



EEG Differences in Arithmetic Processing in Bilingual and Monolingual Adults

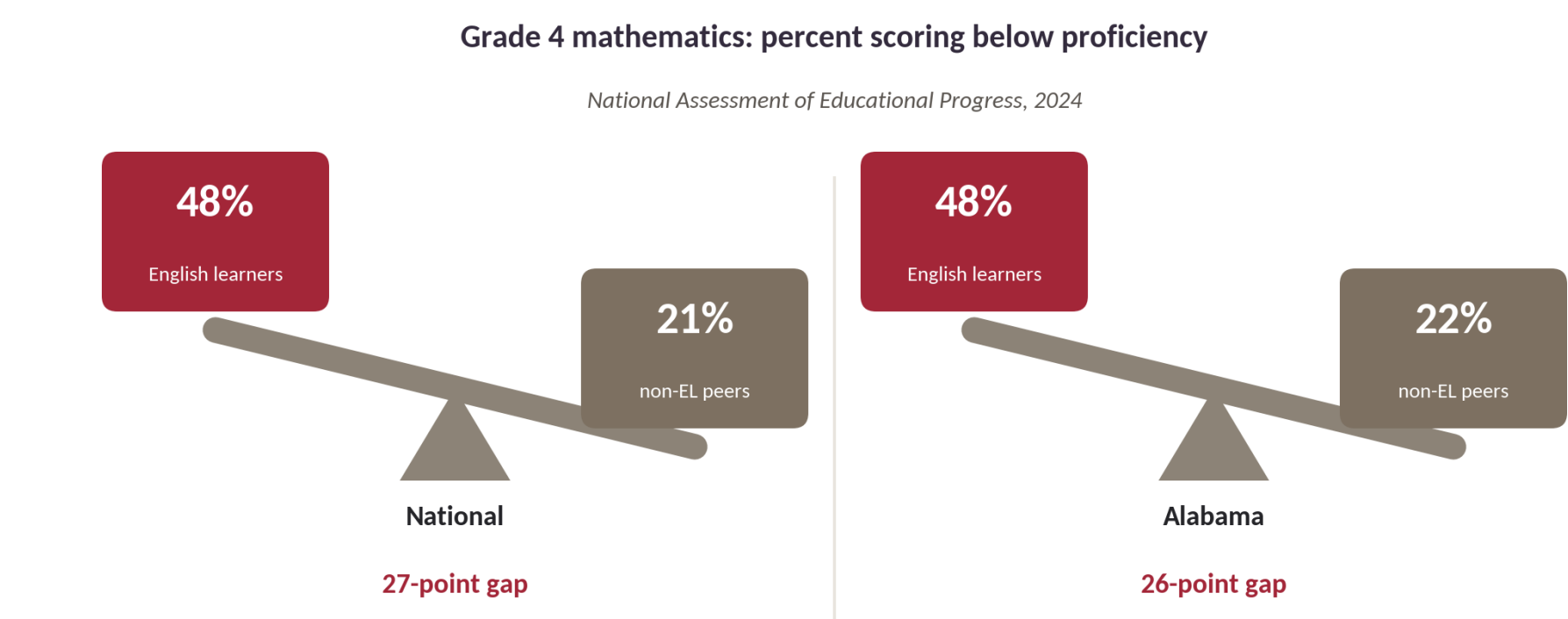
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Abstract

22% of U.S. students come from immigrant households speaking a non-English home language but are taught and assessed in English. How bilinguals process mathematics remains poorly understood. We examined how language proficiency and problem difficulty shape arithmetic processing, recording 32-channel EEG from **30 English monolinguals** and **30 Argentinian Spanish-English bilinguals** (Spanish-dominant, L1) as they solved single- and double-digit additions aloud. Accuracy was equivalent; oscillatory activity was not. **Theta — linked in arithmetic to retrieval of facts from long-term memory** — tracked the language of the problem: in English, bilinguals showed **less** theta than monolinguals; within bilinguals, theta was greater in Spanish, their dominant language. Bilinguals reached comparable accuracy through a different oscillatory profile and with higher beta activity in Spanish, which remains to be interpreted.

Introduction



Fourth-grade students scoring below math proficiency (NAEP, 2024). English learners trail non-EL peers by 27 points nationally and 26 points in Alabama.

Bilinguals solve arithmetic faster in their first language, and are slower to transfer calculation from L1 to L2 (Van Rinsveld et al., 2015, 2016).

