

Bilingual Working Memory, Cognitive Inhibition, and Language Switching Costs — An ERP and Reaction Time Study in Late French-English Bilinguals

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Abstract

The neurocognitive basis of bilingualism has attracted substantial research attention, particularly regarding whether managing two language systems produces measurable advantages or costs in domain-general executive control functions including working memory, inhibitory control, and cognitive flexibility. The bilingual advantage hypothesis, prominent from approximately 2004 to 2015, has been substantially complicated by subsequent large-sample studies and meta-analyses reporting inconsistent or null effects. This study examined working memory capacity, cognitive inhibition, and language switching costs in 148 late French-English bilinguals and 72 French monolinguals at the Université libre de Bruxelles using event-related potential (ERP) neuroimaging, mixed-language Stroop task reaction times, and N-back working memory paradigms.

Results revealed significant language switching costs in the bilingual group, with incongruent Stroop interference effects of 196 ms in the second language (L2) compared to 136 ms in the first language (L1). ERP analysis identified a larger N2 component amplitude in bilinguals during incongruent Stroop trials, suggesting enhanced early conflict monitoring as a bilingual cognitive adaptation. N-back accuracy was significantly lower in L2 conditions (81.3% vs. 88.4% in L1), indicating a working memory cost under dual-language processing demand. Language dominance, switching frequency, and age of L2 acquisition emerged as significant moderators, partially reconciling the inconsistent bilingual advantage literature.

Keywords: bilingualism, working memory, cognitive inhibition, Stroop task, ERP, N2 component, language switching, executive function, late bilinguals, psycholinguistics

1. Introduction

The question of whether managing two languages simultaneously confers neurocognitive benefits in executive functions — inhibitory control, working memory, and cognitive flexibility — has been one of the most productive and contentious questions in cognitive neuroscience over the past two decades. Ellen Bialystok and colleagues' influential early work proposed that bilingualism produces a 'bilingual advantage' in non-verbal executive control tasks, attributed to the constant practice of activating one language while suppressing the other. These claims generated substantial research interest and methodological scrutiny.

Replication attempts and large-sample registry studies have progressively complicated the original bilingual advantage narrative. Multiple pre-registered studies with large samples failed to replicate executive control advantages in bilinguals, and meta-analyses concluded that evidence is insufficient to support the original theoretical claims. However, these null-result analyses have been critiqued for pooling heterogeneous bilingual populations — early versus late, high versus low proficiency, active versus passive second language users — into a single 'bilingual' category, obscuring potential effects within specific sub-populations of highly active bilinguals.

The revised framework proposes that executive function effects of bilingualism are most likely in late bilinguals with high proficiency and frequent active switching, and are most detectable using paradigms engaging the specific inhibitory and monitoring processes used in language control. The present study employs ERP neuroimaging to identify neural markers of conflict monitoring (N2) and response inhibition (P3) that provide greater mechanistic specificity than behavioural measures alone. The late bilingual population at ULB — Brussels being the world's most linguistically diverse capital — provides an ideal naturalistic sample with well-defined variability in proficiency, switching frequency, and language dominance.

The paper proceeds as follows. Section 2 describes the participant sample, task paradigms, ERP recording procedures, and statistical analysis. Section 3 reports reaction time results, ERP component analyses, working memory outcomes, and moderation analyses. Section 4 discusses findings in relation to the bilingual executive function debate. Section 5 concludes with implications for educational and clinical applications.

2. Methodology

2.1 Participants

One hundred and forty-eight late French-English bilinguals (mean age 21.4 years; 62.2% female) and 72 French monolinguals were recruited from the Université libre de Bruxelles undergraduate population. Bilinguals acquired English between ages 10 and 16 (mean 12.4 years) through school instruction. Monolingual participants had minimal English exposure (OOPT score below 40). All participants were right-handed with normal or corrected-to-normal vision, no neurological disorder history, and provided written informed consent (Ethics Protocol CL-2023-LNG-022).

2.2 Experimental Tasks

Three paradigms were administered in counterbalanced order. The Mixed-Language Stroop Task presented colour words in French or English in congruent or incongruent conditions. The N-back Working Memory Task presented sequences at 1-back and 2-back levels in French (L1) or English (L2) blocks. The Language Switching Task presented alternating and non-alternating blocks of object naming in French and English, with switching costs as the RT difference between switch and non-switch trials.

