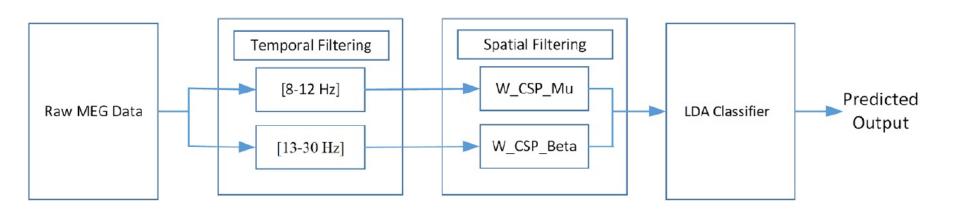
Timing diagram of MEG-based BCI paradigm



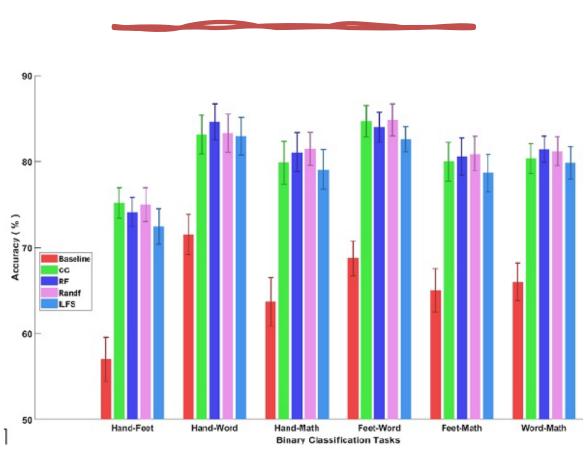
Schematic diagram of signal processing pipeline using band power feature



The data processing pipeline using CSP

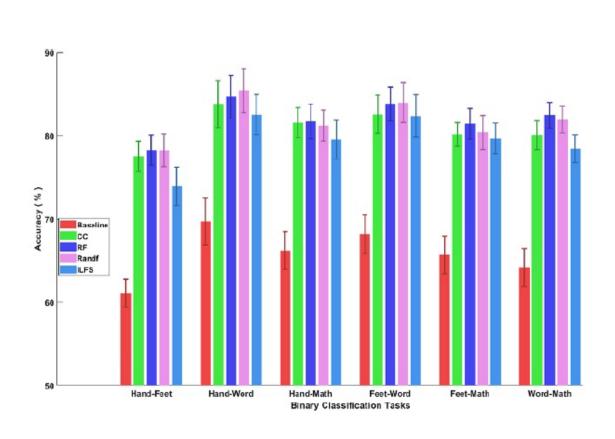


Mean classification accuracies (CAs) for α band (8-12 Hz) for session-1 using 10-fold cross-validation

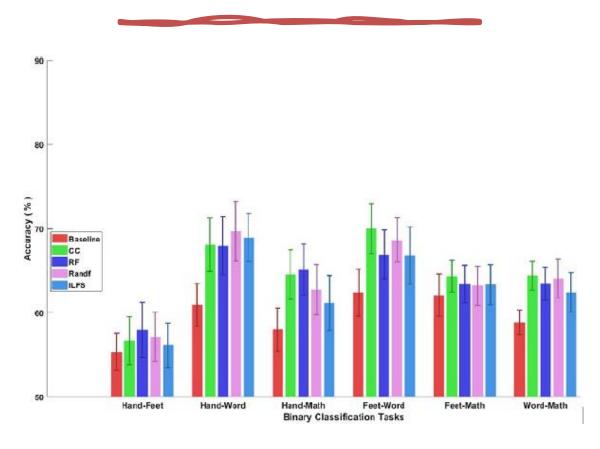


- ✓ RandF provided a statistically significant improvement over ILFS in H-F, H-M, W-M, F-W and W-M task pairs (p < 0.05).
- ✓ Overall mean CA across subjects using RandF is 81.11% (±6.02), ILFS is 79.30% (±6.51), CC is 81.72% (±6.25), and RF is 81.14% (±6.22) for session 1 whereas baseline was 65.32% (±8.09).

Mean CAs for the α band (8-12 Hz) for session-2 using 10-fold cross-validation



Mean classification accuracies (CAs) for α band for a classifier trained on session-1 data and tested on session-2 data



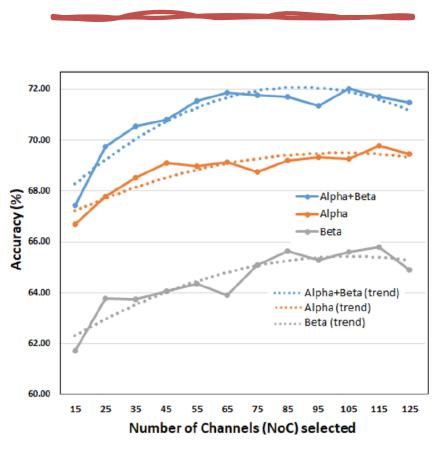
- ✓ Because of substantial inter-session non-stationarities due to head movements, there is a significant drop in mean CAs obtained, with classifiers trained on a data-set from a different session.
- ✓ Channel selection does improve inter-session classifier performance.
- ✓ H-W group provided higher accuracy than the MI (H-F) group.

