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A Hybrid Gaze-Motor Imagery BCI Framework for Effective Decision Communication

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Problem & Motivation

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- Existing hybrid BCIs largely overlook the effects of gaze, fixation, and perceptual processing on MI-related neural activity, treating these components independently rather than modelling their interaction during decoding.
- To systematically investigate how MI EEG is influenced by gaze behaviour, fixation, and perceptual processing, and to determine how these factors affect MI decoding performance.

- Existing hybrid BCI systems are predominantly **cue-paced (synchronous)**, where user interactions are constrained by predefined cues and fixed time windows for decoding left- and right-hand motor imagery.
- Relatively few studies explore **self-paced (asynchronous) frameworks**, particularly **one-versus-rest MI** strategies in which a single MI class acts as a selection command and the rest-state serves as a non-control “waiting” state, thereby reducing cognitive load.
- Perceptual decision-making, gaze behaviour, and MI-based BCI paradigms have largely been investigated **in isolation**, with limited effort toward their unified integration.
- The potential of **visual fixation to stabilise neural responses** and enhance real-time MI-based BCI performance remains underexplored, and most systems still assume full EEG montages.

Contributions

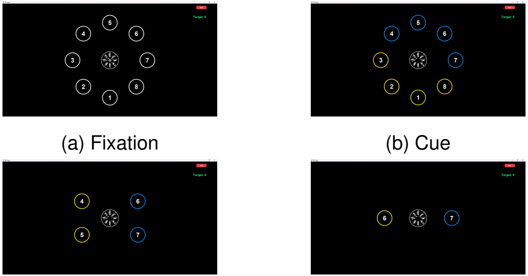
- Designing an attention-aware MI hybrid BCI paradigm incorporating fixation, peripheral targets, colour cues, and dot-motion feedback to modulate attention.
- Developing an asynchronous hybrid MI–eye-tracking framework enabling self-paced, low cognitive-load decision-making (one-versus-rest, brain-switch architecture).
- Conducting a comprehensive comparison with conventional MI and hybrid MI, demonstrating improved performance and efficiency.

MI Paradigm Design

- Eight targets on a **circular layout**, each with a distinct spatial cue.
- **Hierarchical binary decision strategy:** targets progressively narrowed by successive splits.
- Groups of four are colour-coded; the participant selects a group in the **perceived coherent motion direction** (left/right).
- The selected group is split into two, another selection is made, and the tree continues until a **single target** remains.
- Decoding is **cue-paced**: left- vs right-hand MI within a fixed window.

$$\mathbf{8 \rightarrow 4 \rightarrow 2 \rightarrow 1}$$

requires **three sequential MI executions** per target



(a) Fixation (b) Cue

(c) First Decision (d) Second Decision

Fig.1. Illustration of the proposed MI-based target selection paradigm showing fixation, cue presentation, and hierarchical decision stages.

Hybrid Gaze - MI Paradigm

- Same trial structure as the MI paradigm (fixation, coloured cue, decision, ITI), with **synchronised eye-tracking** added.
- During the decision phase the participant **fixates the cued target** while simultaneously performing the MI task.
- **Asynchronous, one-vs-rest** design: right-hand MI acts as the *selection* command, the rest/idle state as the *waiting* state (brain-switch architecture).
- Eye tracking identifies the target; **MI confirms** it before execution.

Experimental Paradigm: https://youtu.be/K5K3pO6PDpE

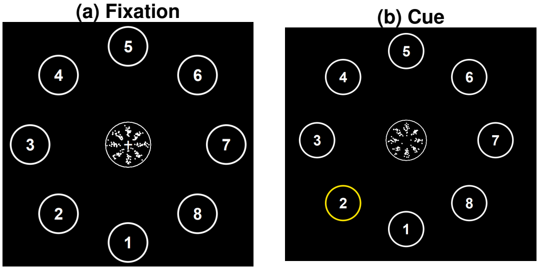
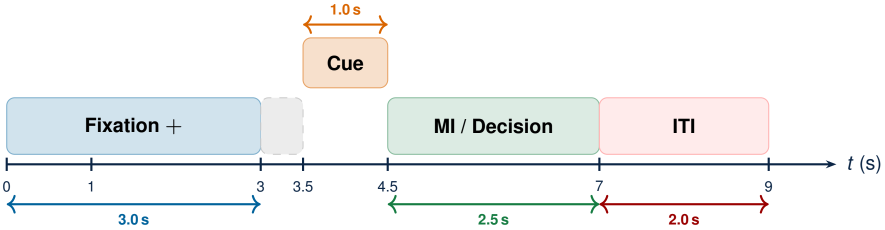


Fig. 2. Illustration of a single hybrid trial fixation (left) and coloured cue (right).

Trial Timing Structure



- **3 s fixation cross** stabilises the participant and minimises motion artefacts.
- Cue onset is **jittered within the 3–3.5 s window** (shaded) and persists for 1 s.
- **2.5 s response window** for MI execution, followed by a **2 s ITI**.
- Identical timing is used for both the MI and hybrid paradigms.