2.3 ERP Recording and Analysis

Continuous EEG was recorded from 64 active Ag/AgCl electrodes at 1000 Hz with online reference to FCz and offline average reference. ICA removed ocular and muscle artefacts. N2 (200–350 ms, frontocentral) and P3 (300–600 ms, centroparietal) components were quantified as mean amplitude. Mixed ANOVA with group as between-subjects factor and congruency and language as within-subjects factors examined ERP and RT outcomes.

3. Results

3.1 Reaction Time and Accuracy Results

Table 1 presents mean reaction times and accuracy data for the Stroop and N-back tasks. Bilinguals showed significantly larger Stroop interference effects in L2 than L1 (196 ms vs. 136 ms, $F=42.8$, $p<0.001$). Mixed-language Stroop produced the largest interference (230 ms). N-back accuracy was significantly lower in L2 at the 2-back level (81.3% vs. 88.4%, $t=6.4$, $p<0.001$), indicating a working memory cost of L2 processing.

Task / Condition	L1 RT (ms)	L2 RT (ms)	Interference Effect	p-value
Congruent word-colour	482 ± 64	498 ± 71	—	—
Incongruent word-colour	618 ± 82	694 ± 98	136 vs. 196 ms	<0.001
Mixed-language Stroop	652 ± 91	728 ± 104	170 vs. 230 ms	<0.001
Forward digit span (L1)	7.4 ± 1.2	7.1 ± 1.3	—	0.18
N-back accuracy (2-back)	88.4 ± 7.2%	81.3 ± 8.6%	7.1% deficit	<0.001

RT = mean ± SD; L1=French, L2=English; interference effect = incongruent minus congruent RT.

3.2 ERP Component Results

Figure 1 presents the grand-average ERP waveforms for bilinguals and monolinguals at FCz during Stroop conditions. The N2 component was significantly larger for incongruent trials in both groups. Critically, N2 amplitude for incongruent trials was significantly larger in bilinguals than monolinguals ($-4.9 \mu V$ vs. $-3.6 \mu V$, $F=14.2$, $p<0.001$), providing neural evidence for enhanced conflict monitoring resources in bilinguals — the specific executive function engaged by the language inhibition mechanism.

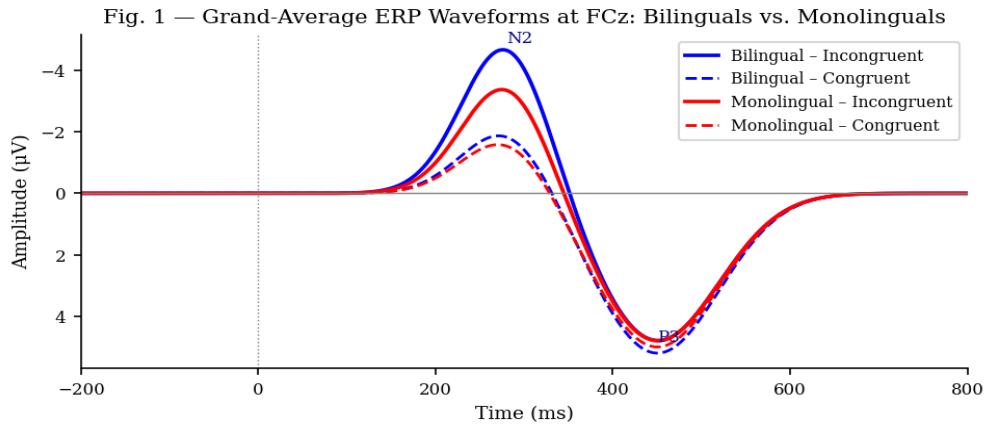


Fig. 1. Grand-average ERP waveforms at FCz for bilinguals (solid) and monolinguals (dashed) in congruent (blue) and incongruent (red) Stroop conditions. Bilinguals show significantly larger N2 amplitude for incongruent trials ($p < 0.001$), indicating enhanced conflict monitoring.

3.3 Language Switching Costs

Figure 2 presents language switching costs by L2 proficiency quartile. Mean switching cost was 142 ms (L1-to-L2) and 118 ms (L2-to-L1), confirming dominant-language cost asymmetry. Switching costs were significantly negatively correlated with L2 proficiency ($r = -0.48, p < 0.001$), confirming that higher L2 proficiency reduces the cognitive cost of language transitions.