Number of channels contributing to maximum accuracy using RandF method in α+β band using bandpower feature

Participants	Hand vs Foot		Hand vs Word		Hand vs Math		Feet vs Word		Feet vs Math		Math vs Word	
	S01	<i>S</i> 02	S01	S02	S01	S02	S01	S02	S01	S02	S01	S02
P01	7	7	14	5	16	5	9	7	14	19	11	12
P02	13	11	14	4	23	12	15	12	6	15	9	9
P03	10	8	10	13	10	12	9	9	8	8	14	13
P04	14	11	5	13	8	14	14	16	17	1	12	10
P05	9	9	14	9	7	21	5	6	8	6	16	9
P06	14	6	24	15	11	15	18	17	14	9	18	6
P07	16	6	19	11	14	10	11	10	6	9	14	6
P08	13	12	13	14	9	14	13	10	8	12	10	21
P09	22	12	18	9	13	13	16	9	13	2	13	9
P10	4	13	9	16	10	12	15	18	10	16	18	6
P11	16	11	9	12	14	14	19	18	14	7	12	14
P12	9	19	2	12	3	7	17	12	7	12	9	6
P13	13	11	16	7	10	13	10	11	3	8	5	4
P14	7	5	12	8	15	14	10	5	6	20	7	2
P15	11	18	16	8	9	11	16	18	8	13	11	11
Mean	11.87	10.6	13	10.4	11.47	12.47	13.13	11.87	9.47	10.47	11.93	9.2

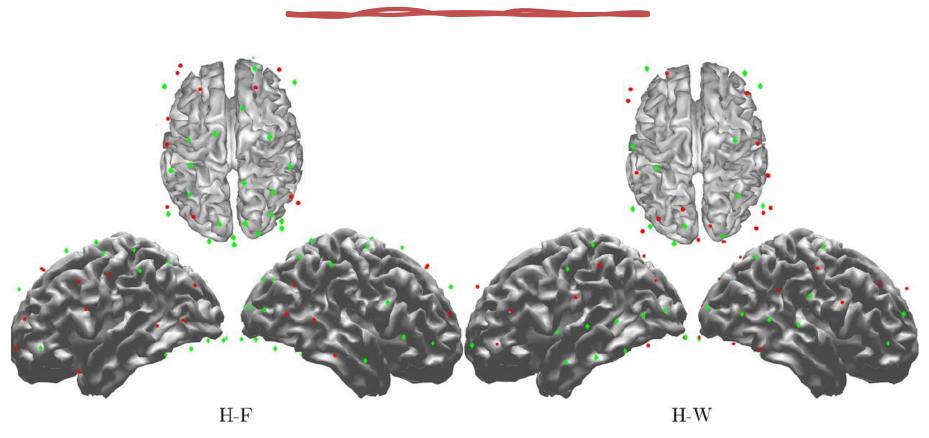
Optimal number of channels range between 2 and 23 out of 204 gradiometer channels used. So, there is substantial reduction in selected channels, whilst there is a large gain in CAs. 2

Mean transfer-session accuracy with the channels selected using CSP in all the three bands



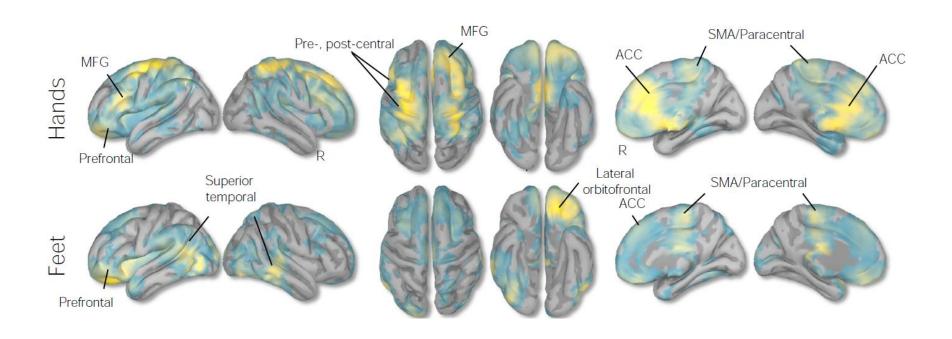
✓ However, if we feed the CSP algorithm with a larger number of channels (NoC) it can
optimize the CSP projection matrix very well which could lead to higher discriminability
between the two classes.

