Bilingualism shapes neural control: Distinct experiences predict conflict monitoring and sustained attentional control

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Abstract

This study used event-related potentials (ERPs) to examine how bilingual experiences shape neural responses to contextual cues and conflict resolution. Fifty bilingual undergraduates completed a context-specific proportion congruency (CSPC) Stroop task while EEG was recorded. Greater L2 usage was associated with reduced conflict effects, consistent with more efficient control. The N2 was larger for incongruent than congruent trials and varied by context, with lower L2 proficiency associated with greater context-dependent increases in N2 amplitude, whereas higher proficiency was associated with more stable responses. The conflict slow potential (SP) showed that earlier L2 acquisition was associated with greater sustained attentional resource availability across contexts. Together, these findings indicate that processing efficiency is reflected in how control demands are distributed across early and late stages of processing. More broadly, bilingual experiences shape distinct neural control profiles, highlighting the importance of interpreting behavioral and neural measures jointly.

Keywords: Bilingualism, individual differences, executive functions, domain-general, ERP, EEG

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Bilingual experience and attentional control

Bilinguals often outperform monolinguals on executive function (EF) tasks measuring attentional control (e.g., Bialystok et al. 2004; Costa et al. 2008, 2009; Esposito et al. 2013; review in Bialystok, 2017), which is often attributed to their experiences managing two languages that are constantly competing for selection (Bobb et al. 2020; Kroll et al. 2012, 2014). However, bilingualism is complex and individual bilingual experiences may impact attentional control differently (Chung-Fat-Yim et al., 2022; Dass et al., 2024; Green & Abutalebi, 2013; Leivada et al., 2021). Evidence suggests that language switching frequency (Fan et al., 2021), second-language (L2) usage (Carlson, & Meltzoff, 2008), age of L2 acquisition (Durand Lopez, 2021), and L2 proficiency (Sun et al., 2019) all impact cognition and the brain, and the field is now pushing for examination of bilingualism along a continuum rather than a dichotomy (Dass et al., 2024; Grundy, 2020, Leivada et al., 2021; Luk & Bialystok, 2013; Titone & Tiv, 2023; Yurtsever et al., 2023, 2025). To this end, the present study tested an all-bilingual sample and used event-related potentials (ERP) alongside an individual differences approach to examine the effects of bilingualism on attentional control. By treating bilingualism as a continuum of experiences (rather than a dichotomy), we address prior inconsistencies and capture nuanced effects of specific language experiences. We expect that these language experiences will uniquely influence sensitivity to contextual cues and conflict, predicting the amount of attentional control required.

Context-specific proportion congruency (CSPC) and attentional control

The context-specific proportion congruency (CSPC; Crump, Gong, Milliken, 2006) paradigm is a powerful tool for examination of how contextual cues can modify the amount of attentional control applied to conflicting and non-conflicting stimuli on a Stroop task. The CSPC effect refers to the finding that the congruency effect (slower responses on incongruent than congruent trials) is typically larger in a context where most trials are congruent (high proportion congruent, HPC) than in a context where most trials are incongruent (low proportion congruent, LPC). This indicates that participants use contextual cues (e.g., stimulus location) to adjust their attentional control "on-the-fly", applying more control in contexts that are likely to have conflict. The CSPC paradigm thereby assesses reactive control – dynamic, trial-by-trial adjustments in attention based on implicit contextual cues (Crump et al., 2006; 2017). By contrast, list-wide proportion congruency manipulations involve proactive control, as participants can adopt a sustained strategy across a whole block (Logan & Zbrodoff, 1979; Braver, 2012). While some studies suggest that bilinguals may rely more on proactive control strategies (Morales et al., 2013), other evidence indicates that bilingual experience specifically affects how reactive control is engaged when task demands shift (Morales et al., 2015; Wu & Thierry, 2013). Thus, the CSPC paradigm is well-suited for examining how bilingual experiences influence dynamic, trial-by-trial adjustments in attentional control under changing contexts.

Sequential congruency effects and the interpretation of conflict adaptation

A theoretically related construct, in which the congruency of the previous trial influences the size of subsequent congruency effects is known as the sequential congruency effect (SCE), or more commonly, *conflict adaptation*[1](Botvinick et al., 2001). Traditional conflict-monitoring

[1] The term conflict adaptation is theoretically biased because it gives the impression that the mechanism is necessarily adaptive, but as we show later, this is not always true. We prefer to use the unbiased descriptive term

models assume that larger SCEs reflect more adaptive control, as they indicate sensitivity to prior conflict and subsequent adjustment (Botvinickonal et al., 2001; Egner, 2007; Kerns et al., 2004). However, accumulating evidence suggests that the size of the SCE does not provide a straightforward measure of control efficiency. In fact, smaller SCEs often emerge in conditions associated with greater cognitive stability and efficiency. For example, SCEs tend to shrink with practice, suggesting that individuals who develop more fluent task performance require fewer reactive adjustments (Mayr & Awh, 2009; van Steenbergen et al., 2015). Similarly, longer response-to-stimulus intervals lead to smaller SCEs, indicating that when participants have more time to regulate control proactively, transient trial-by-trial adaptations become less necessary (Duthoo et al., 2014; Egner et al., 2010).

