Functional Neuroarchitecture of Brain Activation and Network Organization in Bilinguals During Native and Second Language Processing

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Overview

Goal:

To examine how bilinguals' brain networks **dynamically reorganize during semantic processing** in their native (L1: Spanish) vs. second (L2: Basque) language, and how these dynamics differ between **advanced and intermediate** speakers.

Core Question:

How do large-scale brain networks adapt when bilinguals switch between their first and second language, and how does this reorganization depend on language proficiency?

Rationale:

- Traditional fMRI studies often treat brain connectivity as static, overlooking how network interactions fluctuate over time.
- In this study, we used dynamic functional connectivity (dFC) and Hidden Markov Models (HMMs) to capture these moment-to-moment changes in network organization.
- Our work tests the Neurocognitive Adaptation Hypothesis, which predicts that greater bilingual proficiency leads to enhanced network stability, efficiency, and flexibility during second-language processing.

Background

Understanding how bilinguals process multiple languages helps reveal how the brain adapts to linguistic demands.

Prior studies show that L2 (second language) use engages broader and more distributed brain networks than L1.

However, temporal network dynamics—how these networks fluctuate over time—remain less explored.

By combining Independent Component Analysis (ICA) and Yeo 7-network mapping, we explored both static and dynamic network organization during semantic processing in bilinguals.

- Dynamic Functional Connectivity (dFC) captures how brain network interactions fluctuate over time.

This approach allows us to measure:

- *Mean Dwell Time (MDT): how long the brain maintains a network configuration.*
- *Transitions: how often it switches between configurations.*
- *Fractional Occupancy (FO): how much time is spent in each configuration.*

Why Independent Component Analysis (ICA)?

- We used ICA to decompose whole-brain fMRI data into spatially independent functional networks, providing a data-driven view of large-scale systems engaged during bilingual language processing.
- This approach captures individual and group-level network dynamics without imposing predefined anatomical constraints, enabling us to track how these networks reconfigure over time across languages and proficiency levels.

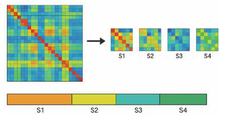
Our focus:

1. Identify core networks engaged during L1 and L2 processing.
2. Examine temporal flexibility and network occupancy across proficiency levels.
3. Relate dynamic metrics (Fractional Occupancy, Dwell Time) to bilingual proficiency.

Approach

Dynamic State Modeling and Network Integration

Time-varying functional connectivity (FC) matrices were computed and clustered. A Hidden Markov Model (HMM) cross-validated these patterns, yielding a discrete sequence of recurring "brain states."



Network Mapping (Yeo-7 Integration)

Each ICA component was mapped to canonical Yeo-7 networks (Visual, Somatomotor, Dorsal Attention, Ventral Attention, Limbic, Control, DMN). This established a link between ICA-derived spatial maps and known functional systems.

$$Network\ Similarity\ L1, L2 = corr\ (ZL1, Z_{L2})$$

Methods

26 Right-handed Native Spanish speakers learning Basque

Participants

Intermediate (40< CEFR scores <60, n=10)

Advanced (70< CEFR scores <100, n=16)

All living in Spanish-Basque bilingual environments

Semantic Animacy Judgment Task

Reading condition – printed words shown for 1000 ms

Listening condition– auditory words (~585 mc)

Decide: Living or Non-living?

Respond with right-hand button press

dog → LIVING

chair → NON-LIVING

Experimental Structure (Inside the Scanner)

Action	Rest	Intermixed (auditory/visual) Stimuli	Rest	Intermixed (auditory/visual) Stimuli	Rest
Time (sec)	20	~150	20	~150	20

Language 1 (Spanish 🇪🇸) — 3 runs — 48 stimuli/run

Language 2 (Basque 🇪🇺) — 3 runs — 48 stimuli/run

Order counterbalanced across participants to avoid switching effects.

Approach

The fMRI Preprocessing Pipe Line and Data Preparation

Motion Correction → Slice Timing Correction → Brain Extraction → Spatial Registration → Spatial Smoothing → Temporal Filtering → Data Concatenation

The fMRI data were preprocessed, we integrated Independent Component Analysis (ICA), and Dynamic Functional Connectivity (dFC) modeling to characterize how bilingual brain networks reorganize across native (L1) and second language (L2) processing.