Arithmetic recruits the intraparietal sulcus, angular gyrus and posterior superior parietal lobe, with frontal SFG/ACC support as load increases.

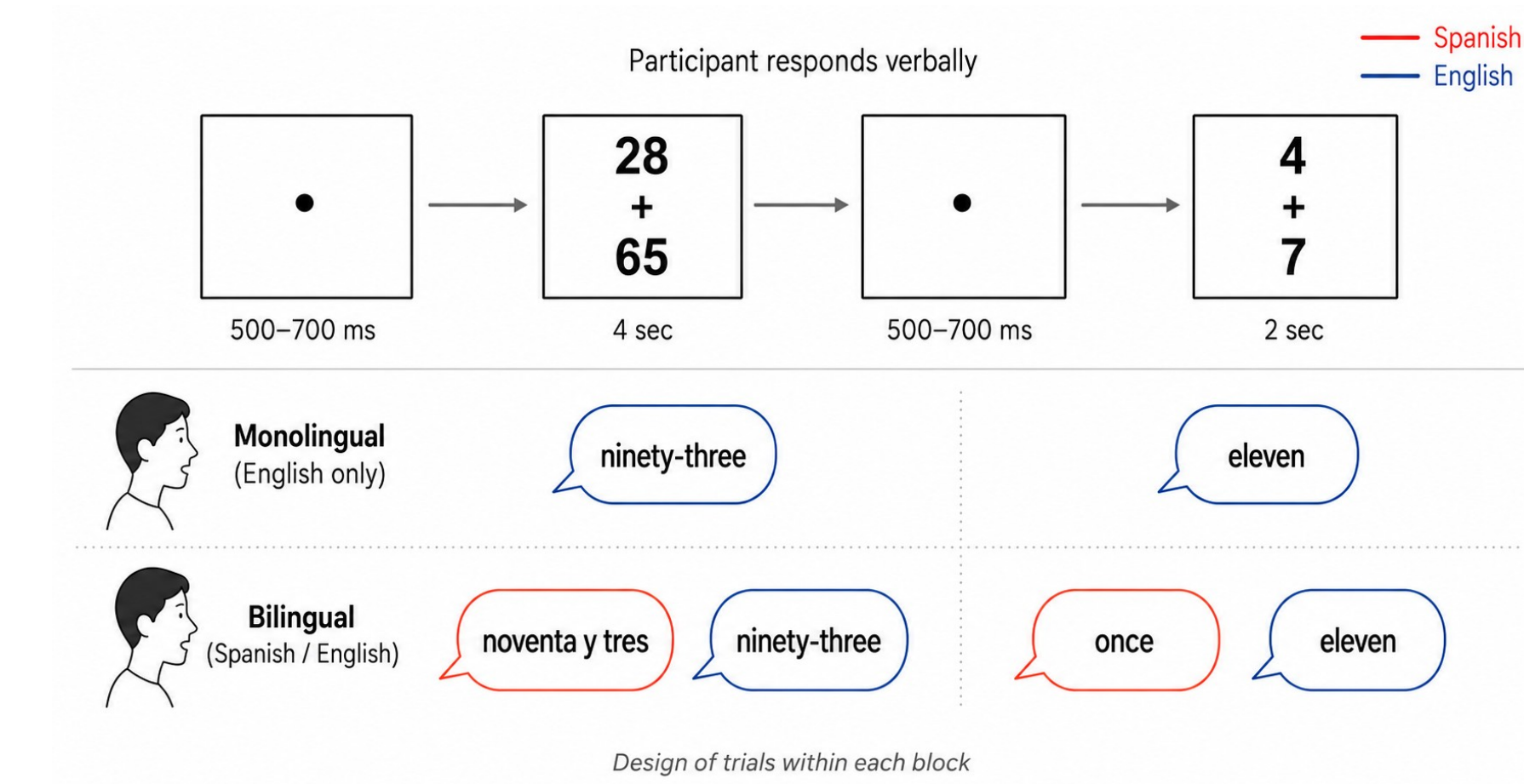
Research Questions

- How do English-only monolinguals and Spanish-dominant bilinguals differ when both solve arithmetic in English?
- How does difficulty — single-digit retrieval vs. double-digit calculation — interact with language status?
- For bilinguals, how does processing differ between Spanish (L1, dominant) and English (L2)?

Methods

Participants

30 U.S. **English monolinguals** and 30 Argentinian **Spanish-English sequential bilinguals** (highly proficient in English, their second language).