Beyond task structure, individual differences in cognitive efficiency also predict SCE size. Higher fluid intelligence is associated with smaller SCEs, supporting the argument that greater cognitive stability[2] results in reduced reliance on transient control adjustments (Liu et al.,2016). Conversely, anxiety and subjective cognitive decline have been linked to larger SCEs, suggesting that heightened sensitivity to conflict, rather than enhanced control, may underlie larger adaptation effects (Schuch & Koch, 2015; Osinsky et al., 2010; Trikojat et al.,2015). Additionally, research on conflict processing indicates that SCEs may reflect avoidance learning, as conflict trials are often aversive (Botvinick, 2007; Dreisbach & Fischer, 2012). Supporting this, van Steenbergen, Band, and Hommel (2009) found that reward signals between trials eliminated SCEs, demonstrating that adaptation effects can be modulated by motivational factors.

sequential congruency effect (SCE).

[2] Clarification: In this context, we use "cognitive stability" to refer to stronger goal maintenance and resistance to distraction (i.e., maintaining a stable task set), which is one theoretical component of fluid intelligence and has been linked to reduced reliance on transient, trial-by-trial control adjustments.

In summary, recent work indicates that smaller SCEs (or “conflict adaptation” effects) do not necessarily imply a failure of control. They may instead reflect a shift toward a more stable, efficient attentional control strategy that minimizes the need for reactive, trial-by-trial adjustments. Bilinguals continuously manage competing linguistic representations, which may result in a regulatory mode that minimizes reliance on transient, reactive adjustments in favor of a more sustained attentional control process (Grundy & Bialystok, 2019). Instead of adjusting control dynamically in response to individual trials, bilinguals may maintain a consistent level of attentional engagement, leading to more stable task performance over time. In line with this reasoning, Grundy et al. (2017b) reported that bilingual young adults showed smaller sequential congruency effects than monolinguals, which was interpreted as evidence of a more efficient control process that does not depend as heavily on trial-by-trial control engagement. Likewise, Grundy and Bialystok (2018) found that bilinguals more rapidly disengage attention from irrelevant conflicting stimuli, further suggesting a refined control mechanism in bilinguals that reduces carryover effects across trials.

ERP indices of conflict monitoring and sustained control (N2 and conflict SP)

While a growing body of literature has examined bilingual effects on behavioral performance, fewer studies have used electrophysiological measures (e.g., event-related potentials; ERPs) to investigate how bilingual experiences relate to the neural dynamics of attentional control. ERPs are well suited for this purpose because they provide millisecond-level temporal resolution, allowing early and later stages of processing during conflict tasks to be dissociated. Two ERP components are especially relevant in this context: the N2 and the conflict slow potential (SP).

The N2 is a fronto-central negative deflection peaking approximately 250–350 ms following stimulus onset and is commonly associated with conflict monitoring and the detection of competing response information (Donkers & van Boxtel, 2004; Fong et al., 2018; Jost et al., 2022). This component is thought to reflect early engagement of attentional control, likely involving anterior cingulate cortex (ACC) signaling the need for increased attentional allocation (Nieuwenhuis et al., 2003; van Veen & Carter, 2002a, 2002b). Importantly, bilingual experience has been shown to modulate both ACC function (Abutalebi et al., 2012; Blanco-Elorrieta et al., 2016; Cachia et al., 2017; Seo et al., 2018) and N2 amplitude during conflict tasks (Grundy et al., 2017a; Antoniou, 2023). Bilinguals have often been reported to show larger N2 amplitudes on conflict tasks alongside reduced late-stage components, a pattern that has motivated accounts emphasizing how attentional control demands may be redistributed across early and late stages of processing rather than expressed as a single uniform neural signature (Grundy et al., 2017a; Antoniou, 2023). Recent work further highlights substantial variability in how such early–late tradeoffs manifest across individuals and tasks (e.g., Carter et al., 2023), reinforcing the need to evaluate processing efficiency through joint behavioral–neural profiles rather than isolated component effects.

The conflict SP is a later, sustained negative-going slow wave that emerges several hundred milliseconds after stimulus onset and can extend beyond the response (Larson et al., 2014; West, 2003). This component is thought to index later-stage or compensatory adjustments to attentional demands following conflict detection, particularly when early control engagement is insufficient to fully resolve competing information (Larson et al., 2009, 2011; Pan et al., 2016). Evidence from individual-differences research supports this interpretation: for example, individuals with traumatic brain injury show reduced conflict SP amplitudes, consistent with diminished ability to sustain control following conflict detection, whereas individuals with higher intelligence exhibit larger SP amplitudes alongside smaller behavioral adaptation effects, suggesting greater available resources for resolving conflict efficiently (Liu et al., 2016). Accordingly, in the present study, we interpret variation in conflict SP amplitude as reflecting differences in the availability and deployment of attentional resources at later stages of processing.

Bilingual interactional contexts and sensitivity to contextual cues

It is also crucial to consider theoretical frameworks regarding bilingual language use and attention. Green and Abutalebi's (2013) Adaptive Control Hypothesis distinguishes between interactional contexts that impose different control demands: single-language contexts (use one language per environment), dual- language contexts (switch languages depending on interlocutor), and dense code-switching contexts (free mixing of two languages within a conversation). Each context is thought to tax control processes differently. In a dense code-switching environment, for instance, bilinguals switch languages frequently but with relatively low interference, because all interlocutors understand both languages; as a result, monitoring external cues for language selection may be less critical (Green & Abutalebi, 2013). By contrast, in a single-language context, switching is infrequent and triggered by distinct contexts, so interference from the non-target language is minimal until a context switch occurs. We reasoned that these differing demands might map onto how bilinguals handle contextual cues in a non-linguistic task like the CSPC Stroop. Specifically, an individual who frequently switches languages in a dense code-switching environment might be less attuned to contextual cues indicating when to up- or down-regulate control, because their daily experience deemphasizes context signals (since both languages are always in play). Thus, we tentatively predicted that greater language switching frequency might correlate with smaller context-specific adjustments (a reduced CSPC effect), reflecting a tendency to apply a more uniform level of control regardless of context.