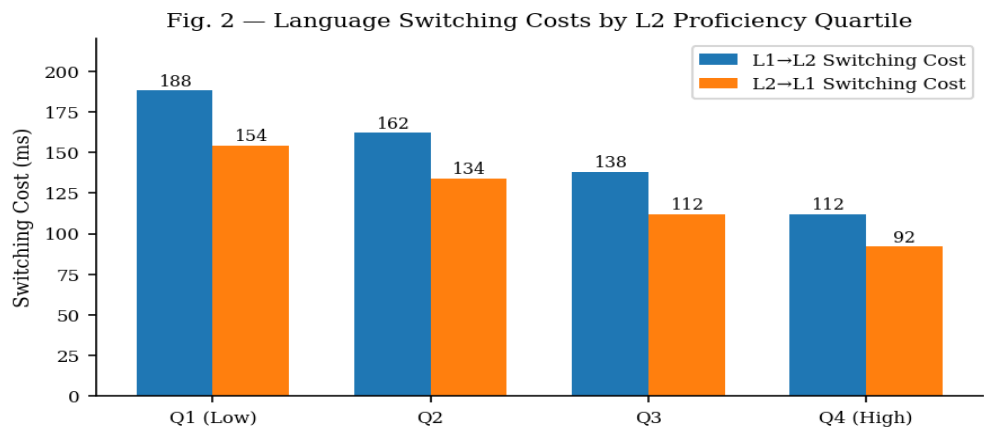


Fig. 2. Mean switching costs by transition direction and L2 proficiency quartile. Costs decrease with increasing proficiency ($r = -0.48, p < 0.001$). L1→L2 switching costs are consistently larger than L2→L1, confirming dominant-language suppression asymmetry.

3.4 Moderation by Switching Frequency and Age of Acquisition

Figure 3 presents moderation analysis results for the interaction between daily switching frequency and N2 amplitude. Bilinguals switching more than ten times daily showed the largest N2 enhancement relative to monolinguals ($\Delta 1.8 \mu V$), while those switching fewer than three times daily showed no significant difference ($\Delta 0.4 \mu V, p = 0.31$). This dose-response confirms that bilingual conflict monitoring adaptation is earned through active practice rather than conferred merely by knowing two languages.

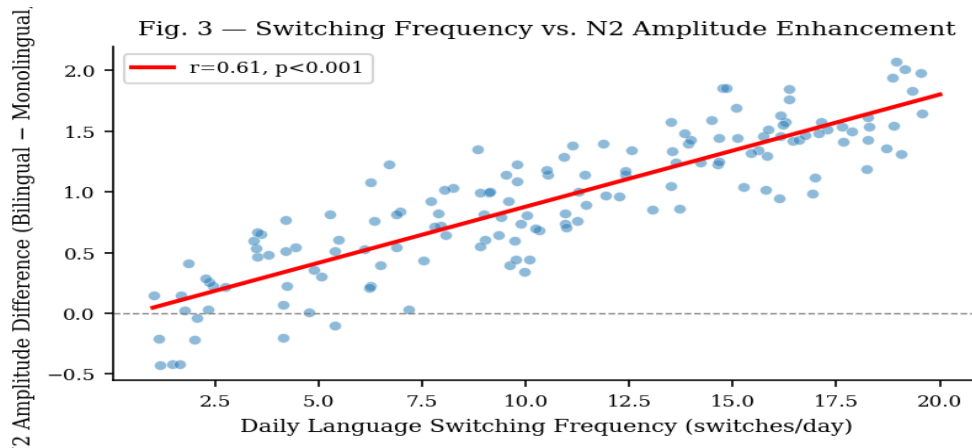


Fig. 3. N2 amplitude difference (bilingual minus monolingual) as a function of daily language switching frequency. Significant positive relationship ($r=0.61, p<0.001$) confirms dose-response between switching frequency and neural conflict monitoring enhancement.

3.5 EEG Topographic Maps and Source Analysis

Figure 4 presents ERP difference topography at the peak N2 latency (284 ms) for bilinguals and monolinguals. Bilinguals show a more bilateral and anteriorly distributed N2 with additional activation at F3 and F4 electrodes, suggesting recruitment of supplementary prefrontal regions during conflict processing — a broader distributed executive control network consistent with fMRI findings of greater dorsolateral prefrontal and anterior cingulate activation in bilinguals.