Probabilistic Independent Component Analysis (ICA)

We applied Probabilistic ICA (DictLearning) to identify large-scale functional networks shared across participants.



$$X_i(t,v) = \sum_{k=1}^{K} S_k(v) A_{i,k} + \varepsilon_i(t,v), \qquad K = 20$$





$S_k(v)$: Spatial Maps (Network components)

$A_{i,k}(t)$: Subject-specific time courses

Dynamic Functional Connectivity (dFC)

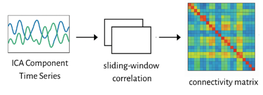
To capture time-varying connectivity, we extracted ICA component time series and applied a sliding-window correlation:

Lorem ipsum

$$FC_w(k_1, k_2) = corr\ (Ai, k_1(t{:}\ t + W), A_{i,k_2}(t{:}\ t + W))$$

W = 30 TRs, step = 5

Each window yielded a connectivity matrix representing the brain's evolving network configuration.



Results

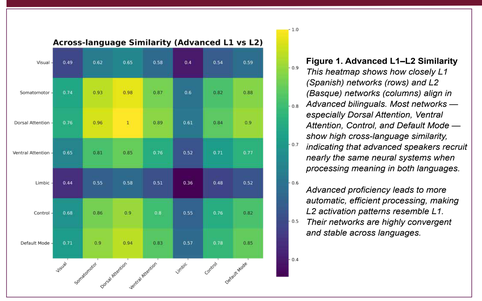


Figure 1. Advanced L1–L2 Similarity *This heatmap shows how closely L1 (Spanish) networks (rows) and L2 (Basque) networks (columns) align in Advanced bilinguals. Most networks — especially Dorsal Attention, Ventral Attention, Control, and Default Mode — show high cross-language similarity, indicating that advanced speakers recruit nearly the same neural systems when processing meaning in both languages.*

Advanced proficiency leads to more automatic, efficient processing, making L2 activation patterns resemble L1. Their networks are highly convergent and stable across languages.

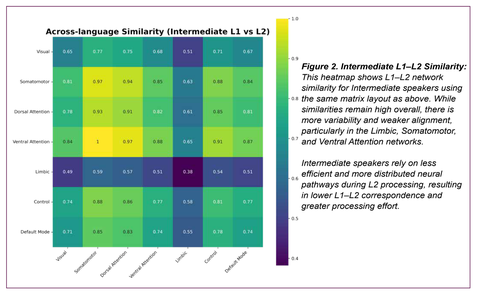


Figure 2. Intermediate L1–L2 Similarity: *This heatmap shows L1–L2 network similarity for Intermediate speakers using the same matrix layout as above. While similarities remain high overall, there is more variability and weaker alignment, particularly in the Limbic, Somatomotor, and Ventral Attention networks.*

Intermediate speakers rely on less efficient and more distributed neural pathways during L2 processing, resulting in lower L1–L2 correspondence and greater processing effort.

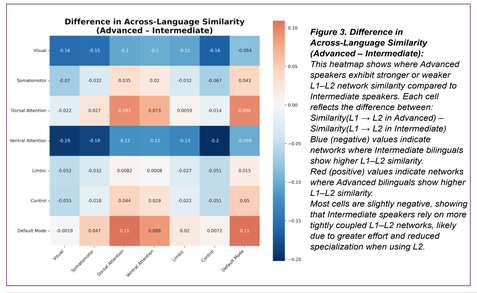


Figure 3. Difference in Across-Language Similarity (Advanced – Intermediate): *This heatmap shows where Advanced speakers exhibit stronger or weaker L1–L2 network similarity compared to Intermediate speakers. Each cell reflects the difference between: Similarity(L1 → L2 in Advanced) – Similarity(L1 → L2 in Intermediate) Blue (negative) values indicate networks where Intermediate bilinguals show higher L1–L2 similarity. Red (positive) values indicate networks where Advanced bilinguals show higher L1–L2 similarity. Most cells are slightly negative, showing that Intermediate speakers rely on more tightly coupled L1–L2 networks, likely due to greater effort and reduced specialization when using L2.*