In addition to switching frequency, L2 experiences such as proficiency, age of acquisition (AoA), and usage, might be predictive of changes in response to conflict and context on the CSPC paradigm, given that these bilingual experiences have been shown to modify conflict processing and brain adaptations (Anderson et al., 2021; DeLuca et al., 2020; DeLuca & Voits, 2022; Luk & Grundy, 2023; Titone & Tiv, 2023). For example, Wu and Thierry (2013) and others (e.g., Jiao et al., 2020) have shown that bilinguals adapt their attentional control and conflict processing on a flanker task based on linguistic context cues.

Inconsistencies in the literature on the effects of bilingualism on executive functions and attentional control (meta-analyses in Grundy, 2020; Gunnerud et al., 2020; Lehtonen et al., 2018; Ware et al., 2020; Yurtsever et al., 2023) can be at least partly explained by the complexity of bilingual experiences and environmental contexts in which participants reside. For example, Yurtsever, Sotebeer, and Grundy (2025) demonstrated that age of second language acquisition (L2 AoA) and language switching frequency between two languages sometimes uniquely predicted performance in opposite ways (faster or slower reaction times) on flanker and Stroop mouse-tracking paradigms. This means that when different bilingual experiences are collapsed together, researchers risk eliminating real effects; the two experiences effectively cancel each other out. It is for reasons like this one that researchers have been pushing to look at bilingualism along a continuum rather than a dichotomy of “bilingual” and “monolingual” (Deluca et al., 2019; Grundy, 2020; Luk & Bialystok, 2013; Rothman et al., 2023a, 2023b; Yurtsever et al., 2023).

The Present Study

To clarify how bilingual engagement relates to contextual cue use and conflict processing, we examined behavioral performance and two complementary ERP indices (the N2 and the conflict slow potential [SP]) during a context-specific proportion congruency (Crump, Gong, & Milliken, 2006) Stroop task in a heterogeneous sample of bilinguals. One primary expectation was that greater bilingual engagement—indexed by higher L2 proficiency, greater L2 usage, and earlier L2 age of acquisition (AoA)—would be associated with more efficient performance on a conflict task. However, efficiency can be expressed through multiple behavioral–neural configurations (e.g., smaller behavioral conflict effects and/or faster responses with comparable accuracy, accompanied by equal or reduced reliance on compensatory control). Likewise, changes in early versus late neural recruitment can trade off across time; therefore, behavior, N2, and conflict SP must be interpreted jointly rather than in isolation. Importantly, Table 1 is intended as an interpretive framework rather than a set of one-to-one predictions linking specific bilingual experiences to specific profiles; different experience dimensions may give rise to different efficient configurations, and some patterns (e.g., increased sustained neural responses in the absence of behavioral change) may also reflect differences in available attentional resources rather than increased neural cost. Throughout this paper, efficiency is defined at the level of task performance on a conflict task rather than conflict-specific differentiation per se. Finally, based on interactional-context reasoning (Green & Abutalebi, 2013), we expected that more frequent language switching would be associated with reduced sensitivity to contextual cues (i.e., smaller context-specific adjustments), which we evaluate cautiously.

Table 1 - *Interpretable profiles of processing efficiency across behavioral and neural measures as a function of increasing bilingual experience. The table illustrates representative configurations of behavioral performance and neural engagement that may emerge with increasing bilingual experience. Profiles are organized by conflict-effect (difference between incongruent and congruent trials) and overall-amplitude (mean across trial types) measures and are intended to provide a general interpretive framework for evaluating how efficiency can be expressed across early (N2) and late (conflict SP) stages of processing.*

ERP profile type	Behavioral pattern	N2 pattern	Conflict SP pattern	Interpretation	Experience-linked control profile (increasing bilingual experience)
Conflict-effect	Smaller behavioral conflict effect	Larger N2 conflict effect	Smaller SP conflict effect	**Greater efficiency.** Stronger early conflict differentiation reduces later conflict-related effort and improves performance.	Greater bilingual experience with enhanced early conflict engagement and reduced reliance on sustained control
Conflict-effect	Smaller behavioral conflict effect	Larger N2 conflict effect	No change in SP conflict effect	**Greater efficiency.** Stronger early conflict differentiation improves performance without added late conflict-related effort.	Greater bilingual experience with enhanced early conflict engagement
Conflict-effect	Smaller behavioral conflict effect	No change in N2 conflict effect	Smaller SP conflict effect	**Greater efficiency.** Performance improves while late conflict-related effort decreases.	Greater bilingual experience with reduced reliance on sustained control
Conflict-effect	Comparable behavioral conflict effect	Larger N2 conflict effect	Smaller SP conflict effect	**Greater efficiency.** Equivalent performance is maintained through earlier control allocation and reduced later effort.	Greater bilingual experience with earlier allocation of control across processing stages
Conflict-effect	Comparable behavioral conflict effect	Smaller N2 conflict effect	Smaller SP conflict effect	**Greater efficiency.** Equivalent performance is achieved with reduced conflict-related neural engagement across stages.	Greater bilingual experience with reduced conflict-related neural engagement across stages
Conflict-effect	Comparable behavioral conflict effect	No change in N2 conflict effect	Smaller SP conflict effect	**Greater efficiency.** Equivalent performance is achieved with reduced late conflict-related effort.	Greater bilingual experience with reduced reliance on sustained control

