Bilingualism modulates domain-general functional connectivity: insights from resting-state EEG

Alex Sheehan[1] | Douglas Saddy[1] | Christos Pliatsikas[1,2]

[1]School of Psychology and Clinical Language Sciences, University of Reading, UK
[2]Universidad Antonio de Nebrija, Facultad de Lenguas y Educación, Centro de Ciencia Cognitiva, Spain

Introduction

- Bilingualism leads to **experience-dependent**, **non-linear structural adaptations** in white and grey matter **in language & cognitive control brain regions**[1].
- When it comes to **functional** adaptations, the Bilingual Anterior to Posterior and Subcortical Shift (BAPSS) model proposes that bilinguals **shift from relying on frontal regions** to **posterior & subcortical regions**[2]– see also[3,4].
- However, **little is known about the dynamic non-linear effects** of bilingualism on brain function.
  - No evidence exists for any short-term dynamic shifts in brain states when exposed to the external demands of a cognitively demanding task.
- Here we use **task-driven resting-state electroencephalogram (rs-EEG)** employing pre- and post-task recordings, to determine how bilingualism modulates whole-brain connectivity in response to task demands[5-7].
- We used a **cognitive domain-general task**, requiring implicit statistical learning and hierarchical structure processing – two generalised skills necessary for a multitude of processes.
- We used **Granger Causality functional connectivity analysis**, which, as a **directional** measure, allows us to determine the flow of information in the brain[8]. This allows greater interpretability of the functional connections.

Method

Participants:

- 29 highly experienced **bilinguals (L2 speakers of English)**
  - Neurotypical, no history of head injury, unconsciousness, meningitis, or encephalitis, and had been **living in the UK for at least 3 years.**

Task:

- The grammar-learning task uses an artificial grammar that generates a **binary string of 0s and 1s**.
- This string is **presented on-screen as blue or red circles** (see Figure 1), and the participant must respond on the keyboard indicating which colour they had just seen.
- The grammar follows **two rules**, which in turn creates **three laws** as to what can occur within the grammar, allowing specific points to become unambiguous as to which symbol will occur next[9,10].
  - Rule one: 0 → 1
  - Rule two: 1 → 01
    - First law: Every 0 is followed by a 1 (i.e., 00 cannot occur).
    - Second law: Two 1s are always followed by a 0 (i.e., 111 cannot occur).
    - Third law: A single 1 may be followed by either a 1 or a 0.
- This task requires participants to **implicitly track the statistical regularities within the hierarchical structure** of the grammar, thus **engaging domain-general abilities** due to the task's cognitive demands.

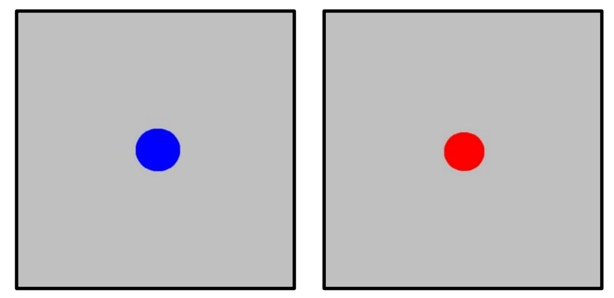

Figure 1: Example stimuli from the artificial grammar task

Procedure:

- Participants filled out demographics and language history questionnaire (**Language and Social Background Questionnaire** – LSBQ[11]). For this study, we used the LSBQ composite score for as a continuous predictor.
- After fitting the **EEG electrode cap**, the procedure occurred as follows:
  - Pre-task recording at rest (5 mins)
  - **Domain-general – Serial Reaction Time Artificial Grammar Learning task**[10]. (~20 mins)
  - Post-task 3 recording at rest (5 mins)
- Participants completed two more tasks as part of this protocol. The order of task presentation was counter-balanced.

Analysis:

- Re-referenced in EEGLAB, then pre-processed in BrainVision Analyzer. **Functional connectivity matrices** computed using BrainStorm. Data statistically analysed using **Generalized Additive Models**[14] in R, which allow **non-linear** relationships to be modelled when justified by the data.
  - Models LSBQ composite score against strength of connectivity between regions.