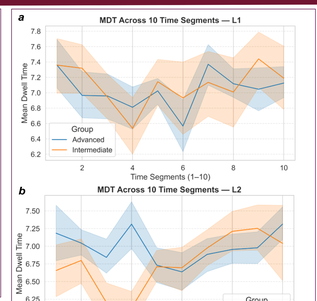


Figure 3: Dynamic Network Analysis of Temporal Brain States During Semantic Processing. *Each plot shows group-averaged dynamic metrics across 10 temporal segments (~10% of task time each).*
(a) MDT – L1: Advanced and Intermediate speakers show nearly identical, stable dwell-time trajectories, consistent with automatized native-language processing.
(b) MDT – L2: Advanced speakers sustain longer dwell times across most segments, indicating more efficient and stable network engagement; Intermediate show shorter, more variable MDTs, reflecting less stable configurations.
(c) Transitions – L1: Both groups show similar transition patterns with minor fluctuations
(d) Transitions – L2: Intermediate show more transitions early and mid-task (greater control demands), while advanced speakers show fewer transitions, indicating more stable dynamics.

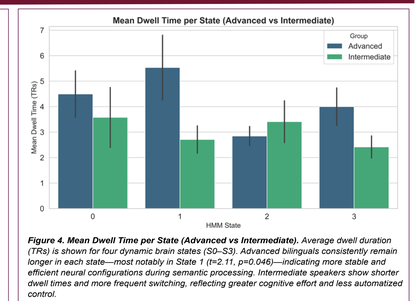


Figure 4. Mean Dwell Time per State (Advanced vs Intermediate). *Average dwell duration (TRs) is shown for four dynamic brain states (S0–S3). Advanced bilinguals consistently remain longer in each state—most notably in State 1 (t=2.11, p=0.046)—indicating more stable and efficient neural configurations during semantic processing. Intermediate speakers show shorter dwell times and more frequent switching, reflecting greater cognitive effort and less automatized control.*

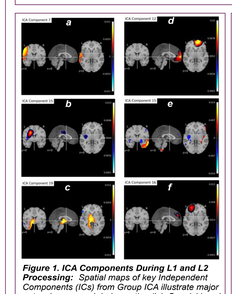


Figure 1. ICA Components During L1 and L2 Processing: *Spatial maps of key Independent Components (ICs) from Group ICA illustrate major networks engaged during native (L1: Spanish) and non-native (L2: Basque) semantic processing. Panels (a–c) show L1 components, and (d–f) show L2 components. Warm colors indicate stronger positive activation and cool colors indicate negative contributions within each IC.*

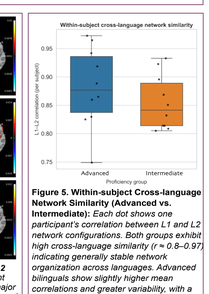


Figure 5. Within-subject Cross-language Network Similarity (Advanced vs. Intermediate): *Each dot shows one participant's correlation between L1 and L2 network configurations. Both groups exhibit high cross-language similarity (r ≈ 0.8–0.97) indicating generally stable network organization across languages. Advanced bilinguals show slightly higher mean correlations and greater variability, with a moderate effect size (Cohen's d = 0.448), suggesting stronger alignment and more integrated, efficient bilingual network architecture.*

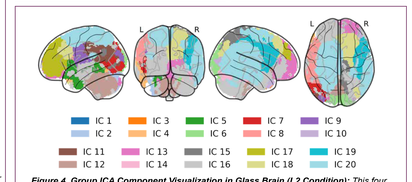


Figure 4. Group ICA Component Visualization in Glass Brain (L2 Condition): *This four displays the spatial distribution of 20 Independent Components (ICs) derived from Group ICA for the Basque (L2) semantic processing condition, visualized on a glass brain. Each color represents a distinct ICA component, showing spatially independent large-scale functional networks identified from the group-level fMRI data.*

Summary of findings

Our results show that cross-language neural similarity increases with proficiency. Advanced bilinguals rely on highly overlapping networks for L1 and L2, indicating automatized and efficient semantic processing across languages. Intermediate speakers show more divergent L1–L2 patterns, reflecting greater effort, reduced automaticity, and heavier reliance on perceptual and control systems in L2.

Cross-language correlation maps reveal that intermediates show broader, less specialized coupling, whereas advanced speakers engage more selective and efficient attention and control networks. Dynamic analyses further show that advanced bilinguals maintain longer dwell times and fewer transitions, supporting greater temporal stability during L2 processing.

Overall, bilingual proficiency shapes how flexibly and efficiently large-scale brain networks interact, revealing a progressive adaptation of neural architecture as second-language skills strengthen.

References

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