ERP profile type	Behavioral pattern	N2 pattern	Conflict SP pattern	Interpretation	Experience-linked control profile (increasing bilingual experience)
Conflict-effect	Comparable behavioral conflict effect	No change in N2 conflict effect	No change in SP conflict effect	**Comparable efficiency.** Behavioral and conflict-related neural engagement are similar across stages.	Greater bilingual experience with stable conflict processing across stages
Conflict-effect	Comparable behavioral conflict effect	Smaller N2 conflict effect	Larger SP conflict effect	**Lower efficiency.** Reduced early conflict differentiation is offset by greater late-stage compensation.	Greater bilingual experience with reduced early engagement and increased reliance on sustained control
Conflict-effect	Comparable behavioral conflict effect	Larger N2 conflict effect	Larger SP conflict effect	**Lower efficiency.** Equivalent performance requires greater conflict-related engagement across stages.	Greater bilingual experience with elevated engagement across early and late stages of conflict processing
Conflict-effect	Larger behavioral conflict effect	No change in N2 conflict effect	Larger SP conflict effect	**Lower efficiency.** Poorer performance is accompanied by increased late conflict-related effort.	Greater bilingual experience with increased reliance on sustained control during conflict processing
Conflict-effect	Larger behavioral conflict effect	Smaller N2 conflict effect	Larger SP conflict effect	**Lower efficiency.** Weaker early conflict differentiation increases reliance on later compensation and performance suffers.	Greater bilingual experience with insufficient early engagement and compensatory reliance on sustained control
Conflict-effect	Larger behavioral conflict effect	Larger N2 conflict effect	Larger SP conflict effect	**Lower efficiency.** Increased engagement across stages fails to prevent behavioral costs.	Greater bilingual experience with elevated but ineffective engagement across processing stages
Overall-amplitude	Faster overall responses with comparable conflict effect	Larger overall N2 amplitude	Smaller overall SP amplitude	**Greater efficiency.** Faster task execution is supported by greater early engagement and reduced sustained effort.	Greater bilingual experience with earlier allocation of control and reduced sustained engagement
Overall-amplitude	Faster overall responses	No change in overall N2 amplitude	No change in overall SP amplitude	**Greater efficiency.** Faster performance is achieved without increased neural engagement.	Greater bilingual experience with improved performance without increased neural engagement
Overall-amplitude	Comparable	No change	Smaller	**Greater efficiency.**	Greater bilingual

ERP profile type	**Behavioral pattern**	**N2 pattern**	**Conflict SP pattern**	**Interpretation**	**Experience-linked control profile (increasing bilingual experience)**
	behavioral conflict effect	in overall N2 amplitude	overall SP amplitude	Equivalent performance is achieved with reduced sustained neural effort.	experience with reduced sustained attentional engagement
Overall-amplitude	Comparable behavioral conflict effect	Smaller overall N2 amplitude	Smaller overall SP amplitude	**Greater efficiency.** Equivalent performance is achieved with reduced overall neural engagement across stages.	Greater bilingual experience with reduced neural engagement across early and late processing stages
Overall-amplitude	Comparable behavioral conflict effect	Larger overall N2 amplitude	Smaller overall SP amplitude	**Greater efficiency.** Equivalent performance is maintained through earlier neural engagement and reduced sustained effort.	Greater bilingual experience with earlier allocation of control and reduced sustained engagement
Overall-amplitude	Comparable behavioral conflict effect	No change in overall N2 amplitude	No change in overall SP amplitude	**Comparable efficiency.** Behavioral performance and overall neural engagement are similar.	Greater bilingual experience with stable overall neural engagement
Overall-amplitude	Comparable behavioral conflict effect	Smaller overall N2 amplitude	Larger overall SP amplitude	**Lower efficiency.** Reduced early engagement is accompanied by increased sustained effort without behavioral improvement.	Greater bilingual experience with reduced early engagement and increased sustained engagement
Overall-amplitude	Comparable behavioral conflict effect	Larger overall N2 amplitude	Larger overall SP amplitude	**Lower efficiency.** Equivalent performance requires increased neural engagement across stages.	Greater bilingual experience with elevated neural engagement across processing stages
Overall-amplitude	Larger behavioral conflict effect	Smaller overall N2 amplitude	Larger overall SP amplitude	**Lower efficiency.** Poorer performance is accompanied by reduced early engagement and increased sustained effort.	Greater bilingual experience with reduced early engagement and increased sustained engagement associated with poorer performance
Overall-amplitude	Larger behavioral conflict effect	Larger overall N2 amplitude	Larger overall SP amplitude	**Lower efficiency.** Increased overall neural engagement fails to prevent behavioral costs.	Greater bilingual experience with elevated neural engagement across stages without performance benefit

Note. Behavioral and neural patterns may reflect changes in conflict-related effects (Δ = incongruent − congruent) and/or overall amplitude across trial types. Table entries describe how these patterns may vary with increasing bilingual experience, treated as a continuous individual-differences variable rather than a between-group comparison. Efficiency is defined at the level of task performance relative to neural engagement, such that faster or equivalent performance achieved with the same or reduced neural engagement reflects greater efficiency. Increased neural engagement without behavioral cost may also reflect differences in available attentional resources depending on context.