Paradigm Comparison

Aspect	Conventional MI	Proposed Hybrid Gaze–MI
Control mode	Cue-paced (synchronous)	Self-paced (asynchronous)
MI classes	Left vs. right hand	Right hand vs. rest (one-vs-rest)
Target selection	Hierarchical $8 \rightarrow 4 \rightarrow 2 \rightarrow 1$	Single-step gaze selection
MI executions	Three per target	One confirmation per target
Role of MI	Selection mechanism	Confirmation of the gaze-selected target
Trials per cycle	24	8

Design rationale

Gaze provides fast, reliable target selection; MI supplies intentional confirmation that gaze alone cannot guarantee. This removes repeated MI executions and lowers cognitive load.

Overview of Analysis Framework

Input signal → Pre-processing → Feature extraction → Classification → Decision

1. **Segmentation** — MI: block-wise on class label, truncated to 1500 samples. Hybrid: event markers for ‘right-hand MI’ (samples 500–1500) and ‘rest’ (first 1000 samples).
2. **Channel configurations** — motor cortex (C3, Cz, C4); extended motor cortex (F3, Fz, F4, P3, Pz, P4); full 16-channel montage.
3. **Filtering** — 4th-order Butterworth into mu (8–12 Hz) and beta (13–30 Hz) bands; FastICA removal of components correlated with Fp1/Fp2.
4. **Feature extraction** — CSP on normalised spatial covariance, 4 components per band, mu and beta concatenated.
5. **Classification** — SVM (RBF), RF, DT, KNN, Gaussian NB with 5-fold cross-validation.

Participants and Protocol

Participants

- 15 healthy participants (20–32 years; 14 M, 1 F)
- Controlled laboratory conditions, standardised acquisition protocol
- Approved by the Institutional Ethics Committee, IIT Gandhinagar; Declaration of Helsinki

Session configuration

- Input mode, fixation condition (on/off), phase (calibration/testing), no. of cycles
- One cycle $=$ **24 MI trials** $+$ **8 hybrid trials**
- 9 trials per task; g.Nautilus, **16 channels**, **500 Hz**, 10–20 montage

Two fixation conditions

Fixation-cross (+): supports attentional alignment and controlled readiness.
No-fixation: evaluates how participants self-regulate attention with no external stabilisation reference.
In both, dot-based visualisation gives progressive feedback during the decision process.

Experimental Results

		Fixation OFF		Fixation ON	
Paradigm	**Channels**	Acc.	SD	Acc.	SD
Eye-tracking	—	0.75	—	0.75	—
	All (16)	0.52–0.55	$\sim$0.11	0.53–0.55	0.08–0.11
	Motor (3)	0.56	0.08	**0.58**	0.11
	Ext. motor (9)	0.50–0.55	—	0.50–0.55	—
Hybrid	**All (16)**	**0.979–1.000**	0.000–0.052	**0.986–1.000**	0.000–0.044
	Motor (3)	0.687–0.723	0.139–0.166	0.678–0.723	0.178–0.190
	Ext. motor (9)	0.792–0.841	0.160–0.192	0.828–0.853	0.174–0.187

Ranges span over five classifiers (SVM, KNN, Gaussian NB, Random Forest and Decision Tree); MI motor-cortex row reports SVM.

Classifier - Wise Results

Classifier	Fixation OFF	Fixation ON
SVM (RBF)	**1.000**	0.999
KNN	**1.000**	**1.000**
Gaussian NB	**1.000**	**1.000**
Random Forest	0.999	0.995
Decision Tree	0.979	0.986

- Near-zero inter-subject variability (SD ≤ 0.052)
- **Wilcoxon signed-rank:** $p = 1.22 \times 10^{-4}$, all classifiers

Conclusion

- Proposed an **asynchronous hybrid gaze–MI BCI**: gaze selects the target, one-vs-rest MI confirms it.
- **0.99–1.00** accuracy vs. **0.54–0.58** for conventional MI, with near-zero inter-subject variability ($p = 1.22 \times 10^{-4}$).
- **Three** sequential MI executions collapse to **one** confirmation step.
- Discriminative activity extends **beyond C3/Cz/C4** -motor-only montage falls to 0.68–0.72.

Limitations & Future Work

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Limitations

- Controlled laboratory conditions only
- **Offline** analysis: latency, adaptation and feedback dynamics untested

Future work

- Real-time closed-loop system; synchronous vs. asynchronous comparison
- Neuromuscular patients and children with dyslexia
- Longitudinal stability and fatigue effects
- Isolate contribution of dot-motion feedback

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Thank You!

Questions?

Contact: `haix.lab@iitgn.ac.in`

github.com/HAIx-Lab/Hybrid-BCI-for-Effective-Decision-Communication

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