Trial structure within each block; spoken responses by group and language.

Task & Design

Mental addition with a spoken response and no answer choices, so processing is probed without priming or guessing. Single-digit problems index fact retrieval; double-digit problems index procedural calculation.

240 trials in 12 blocks of 20 (10 single, 10 double). Monolinguals completed 12 English blocks; bilinguals completed **6 Spanish and 6 English blocks, counterbalanced**.

EEG Analysis Pipeline

- 32-channel EEG; ERSP computed 4–40 Hz.
- Epochs normalized to 0–100% task progress, because response latency differs between conditions.
- Subject-level sign-flip permutation (2,000 permutations), two-sided.
- BH-FDR correction at $q < .05$ across time-frequency bins within each electrode map.
- Language, digit-type and group contrasts computed separately.

Additional Measures

- Pre-survey on math preferences.
- Post-survey on arithmetic strategies.
- Language Experience and Proficiency Questionnaire (LEAP-Q).

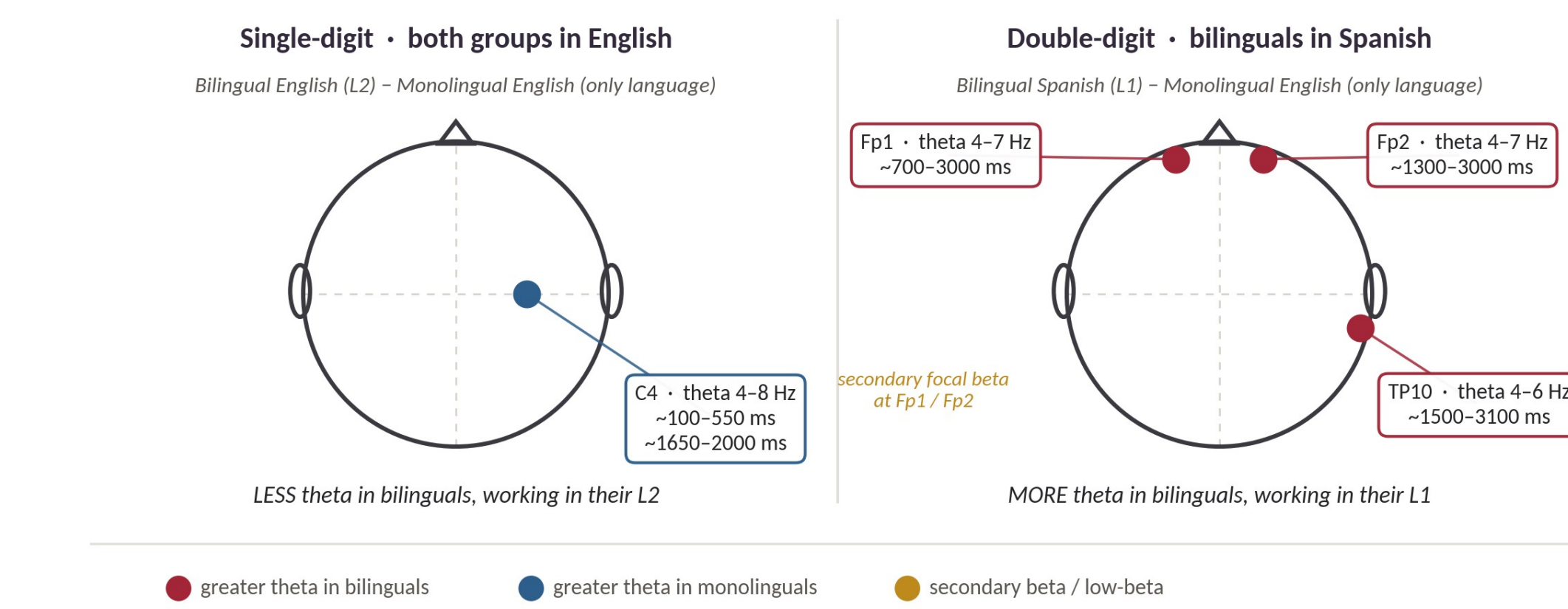
Results

Group, language and problem type each reshaped the time-frequency response — most consistently in theta, the band linked to arithmetic-fact retrieval.

