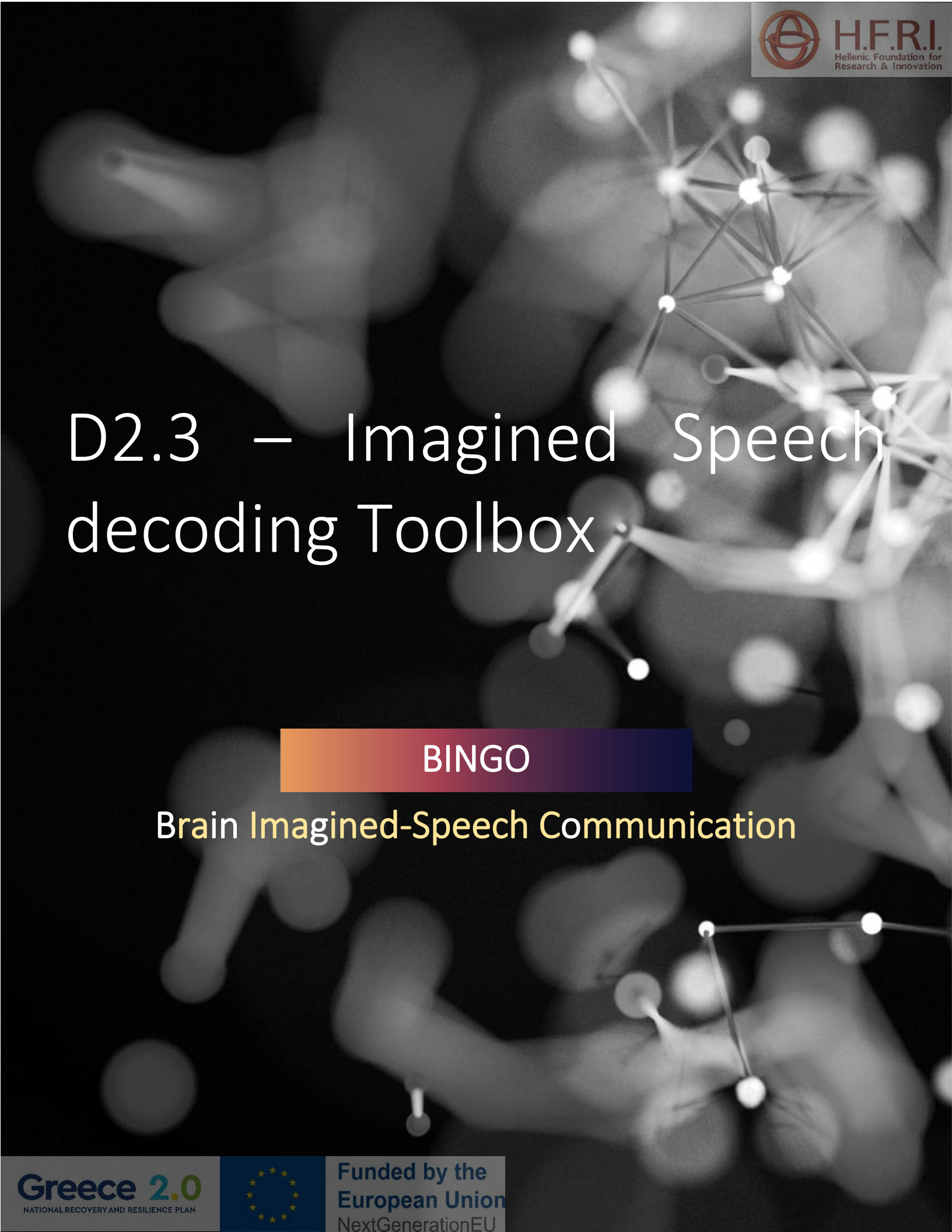


D2.3 – Imagined Speech decoding Toolbox

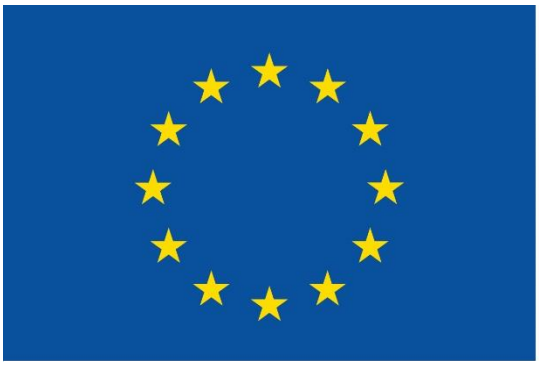
BINGO

Brain Imagined-Speech Communication

H.F.R.I. Hellenic Foundation for Research & Innovation

Greece 2.0 NATIONAL RECOVERY AND RESILIENCE PLAN

Funded by the European Union NextGenerationEU



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Abstract: This document accompanies BINGO's GitHub and presents a detailed overview of the Imagined Speech Decoding Toolbox. The repository comprises a comprehensive toolbox that supports EEG-based imagined speech research across the entire processing pipeline, from experimental data acquisition to preprocessing, segmentation, and downstream data analysis.

HISTORY

Version	Date	Reason	Revised by
V0.1	20/10/2025	Table of Contents	Kostas Georgiadis
V0.2	19/11/2025	Initial Draft	Kostas Georgiadis
V1.0	24/11/2025	Final Draft	Spiros Nikolopoulos

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ABBREVIATIONS AND ACRONYMS

BCI	Brain Computer Interface
EEG	ElectroEncephaloGram
LSL	Lab Streaming Layer

Contents

INTRODUCTION

This deliverable provides a comprehensive description of the **Imagined Speech Decoding Toolbox** GitHub repository (https://github.com/BINGO-BCI/). The repository constitutes a modular, end-to-end toolbox designed to support research on EEG-based imagined speech decoding, covering the full pipeline from experimental data acquisition to preprocessing, segmentation, and data processing/analysis. Emphasis is placed on reproducibility, transparency, and extensibility, enabling researchers to adapt the toolbox to different imagined speech paradigms and datasets.
The repository is structured around three main functional pillars:

1. **Data Collection**
2. **Preprocessing and Segmentation**
3. **Data Processing and Analysis**

Each pillar is implemented as a dedicated set of folders and scripts, described in detail in the following sections.

DATA COLLECTION