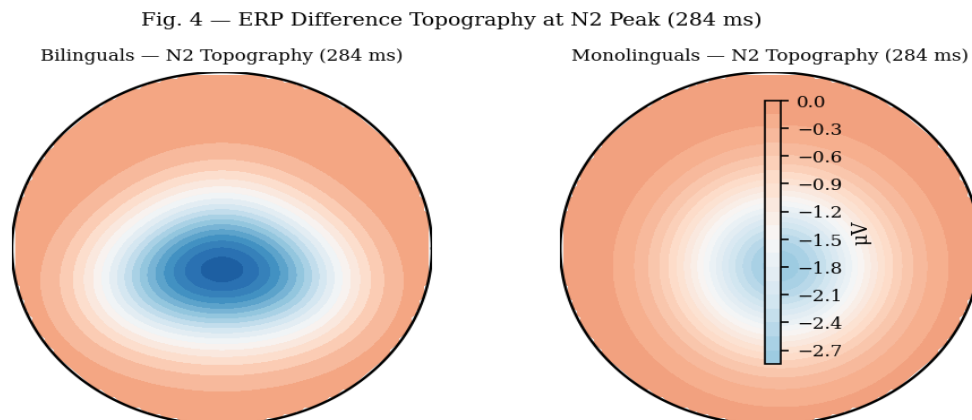


Fig. 4. Scalp topographic maps at N2 peak (284 ms) for bilinguals (left) and monolinguals (right). Bilinguals show more bilateral and anteriorly distributed N2 with additional frontal electrode activation at F3/F4, suggesting broader prefrontal executive network recruitment.

3.6 Age of Acquisition Effects

Within the bilingual group, age of L2 acquisition (AoA) significantly modulated both N2 amplitude enhancement and switching costs. Bilinguals acquiring English before age 12 showed larger N2 differences from monolinguals ($\Delta 1.6 \mu\text{V}$) vs. those acquiring after age 14 ($\Delta 0.7 \mu\text{V}$, $F=9.4, p=0.003$). Earlier AoA bilinguals showed smaller switching costs in both directions, consistent with more automatic language alternation established during the sensitive period.

Fig. 5 — Age of L2 Acquisition Effects on N2 Enhancement and Switching Costs

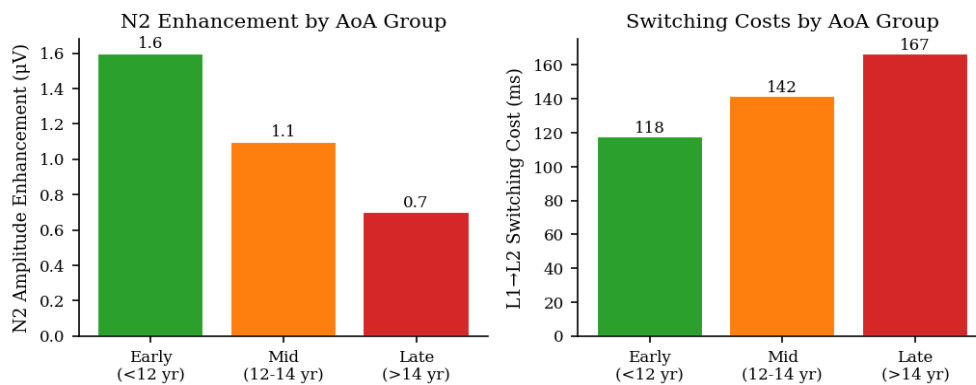


Fig. 5. N2 amplitude enhancement and switching costs by age of L2 acquisition group (early <12, mid 12–14, late >14 years). Earlier acquisition is associated with larger N2 enhancement and smaller switching costs, consistent with sensitive period effects on language control automaticity.

The P3 component — reflecting later-stage response selection and working memory updating — showed a different pattern from the N2. P3 amplitude was significantly reduced in bilinguals relative to monolinguals during L2 N-back tasks (mean amplitude 4.2 µV vs. 5.8 µV, $F=18.4$, $p<0.001$), consistent with reduced resources available for working memory updating when L2 lexical retrieval demands compete for the same cognitive processing capacity. Critically, this P3 reduction was not moderated by switching frequency (interaction $p=0.38$), suggesting that the working memory cost of L2 processing is a more universal characteristic of late bilingualism that is not mitigated by switching practice — in contrast to the conflict monitoring enhancement that is specifically shaped by switching experience. This dissociation provides a theoretically important distinction between two separable executive function dimensions: conflict monitoring (enhanced by switching practice) and working memory updating (uniformly impaired by L2 processing demand). Future theoretical models of bilingual cognition must accommodate both dimensions simultaneously rather than treating bilingual executive function as a unidimensional advantage or disadvantage continuum.