How to read the theta effects

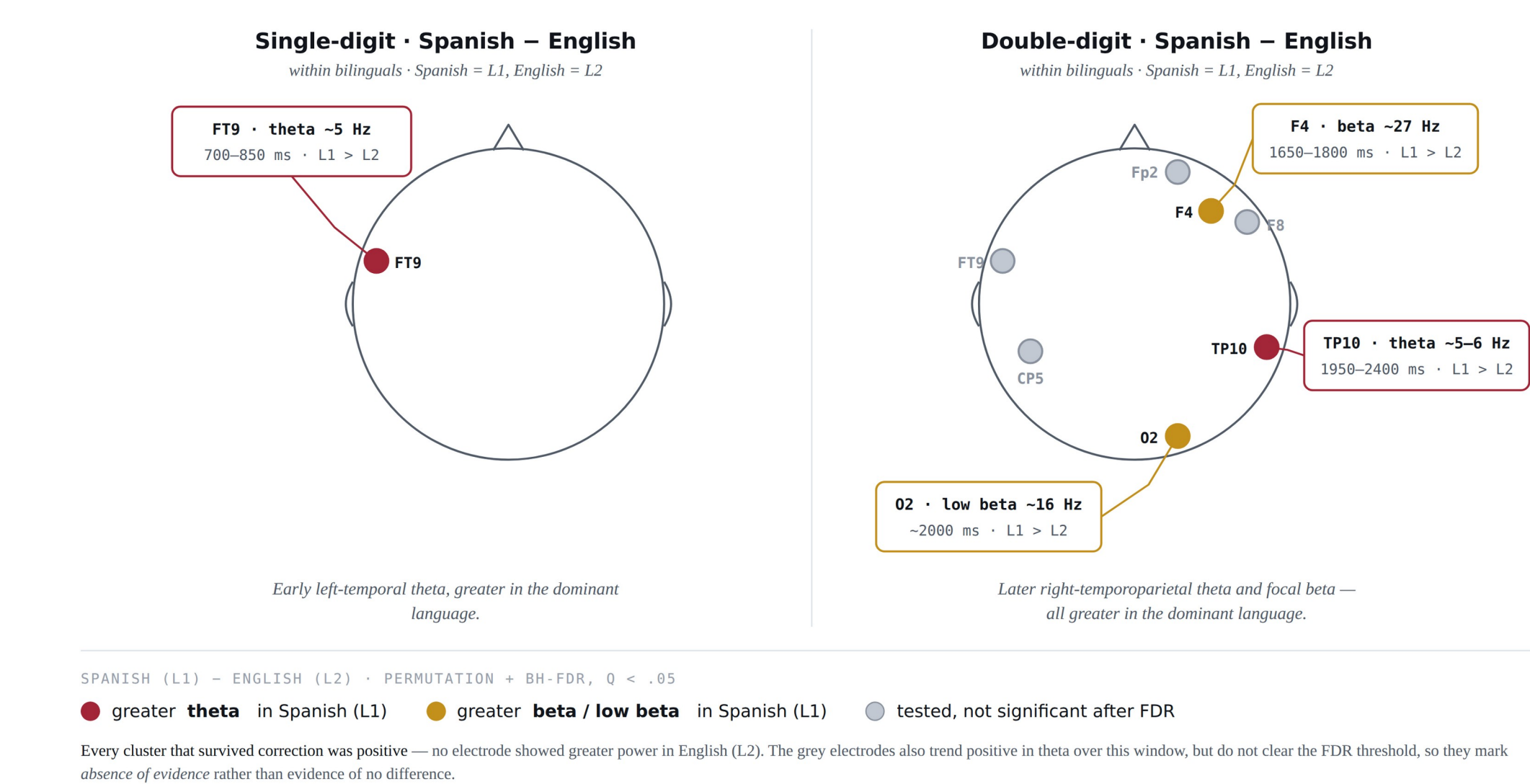
Theta ERS tracks retrieval of arithmetic facts from long-term memory; alpha ERD — not theta — tracks resource-demanding procedural calculation (De Smedt et al., 2009; Grabner & De Smedt, 2012). Theta differences below are therefore read as **retrieval engagement, not effort**. Temporal-site effects (FT9, TP10) index fact retrieval; sustained prefrontal theta (Fp1, Fp2) during double digits may additionally reflect frontal control coordinating multi-step calculation (cf. Hubbard & Federmeier, 2024).

1 · Between groups — bilinguals vs. English-only monolinguals



Single digits, both groups in English: bilinguals showed **LESS** theta at C4. Double digits, bilinguals in Spanish: **MORE** theta, sustained at Fp1, Fp2 and TP10.