The Data Collection component of the repository provides all necessary tools to ensure controlled experimental execution and synchronized multimodal data acquisition. It focuses on the reliable capture of EEG signals together with precise event markers corresponding to imagined speech tasks.

PSYCHOTOOLBOX BASED EXPERIMENTAL PROTOCOL

This subsection includes scripts implemented in **PsychoToolbox**, designed to support the execution of imagined speech experiments in a controlled and reproducible manner. The protocol defines:

- The temporal structure of each trial (e.g., fixation, cue presentation, imagined speech interval, rest).
- Visual and/or auditory cues corresponding to imagined speech prompts (e.g., NATO alphabet letters, English–Greek words).
- Precise triggering of event markers aligned with experimental events.

The PsychoToolbox implementation ensures:

- High temporal precision suitable for EEG experiments.
- Flexibility to adapt the protocol to different imagined speech vocabularies and task designs.
- Consistency across recording sessions and participants.

All experimental parameters (timings, stimuli lists, repetitions) are configurable, allowing the protocol to be reused or extended for future studies.

LABRECORDER FOR SYNCHRONIZED DATA CAPTURE

To enable seamless and synchronized recording of EEG signals and experimental markers, the repository integrates **LabRecorder** based on the Lab Streaming Layer (LSL) framework.
This component ensures:

- Concurrent acquisition of continuous EEG data streams.
- Reliable recording of event markers generated by the PsychoToolbox protocol.
- Accurate temporal alignment between neural signals and imagined speech events.

The provided configuration and usage guidelines facilitate robust data logging across different recording setups, minimizing data loss and synchronization errors. This design choice supports downstream segmentation and analysis with high temporal fidelity.