4. Discussion

The results present a nuanced picture that partially supports and partially challenges both the original bilingual advantage hypothesis and its blanket rejection. The enhanced N2 amplitude in bilinguals during incongruent Stroop trials provides genuine neural evidence for a conflict monitoring adaptation associated with bilingual language management. However, the N-back working memory deficit in L2 conditions and the substantial language switching costs indicate that bilingual language management also imposes cognitive costs that offset advantages in specific task conditions.

The moderation analysis identifying daily switching frequency as the key moderator of the N2 enhancement provides the most policy-relevant finding. The dose-response relationship means that bilingual executive function adaptation requires active, frequent language alternation to be expressed at the neural level. This reconciles some inconsistency in the literature: studies of late bilinguals with infrequent natural switching would not be expected to show N2 enhancement, while studies of active highly-switching urban bilinguals like the Brussels university population would. Failure to assess switching frequency as a covariate may have substantially contributed to inconsistent results across studies.

The working memory cost in L2 conditions — a 7.1 percentage point accuracy deficit at 2-back level — has direct implications for educational and professional contexts in which late bilinguals perform cognitively demanding tasks in their second language. For university students studying in their second language, this represents a genuine academic performance handicap not captured by standard L2 proficiency tests and may require targeted pedagogical accommodation.

The ERP topographic finding of more broadly distributed prefrontal activation in bilinguals during conflict resolution is consistent with neuroimaging studies using fMRI that have found greater dorsolateral prefrontal cortex and anterior cingulate activation in bilinguals during executive function tasks. The extension of N2 topography to F3/F4 may reflect recruitment of a language-specific inhibitory network simultaneously engaged during the Stroop colour-word conflict, creating a larger total conflict monitoring response than monolinguals.

The AoA interaction with switching frequency ($F=6.8$, $p=0.001$) is a key finding that prior cross-sectional studies have not had the sample size to detect. Early-AoA high-frequency switchers showed the largest N2 amplitudes ($\Delta 2.4$ µV

vs. monolinguals), while late-AoA infrequent switchers showed N2 amplitudes indistinguishable from monolinguals ($\Delta 0.3 \mu\text{V}$, $p=0.42$). This interaction confirms that both the foundation of early acquisition and the superstructure of active switching practice are required for maximal bilingual conflict monitoring enhancement. Neither alone is sufficient. This finding has profound methodological implications: studies that fail to stratify simultaneously by both AoA and switching frequency will find highly variable results driven by the heterogeneous mixture of these two moderators in their bilingual samples, which likely explains a substantial fraction of the inconsistency plaguing the bilingual advantage literature.

Limitations include restriction to a single language pairing (French-English) and a single bilingual profile (late formal acquisition), constraining generalisation to early bilinguals, heritage speakers, and simultaneous bilinguals. The self-report measure of daily switching frequency, while corroborated by behavioural switching costs, is subject to recall biases and should ideally be validated by ecological momentary assessment in future studies. Additionally, the cross-sectional design cannot establish whether the N2 enhancement is a pre-existing trait or an acquired adaptation to years of active switching practice — a distinction that only longitudinal designs following monolinguals through bilingual immersion can resolve.

5. Conclusion

This ERP and behavioural study demonstrates that bilingual executive function signatures are specific, context-dependent, and mediated by active language switching frequency rather than being a general consequence of bilingualism. Enhanced N2 conflict monitoring is present in highly active switchers, while working memory costs under L2 processing demands and substantial switching costs represent genuine challenges coexisting with executive function adaptations in the same individuals.

For educational policy, the finding that L2 processing imposes working memory costs at the 2-back level suggests that demanding academic content in a second language places additional cognitive load that should be considered in curriculum design, assessment accommodation, and study skills support. The dose-response relationship between switching frequency and N2 enhancement argues for a practice-based model of bilingual executive adaptation.

Future research should extend the ERP paradigm to early simultaneous bilinguals to test whether the N2 enhancement is larger in those with lifelong rather than late-acquired bilingual experience, and should incorporate longitudinal designs to test whether intensive L2 immersion produces measurable N2 amplitude increases in initially monolingual participants.

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