Methods

Participants

Table 2 provides demographic and linguistic background information for participants in the study. Fifty undergraduate bilinguals from Iowa State University were recruited via the SONA system in exchange for course credit. Ten participants reported having an L3, three an L4, and two an L5. Nineteen participants identified English as their L1, while the remaining participants reported various L1s, including Spanish, Chinese, Arabic, Portuguese, German, Amharic, Telugu, Korean, and Khmer. All participants who did not report English as their L1 had English as their L2, except for one individual who reported it as their L3. One participant reported a prior head injury (remote; no current neurological impairment was reported), and two participants reported taking psychoactive medications. As a sensitivity check, we re-ran the primary behavioral analyses and the key ERP models (N2 and conflict SP) after excluding these three participants; the pattern of results and conclusions was unchanged.

Task language and participant language profiles

Because the Stroop prime words were presented in English, the task was completed in participants' dominant language for some individuals (English L1) and in a highly familiar second language for others (English L2/L3). Importantly, the stimuli were limited to four high-frequency color words, and English proficiency in the sample was high overall, reducing the likelihood that basic lexical comprehension drove the observed context and conflict effects. We now clarify this sample heterogeneity explicitly to aid interpretation of the results.

Power and sample size

The present sample size (N = 50) is within—and on the higher end of—typical sample sizes used in ERP studies of conflict processing. Meta-research suggests that ERP studies often involve comparatively modest samples and are most sensitive to medium-to-large effects, with precision improving as sample sizes grow (Clayson et al., 2019; Szűcs & Ioannidis, 2017). Consistent with current best practices for individual-differences ERP work, we modeled bilingual experience as continuous predictors and entered all predictors simultaneously to estimate unique effects while limiting the number of separate models, thereby improving parsimony and interpretability. We acknowledge that higher-order interactions in modest samples can be underpowered, and therefore emphasize effect sizes, theoretical coherence, and the need for future replication with larger and more diverse samples to improve precision.

Table 2

Demographic and language-background information for participants in the present study. Values represent means (and standard deviations; range), unless otherwise specified.

N	50
Age	20.8 (2.4)
Number of biological sex males	15
Education – Father (1 to 5)	3.4 (1.7; 1-5)
Education – Mother (1 to 5)	3.1 (1.7; 1-5)
L1 proficiency (0 to 100)	93.6 (9.1; 65-100)
L2 proficiency (0 to 100)	75.3 (18.8; 25-100)
L1 usage (0 to 4)	2.9 (0.8; 1-4)
L2 usage (0 to 4)	2.2 (0.9; 0.5-4)

L2 age of acquisition (AoA)	4.4 (4.8; 0-18)
L1/L2 switching frequency (0 to 4)	1.9 (1.1; 0-4)

Tasks & procedures

We used a custom Stroop task implementing a context-specific proportion congruency (CSPC) manipulation (adapted from Crump et al., 2006). On each trial, participants saw a brief color-word prime (presented in black) followed by a colored square target; congruency was defined by the relationship between the prime word and the target color.

In the present study, participants first saw 48 practice trials with feedback on each trial (reaction time for current trial and mean accuracy thus far) presented for 1500 ms, followed by 384 experimental trials spread across four blocks (96 trials per block) without feedback. The overall proportion of congruent to incongruent trials in any given block was 50/50. However, the proportion of congruent trials in a given location was manipulated so that 75% of the trials that appeared above (or below – counterbalanced across participants) the fixation cross and 25% of trials that appeared below (or above – counterbalanced across participants) the fixation cross were congruent (see Figure 1), which created the *high proportion congruent* (HPC) and *low proportion congruent* (LPC) contexts, respectively.

Like the original design, each trial started with a fixation cross for 1000 ms, followed by a blank screen for 250 ms, then a black-ink word prime (red, blue, green, yellow) for 100 ms, and finally a colored square target until a response was made or 2000 ms had elapsed. Participants were instructed to respond as quickly and accurately as possible to the ink color of the square with “z”, “x”, “n”, or “m” for “red”, “blue”, “green”, “yellow”. Responses were made on a standard QWERTY keyboard: participants used the left hand for “z” and “x” and the right hand for “n” and “m”.

Participants first completed the context-specific proportion congruency (CSPC) task followed by the Language and Social Background Questionnaire (LSBQ; Anderson et al., 2018).

Language and Social Background Questionnaire (LSBQ)

Proficiency was assessed via self-ratings for each language on a 0–100 scale (0 = not at all proficient; 100 = native-like). The average L2 Proficiency of speaking, understanding, reading, and writing, was taken as the overall L2 proficiency score. Language usage was computed as the mean frequency of use across speaking, listening, reading, and writing, on a 0–4 scale. Age of L2 acquisition (AoA) reflects the self-reported age (in years) at which participants began learning their L2. Language switching frequency was calculated as the mean of LSBQ items assessing how often participants switch between their two primary languages across contexts (including with parents and family, with friends, and on social media) on a 0–4 scale.

Analyses

For each dependent variable (reaction times, accuracy, amplitudes), we ran a 2 (context: high proportion congruent – HPC, low proportion congruent – LPC) x 2 (congruency: congruent, incongruent) repeated-measures ANOVA. This analysis was followed by a 2 x 2 ANCOVA including second-language (L2) proficiency, L2 usage, age of L2 acquisition (AoA), and switching frequency between languages as covariates in order to assess the effects of L2 experiences on context and congruency and any interactions. All four L2 experiences were added to each model to determine the unique contributions of each L2 experience on outcomes, unconfounded by variance associated with (i.e., independently from) the other L2 experiences.