2 · Within bilinguals — Spanish (L1) vs. English (L2)

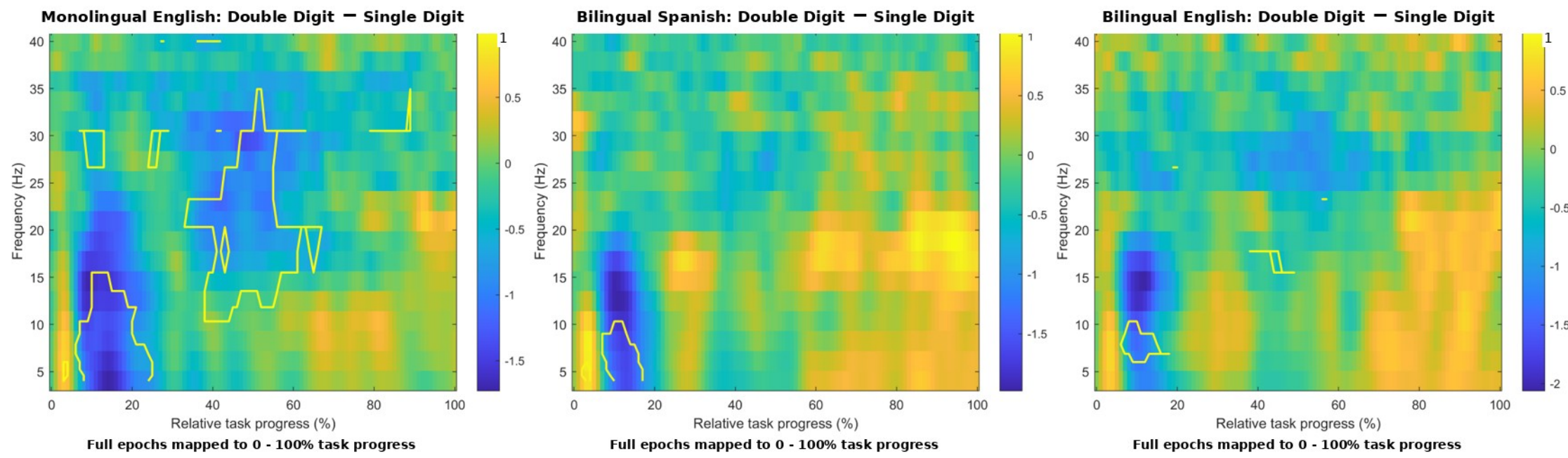


Theta is greater in Spanish (L1) and moves **early → late, left temporal → right temporoparietal**, as the problem becomes procedural. Beta effects (F4, O2) are focal and secondary.

What each contrast can and cannot show

Monolinguals were tested only in English — there is no monolingual Spanish condition. **Within bilinguals (Spanish – English)** is the cleanest language test: same people, same task. **Single-digit** holds language constant but not group; **double-digit** differs in group, language and problem type at once. Longer processing time is behavioral evidence — not evidence of greater neural effort.