Plot of channels common for minimum of three participants' imagery tasks for 8-30 Hz



- represents channels in session 01
- & represents channel in session 02.
- ✓ Due to significant non-stationarities, optimally selected channels are quite different in two sessions.

Group source analysis of task-imagery BCI experiment



Activation maps corresponding to Hands and Feet motor imagery tasks measured by the DICS beamformer source analysis in a frequency range of beta (17-25Hz) from 14 participants. t -maps are thresholded at a whole-cortex corrected p <0.05.

Main Findings of MEG-based BCI Performance Analysis

- Channel selection improved intra-session BCI CA significantly but intersession CA improvement is marginal.
- The optimal channel number varied not only in each session but also for each participant.
- Reducing the NoC helps to decrease the computational cost and maintain numerical stability in cases of low trial numbers.
- For all combinations, the mixed imagery task pairs (H-W, H-M, F-W & F-M) provided higher separability as compared to the H-F and W-M task pairs in α band.
- Findings support that the suppression of alpha band power around 10 Hz is a stronger marker for movement planning, execution and imagery than beta band.
- It resulted into substantial channel reduction, from 204 channels to:
 - a range of 2–23 channels using bandpower as a feature and
 - 15-105 channels using common spatial pattern (CSP) features.
- Roy, Rathee, Chowdhury, McCreadie, & Prasad (2020). Assessing impact of channel selection on decoding of motor and cognitive imagery from MEG data. *Journal of Neural Engineering*, 17(5).

Laboratory Exercise on MEG Data

An MEG dataset for motor and cognitive imagery-based brain-computer interface

Aims

- Study of neuroimaging data obtained from MEG scanner during motor imagery and cognitive imagery tasks.
- Developing a BCI decoder.

Objectives

The exercise document file (*Laboratory Work_CN3_Day_3_MEG_2022.pdf*) is available for download in the GitHub website at: https://github.com/ISRC-CN3. Exercise will help facilitate familiarisation with an MEG data-set and its usage in a BCI decoder design. The data-set is available on-line as part of the following *Scientific Data-Nature* paper.

- Rathee, D., Raza, H., Roy, S., & Prasad, G. (2021). A magnetoencephalography dataset for motor and cognitive imagery-based brain–computer interface. *Scientific Data-Nature*, (8), [120]. https://doi.org/10.1038/s41597-021-00899-7.
- MEG data-set at figshare Collection: A magnetoencephalography dataset for motor and cognitive imagery BCI (figshare.com)

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- McCreadie, K., Coyle, D., & Prasad, G. (2014). Is Sensorimotor BCI Performance Influenced Differently by Mono, Stereo, or 3-D Auditory Feedback? IEEE Transactions on Neural Systems and Rehabilitation Engineering, 22(3), 431-440. https://doi.org/10.1109/TNSRE.2014.2312270.
- Prasad et al. (2010), "Applying a brain-computer interface to support motor imagery practice in people with stroke for upper limb recovery: a feasibility study," **J. Neuroeng. Rehabil**., vol. 7(1)

Conclusion

- Neurorehabilitation system integrating BCI and a hand exoskeleton.
- BCI neurofeedback of motor imagery practice enhances rehab effectiveness and patient focus.
- BCI brain activations in EEG/MEG trigger hand exoskeleton to provide active rehab exercises.
- Exoskeleton proprioceptive neurofeedback enhances BCI effectiveness for focused mental practice of rehab tasks.
- Completed Pilot trial demonstrated enhanced effectiveness through a six week clinical trial on four hemiplegic stroke patients; functional recovery gain in terms of GS and ARAT scores and other transformative change in stroke participants.
- Significantly enhanced decoding accuracy obtained on MEG-based BCI using computational intelligence techniques for channel selection.
- Further data analysis and trials are on-going on the Neurorehabilitation System using MEG-based BCI controlled exoskeleton.

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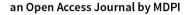














Affiliated Societies



Aim and Scope

Robotics aims to provide an international forum to report the latest developments in robotic systems, autonomous behaviors, multi-sensor fusion, learning algorithms, system modelling, control software, smart actuators, service applications, and human–machine interaction. Special emphasis is given to technological innovation and real-world applications.

The scope of *Robotics* includes but is not limited to:

- · History of robotics;
- Intelligent robotics, mechatronics, and biomimetics;
- Novel and biologically inspired robotics;
- Modelling, identification, and control of robotic systems;
- Biomedical, rehabilitation, and surgical robotics;
- Exoskeletons, prosthetics, and artificial organs;
- Al, neural networks, and fuzzy logic in robotics;

- Multimodal human-machine interaction;
- · Wireless sensor networks for robot navigation;
- Multi-sensor data fusion and SLAM;
- Service robotics, industrial robotizations, space robotics;
- Sensorization, robot navigation, communication robotics;
- Swarm robotics, mobile and flying robotic systems.



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