Clarification of ANCOVA models and control of Type I error

In each outcome model, the four bilingual predictors (L2 proficiency, L2 usage, L2 AoA, and L1/L2 switching frequency) were entered simultaneously as continuous between-participant predictors (mean-centered). To test moderation, we included each predictor’s interactions with context and congruency (context × predictor, congruency × predictor, and context × congruency × predictor) within the same omnibus model rather than running separate models per predictor. Because our focal interaction terms were motivated by a theoretically specified interpretive framework for relating behavioral and early/late ERP measures (Table 1), these terms were specified in advance to constrain interpretation and analytic flexibility. Importantly, this framework does not increase statistical power or sensitivity to detect effects, but rather guides how observed effects are interpreted once detected; all inferences therefore remain subject to the same sample-size constraints.

Although interactions among bilingual experience variables are theoretically plausible, we did not include higher-order interactions among these predictors in the present models. Given the modest sample size ($N = 50$) and the number of predictors already included, such interactions would be underpowered and risk overfitting. Our approach instead focused on estimating the unique contributions of each experience dimension while controlling for shared variance. Future work with larger samples will be required to systematically test how these experience dimensions interact.

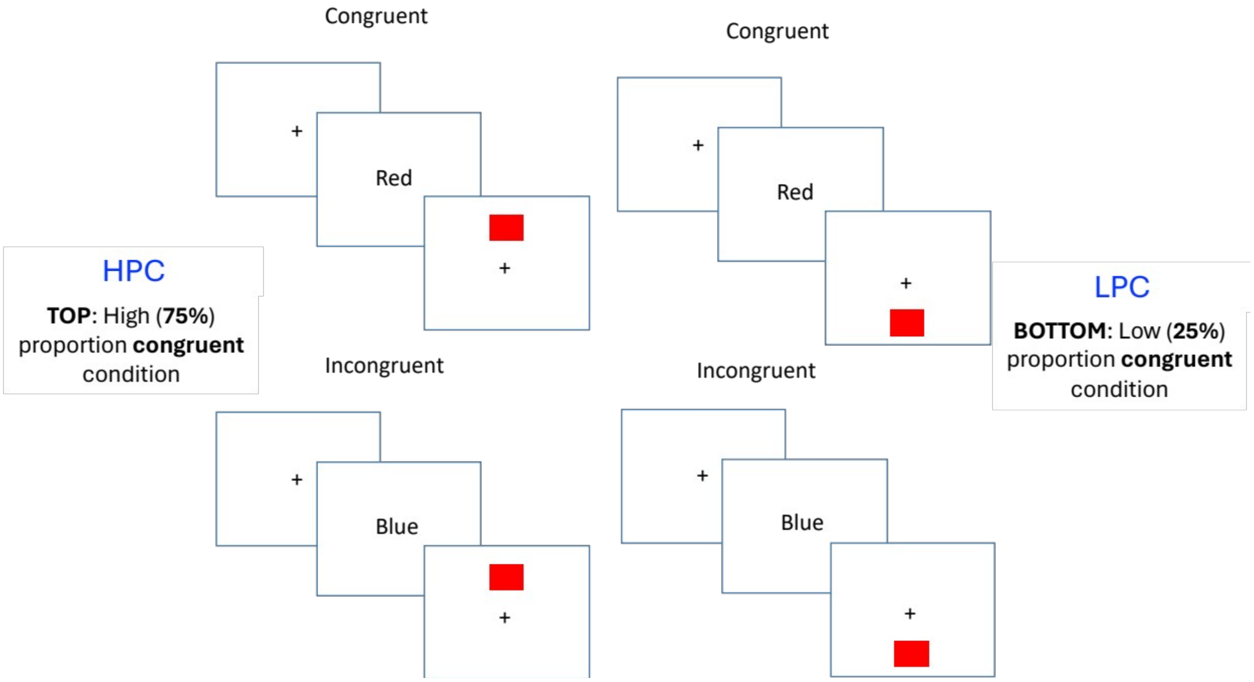

Figure 1 – Examples of four trial types used during the context-specific proportion congruency (CSPC) paradigm in the present study. When the color box appeared above the fixation cross, there was a 75% chance of encountering a congruent trial. When the color box appeared below the fixation cross, there was a 25% chance of encountering a congruent trial. The 75%/25% location mapping was counterbalanced across participants. Timing: fixation (1000 ms), blank (250 ms), prime word (100 ms), target until response (max 2000 ms).

EEG acquisition

Electroencephalographic (EEG) activity was continuously recorded using the ActiveTwo Biosemi electrophysiology system (www.biosemi.com) from 64 Ag/AgCl scalp electrodes, along with four additional electrodes positioned at the outer canthi and below each eye to capture horizontal and vertical eye movements. Two extra electrodes—a common mode sense active electrode and a driven right leg passive electrode—served as replacements for conventional ground electrodes (www.biosemi.com/faq/cms&drl.htm).

The EEG signal was acquired with an open passband ranging from DC to 150 Hz and digitized at 512 Hz. Offline, the signal was bandpass filtered between 0.01–55 Hz and re-referenced to a common average reference. Signal processing and averaging were conducted using EEGLAB version 2023.1 (Delorme, & Makeig, 2023) and ERPLAB version 9.00 (Lopez-Calderon, & Luck, 2023) toolboxes within MATLAB version R2022a (MathWorks, 2022).