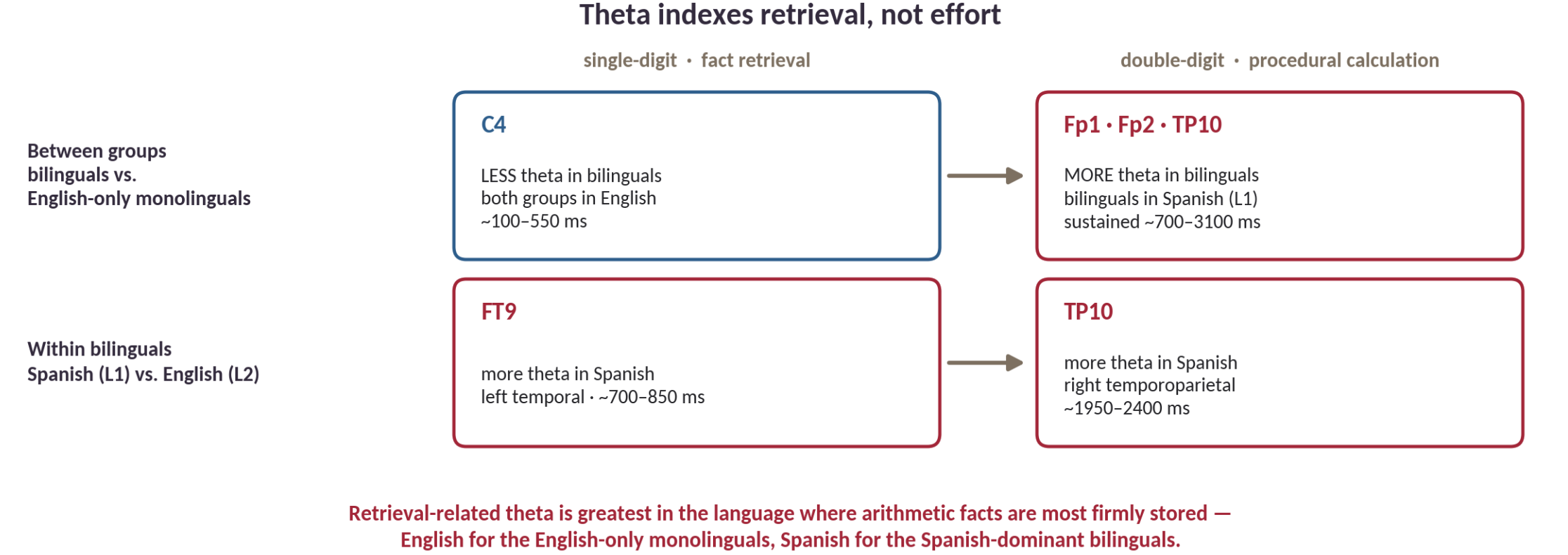
3 · Problem type — calculation – retrieval



Calculation – retrieval at Cz, by group.

- An early 4–20 Hz desynchronization appears at nearly every electrode, in every group.
- Monolinguals additionally show a sustained mid-trial effect reaching 35 Hz.
- Bilinguals instead show a late alpha/beta rebound.

Synthesis — the two analyses converge



Corrected effects were spatially selective. Descriptive Spanish > English increases at CP5, F8, Fp2 and FT9 (double-digit) did not survive permutation + BH-FDR correction.

Key Findings: Language Shifts Oscillatory Timing

Three contrasts summarize the language and timing effects

EVIDENCE	ENGLISH · L2	SPANISH · L1
BETWEEN-GROUP THETA C4 · Fp1 · Fp2 · TP10	θ ↓ vs. monolinguals — less retrieval engagement in L2	θ ↑ Retrieval sustained even in double-digit calculation De Smedt et al., 2009; Grabner & De Smedt, 2012
WITHIN-BILINGUAL THETA FT9 → TP10	lower θ compared to Spanish	higher θ compared to English EARLY in single-digit problems LATER in double-digit problems
CALCULATION DYNAMICS Cz · F4 · O2	β ↓ Only monolinguals showed a sustained mid-trial β desynchronization	late α/β rebound Late β ↑ in bilinguals — attention + procedural maintenance? Lewis et al., 2016; Dekydtspotter et al., 2023
TAKEAWAY	Stronger L1-related θ in both groups + bilingual-specific α/β calculation & response dynamics	

Conclusions

- Bilinguals reach comparable accuracy through a measurably different electrophysiological route, with language-dependent retrieval- and calculation-related oscillatory activity.
- Consistent with resource-allocation — rather than architectural — accounts of nonnative processing: the same computations, with oscillatory resources distributed differently across languages (Dekydtspotter et al., 2021, 2023).
- Retrieval-related theta is greatest in the language where arithmetic facts are most firmly stored — English for monolinguals, Spanish for bilinguals.
- Between-group and within-bilingual analyses converge on theta, strengthening the interpretation.
- Longer response times would be behavioral evidence of processing time; greater theta is not evidence of greater effort.
- Timed assessment in a second language may still disadvantage bilingual students — language access, not mathematical competence.

Future Directions

- Test the alpha prediction: if double-digit problems are more procedural, resource demand should appear as alpha ERD, not theta ERS.
- Formal group × difficulty and language × difficulty interaction tests; the present maps are within-group.
- Matched contrasts that vary language and complexity independently.
- Relate ERSP measures to LEAP-Q, executive function, math anxiety and reported strategy use — retrieval vs. procedural.
- Control for numeral length — Spanish double-digit terms are longer than English (treinta y cinco vs. thirty-five).
- Spoken responses mean late alpha/beta dynamics may partly reflect speech-motor preparation (Jongman et al., 2020); response-locked analyses would separate calculation from articulation planning.

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