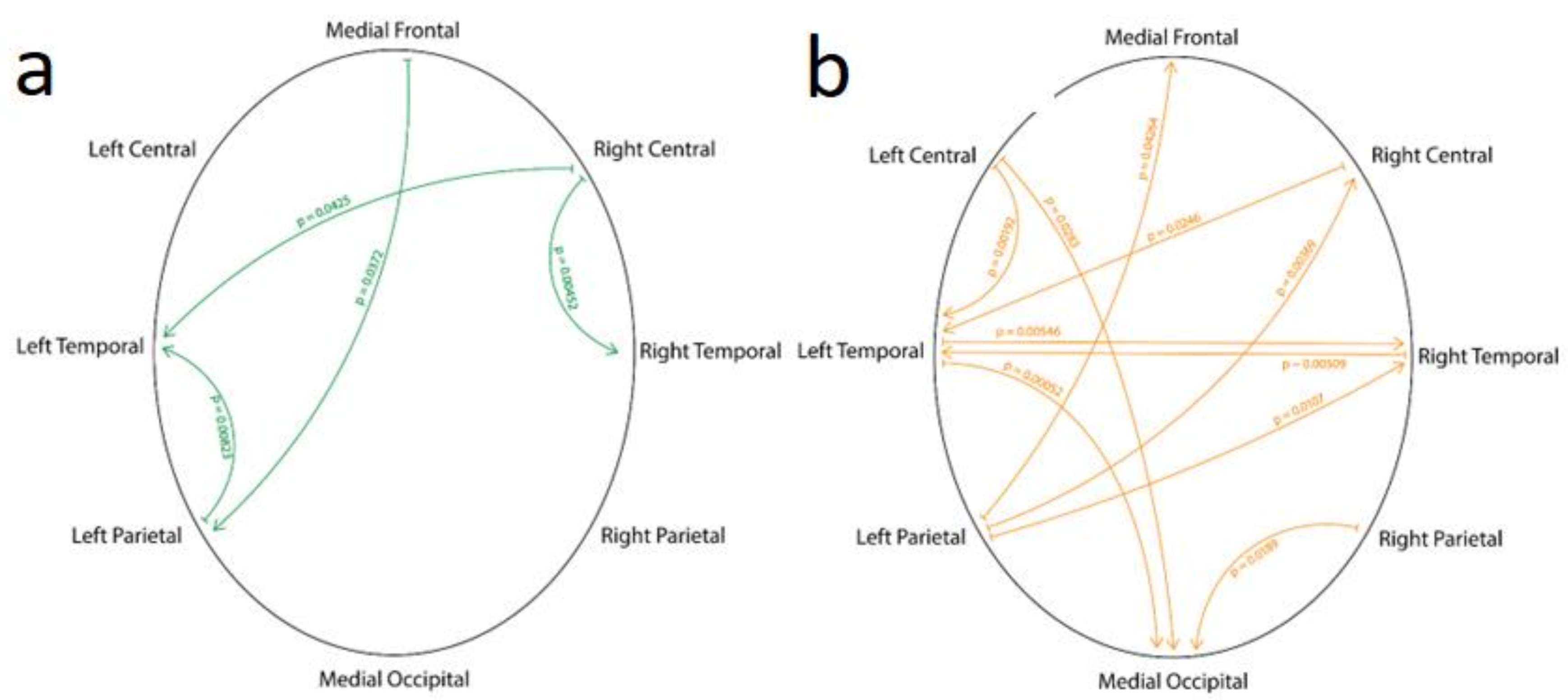

Figure 2: Electrode montage diagrams showing significant bilingualism-modulated connections. Left: pre-task. Right: post-task. Arrows indicate directionality/the flow of information.

Results

- **Four pre-task connections** significantly modulated by level of bilingualism, shown in Figure 2a (green arrows).
- **Ten post-domain-general task connections** significantly modulated by level of bilingualism, shown in Figure 2b (orange arrows).

Discussion

- Findings from **pre-task connections** suggest increased flow of information from frontal to posterior regions with increased bilingual experience
  - This corroborates previous findings and the predictions from the BAPSS model[3]
- **Over double the number of node-to-node connections** significantly modulated by level of bilingualism **post-task** compared to pre-task
  - Bilingual experience significantly affects neural recruitment for hierarchical structure processing and implicit statistical learning.
- This task caused far **more widely distributed bilingualism-modulated connectivity, involving every region included**, compared to pre-task.
  - This is the opposite to the expected effect – at rest, the brain usually shows more widely distributed connectivity, and post-task, usually shows more task-specific localised connectivity[15].
- Increased number of long-distance, inter-hemispheric, and occipital connections are **consistent with the BAPSS model**[3].
  - Solely inbound occipital connections modulated by level of bilingualism suggests recruitment of this region for the processing of the stimuli instead of for passing visual information to other areas for integration.
- Clustering of connections around left temporal region post-task is particularly unexpected. This suggests **strong language network activation despite no language being present** in the task.

References

1. Pliatsikas C. *Bilingualism: Language and Cognition*. 2020;23(2):459-471. doi:10.1017/S1366728919000130
2. Grundy JG, et al. *Annals of the New York Academy of Sciences*. 2017;1396(1):183-201. doi:10.1111/nyas.13333
3. Bice K, et al. *Neurobiol Lang*. 2020;1(3):288-318. doi:10.1162/nol_a_00014
4. Pereira Soares SM, et al.. *Brain Lang*. 2021;223:105030. doi:10.1016/j.bandl.2021.105030
5. Wang Z, et al. *NeuroImage*. 2012;62(1):394-407. doi:10.1016/j.neuroimage.2012.04.051
6. Lor CS, et al. *NeuroImage Clin*. 2023;37:103345. doi:10.1016/j.nicl.2023.103345
7. Kavcic V, et al. *Alzheimer's & Dementia: Diagnosis, Assessment & Disease Monitoring*. 2021;13(1):e12153. doi:10.1002/dad2.12153
8. Wang HE, et al. *Front Neurosci*. 2014;8. https://www.frontiersin.org/articles/10.3389/fnins.2014.00405
9. Krivochen DG. *ArXiv210401363 Cs*. Published online April 3, 2021. http://arxiv.org/abs/2104.01363
10. Schmid S, et al. *Cogn Sci*. 2023;47(1):e13242. doi:10.1111/cogs.13242
11. Anderson JAE, et al. *Behav Res*. 2018;50(1):250-263. doi:10.3758/s13428-017-0867-9
12. Duñabeitia JA, et al. *Sci Data*. 2022;9(1):431. doi:10.1038/s41597-022-01552-7
13. Zelazo PD, et al. Ii. *Monographs of the Society for Research in Child Development*. 2013;78(4):16-33. doi:10.1111/mono.12032
14. Wood SN. *Generalized Additive Models: An Introduction with R*. Chapman and Hall/CRC; 2006. doi:10.1201/9781420010404
15. Wang H, et al. *J Cogn Neurosci*. 2016;28(7):971-984. doi:10.1162/jocn_a_00947

Contact information

- School of Psychology & Clinical Language Sciences, University of Reading, Whiteknights, RG6 6AH, UK
- Email: c.pliatsikas@reading.ac.uk