Stimulus-locked epochs were extracted from −200 to 800 ms relative to stimulus onset, using a 200 ms pre-stimulus baseline. EEG epochs were time-locked to onset of the colored-square target. The −200 to 0 ms baseline period preceded prime onset and therefore does not include stimulus-evoked activity from either the prime or the target. Any electrode sites exhibiting high-frequency noise were interpolated, and trials contaminated by muscle tension or drift were excluded before applying eye artifact detection procedures. A simple voltage threshold of 400 μV was used for trial rejection. To correct for horizontal eye movements and blinks, as well as muscle movement and other artefacts, Independent Components Analysis (ICA; Makeig, Bell, Jung, & Sejnowski, 1995) was applied. Finally, mean amplitudes were extracted for all time windows and analyses of interest.

Mean amplitudes were extracted on correct trials only. Amplitude windows and locations for the N2 and the conflict SP were chosen based on previous literature as well as examination of the grand averages (see results for more detail).

Results[3]

[3] We acknowledge that SES is an important consideration, but given our sample size (N = 50) and the number of covariates already included, we opted not to residualize or add SES as a covariate to preserve statistical power. Adding SES or immigrant status as additional covariates would reduce the degrees of freedom in our analyses,

De-identified raw data used in the present study for analyses are openly available on Figshare at the following link: [note to editor and reviewers: public link to the raw data will be available upon acceptance for publication]. Correlations between L2 variables appear in Figure 2. Note that even though proficiency and usage were significantly correlated, variance inflation factors were all less than 1.61, suggesting that collinearity was not an issue. As an exploratory check, we also examined a standardized proficiency–usage composite; however, we retained separate predictors because proficiency and usage showed dissociable associations with behavioral versus ERP outcomes.

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increasing the risk of overfitting the model and inflating Type II errors. Given that our sample consists of undergraduate students at Iowa State University (ISU), the range of SES variability is likely more restricted compared to studies that recruit from broader community populations. More importantly, we ran a correlation analysis and neither of the variables (using mother's education as proxy for SES) correlated with any of the second-language experiences included (all *p*s > 0.147). Finally, we uploaded our data to Figshare.com to ensure transparency and allow others to do any additional analyses that they deem fit.

Figure 2 – Heatmap for correlations between different bilingual experiences in our sample. Note that even though proficiency and usage were significantly correlated, variance inflation factors (VIFs) were all less than 1.61, suggesting that collinearity was not an issue. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Behavioral

Figure 3 represents reaction times (RTs) and accuracy on the CSPC paradigm used in the present study.

Reaction Times (RTs)

The ANOVA revealed a main effect of congruency $F(1, 49) = 213.7$, $p < 0.001$, with RTs to congruent trials faster than incongruent trials, and a significant interaction between context and congruency, $F(1, 49) = 6.34$, $p = 0.015$. The interaction is explained by the finding that the congruency effect (incongruent RT – congruent RT) was larger in the high proportion congruent (HPC) than the low proportion congruent (LPC) context, displaying a significant context-specific proportion congruency (CSPC) effect, as expected.

The ANCOVA with L2 experiences in the model revealed a significant congruency x L2 usage interaction, $F(1, 37) = 4.13$, $p = 0.049$. The interaction demonstrated that more L2 usage was associated with smaller congruency effects (Figure 3, bottom panel). No other effects reached significance (all *p*s > 0.18).

Figure 3 – Behavioral responses on the context-specific proportion congruency (CSPC) Stroop task. Panel A shows reaction times and proportion correct during the CSPC task. Panel B represents the correlation between the congruency effect (incongruent minus congruent trial RTs) and L2 usage. Error bars represent standard errors of the mean. LPC = Low Proportion Congruent, HPC = High Proportion Congruent.

Accuracy

The ANOVA revealed a significant main effect of congruency, $F(1, 49) = 7.82$, $p = 0.007$, displaying more accurate responses for congruent than incongruent trials. No other effects reached significance (*p*s > 0.35).

The ANCOVA with L2 experiences in the model demonstrated no significant main effects or interactions (*p*s > 0.09).

Together with RT findings, no evidence of speed–accuracy tradeoffs were observed, allowing faster responding to be interpreted as reflecting more efficient task performance with all else being equal.

Neural: Event-Related Potentials (ERPs)

N2

Figure 4 displays the N2 neural responses at electrode FCz (280-320 ms). The N2 component and its location were chosen based on previous work suggesting that the N2 plays a role in conflict monitoring and that it is commonly observed at FCz (e.g., Groom & Cragg, 2015; Hong et al., 2021; Nieuwenhuis et al., 2003). Visual inspection of the grand average confirmed that the N2 was most robust at this location.

The ANOVA revealed a significant main effect of congruency, $F(1, 49) = 7.41$, $p = 0.009$, with greater N2 amplitudes for incongruent than congruent trials. This effect was qualified by an interaction between context and congruency, $F(1, 49) = 8.51$, $p = 0.005$, such that the congruency effect was significant in the LPC context, $t(49) = 3.98$, $p < 0.001$, but not in the HPC context ($p = 1$).