PREPROCESSING AND SEGMENTATION

The *Preprocessing and Segmentation* component focuses on transforming raw EEG recordings into structured, analysis-ready datasets. It includes dataset-specific segmentation scripts and reusable preprocessing functions.

SEGMENTATION: NATO ALPHABET IMAGINED SPEECH EXPERIMENT

This subsection contains a dedicated file for segmenting EEG recordings from the **NATO alphabet imagined speech experiment**. The script:

- Parses recorded LSL markers corresponding to individual NATO alphabet prompts.
- Extracts time-locked EEG epochs associated with imagined speech intervals.
- Organizes segmented trials into a structured format suitable for machine learning and statistical analysis.

The segmentation logic is parameterized, allowing adjustments to epoch lengths, baseline periods, and class definitions.

SEGMENTATION: ENGLISH–GREEK IMAGINED SPEECH DATASET

A separate segmentation file is provided for the **English–Greek imagined speech dataset**. This script accounts for dataset-specific characteristics, including:

- Language-dependent prompt labeling.
- Potential differences in trial structure or timing.
- Harmonized output formatting to ensure compatibility with shared preprocessing and analysis pipelines.

By maintaining separate segmentation scripts, the repository preserves clarity while supporting heterogeneous experimental designs.

PREPROCESSING FUNCTIONS

The repository includes a collection of reusable preprocessing functions applied consistently across datasets. These functions address common EEG signal conditioning requirements, including:

- **Artifact Subspace Reconstruction (ASR):** Automated detection and attenuation of high-variance artifacts, improving signal quality while preserving neural information.
- **FORCe-based preprocessing:** Advanced signal conditioning methods aimed at enhancing robustness and consistency across sessions and subjects.

Additional standard preprocessing steps (e.g., filtering, re-referencing, normalization) are implemented in a modular fashion, allowing users to enable, disable, or customize each step as needed.

DATA PROCESSING AND ANALYSIS

The *Data Processing* component of the repository is organized into two main subfolders, corresponding to the two primary imagined speech datasets supported by the toolbox.

NATO ALPHABET DATA PROCESSING

The NATO alphabet processing folder focuses on quantitative decoding and classification approaches, including both classical and modern machine learning techniques.
Key components include:

- **Riemannian Geometry-Based Methods:**
    - Feature extraction based on covariance matrices.
    - Classification approaches operating on the Riemannian manifold of symmetric positive definite matrices.
    - Baseline and comparative pipelines suitable for low-sample, high-dimensional EEG data.
- **Deep Learning Approaches:**
    - Neural network architectures tailored to time-series EEG data.
    - End-to-end learning pipelines for imagined speech classification.
    - Configurable training and evaluation scripts enabling systematic experimentation.

Together, these methods support rigorous performance evaluation and benchmarking across different decoding paradigms.

ENGLISH–GREEK DATA PROCESSING

The English–Greek processing folder emphasizes **qualitative and exploratory analyses**, aimed at understanding neurophysiological differences across languages and imagined speech conditions.
Included analyses comprise:

- **Topographic Maps (Topoplots):** Visualization of spatial activation patterns across the scalp.
- **Power Spectral Density (PSD) Analysis:** Frequency-domain characterization of imagined speech-related EEG activity.

- **Additional EEG-Related Metrics:** Time-domain and frequency-domain descriptors supporting qualitative comparison between conditions and languages.

These analyses provide interpretability and neurophysiological insight, complementing the quantitative decoding approaches applied to the NATO alphabet dataset.

SUMMARY AND OUTLOOK

The **Imagined Speech Decoding Toolbox** repository delivers a coherent and extensible framework for EEG-based imagined speech research. By covering data collection, preprocessing, segmentation, and dataset-specific processing within a unified structure, the toolbox supports both methodological development and reproducible experimentation.

The modular design facilitates future extensions, including the integration of additional datasets, alternative preprocessing strategies, and novel decoding algorithms, positioning the repository as a solid foundation for ongoing and future research in imagined speech decoding.