The ANCOVA with L2 experiences included in the model revealed a significant main effect of context, $F(1, 37) = 11.72$, $p = 0.002$, where N2 amplitudes were greater for HPC contexts than LPC contexts. Importantly, this effect was qualified by a significant context by L2 proficiency interaction, $F(1, 37) = 5.00$, $p = 0.032$. The interaction is explained by the finding that enhanced (more negative) N2 amplitudes for HPC than LPC were more evident in individuals with low L2 proficiency than in those with high L2 proficiency ($r = 0.345$). In other words, high L2 proficiency individuals showed similar N2 responses regardless of context. Furthermore, these N2 amplitudes were smaller (less negative) for high than low L2 proficiency individuals in the HPC but not the LPC context. For illustrative purposes in observing these patterns in Figure 4, we divided individuals into high and low L2 proficiency based on a median split. No other effects reached significance (*p*s > 0.30).

Figure 4 – N2 ERP responses and its relationship with L2 proficiency on the context-specific proportion congruency (CSPC) Stroop task. Panel A represents the N2 ERP waveform. To facilitate visualization of condition differences, the figure to the right represents mean

amplitudes during the N2 window. Panel B represents the correlation between L2 proficiency and the context effect (HPC – LPC). To facilitate interpretation, the figure to the right represents mean amplitudes by context and L2 proficiency group (median split into high and low groups for visualization purposes only). Error bars represent standard errors of the mean (line graphs) and 95% confidence intervals around the line of best fit (scatterplot).

Conflict SP

Figure 5 displays the conflict SP wave neural responses at electrode POz (550-650 ms), which was chosen based on previous work examining the conflict SP (review in Larson et al., 2014) and visual inspection of the grand average to confirm.

The ANOVA revealed a significant main effect of congruency, $F(1, 49) = 26.98$, $p < 0.001$, with greater conflict SP amplitudes for incongruent than congruent trials. The effect of context, where HPC contexts showed greater conflict SP amplitudes than LPC contexts, approached, but did not reach, conventional levels of statistical significance, $F(1, 49) = 3.53$, $p = 0.066$.

The ANCOVA with L2 experiences added to the model revealed a main effect of L2 age of acquisition (AoA), $F(1, 37) = 4.92$, $p = 0.033$, where earlier L2 AoA was associated with greater conflict SP, regardless (i.e., independent) of trial type ($r = -0.343$). The two-way interaction between language switching frequency and context also approached, but did not reach, conventional levels of significance $F(1, 37) = 3.50$, $p = 0.069$. However, given that we had an a priori theoretical prediction for the interaction between language switching frequency and context, we explored the term further. We also considered this term as one-way rather than two-way given our prediction, in which case the p-value reaches conventional levels of significance ($p = 0.035$). The interaction is explained, as predicted, by the finding that more switching between languages predicted smaller context effects ($r = -0.294$, see Figure 5). No other effects reached significance ($ps > 0.09$).

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Figure 5 – Conflict SP ERP responses and its relationship with L1/L2 switching frequency on the context-specific proportion congruency (CSPC) Stroop task. Panel A represents the conflict SP ERP waveform. To facilitate visualization of condition differences, the figure to the right represents mean amplitudes during the conflict SP window. Panel B represents the correlation between language switching frequency and the context effect (HPC – LPC). To facilitate interpretation, the figure to the right represents mean amplitudes by context and switching frequency group (median split into high and low groups for visualization purposes only). Panel C represents the correlation between the mean overall amplitude of the conflict SP and L2 age of acquisition (AoA). To facilitate interpretation, the figure to the right represents mean amplitudes by L2 AoA group (median split into earlier and later groups for visualization purposes only). Error bars represent standard errors of the mean (line graphs) and 95% confidence intervals around the line of best fit (scatterplot).

Discussion

The present study examined the neural correlates of different bilingual experiences on conflict processing during a context-specific proportion congruency (CSPC; Crump et al., 2006) paradigm. We found that second language (L2) usage was predictive of behavioral adaptations, that L2 proficiency levels changed how contextual cues were processed at the N2, and that L2 age of acquisition (AoA) and language switching frequency were predictive of the conflict slow wave potential (SP). These findings have important implications for theoretical discussions surrounding how individual bilingual experiences contribute to domain-general context and conflict processing.

Reaction time (RT) data demonstrated that larger congruency effects were observed in the high proportion congruency (HPC) conditions than the low proportion congruency (LPC) conditions, replicating previous work using a CSPC paradigm (Crump et al., 2006; Crump et al., 2017; Jiménez-Moya et al., 2018). This finding demonstrates the ability of individuals to use contextual cues to adjust attentional demands on-the-fly. Importantly, the ability to adjust attentional demands based on conflict was predicted by L2 usage. While the CSPC effect is typically used to assess context-sensitive adjustments in attentional control, the observed interaction between L2 usage and the congruency effect suggests that using a second language may influence conflict resolution at a broader level. Rather than being limited to context-driven mechanisms, bilinguals may develop a more generalized ability to resolve cognitive conflict across varying task demands. This interpretation aligns with prior research indicating that bilingualism enhances domain-general executive function mechanisms, which may not always manifest as changes in context-specific adaptation effects (Morales et al., 2015; Kousaie & Phillips, 2012).

Greater L2 usage was associated with smaller RT congruency effects, highlighting the importance of continual use of a second language in efficiently processing conflict. Previous work has shown that L2 usage is particularly important for structural brain outcomes, including both grey and white matter adaptations in the brain (DeLuca et al., 2019a, DeLuca et al., 2024; Grundy et al., 2017; Pliatsikas, 2020). For example, DeLuca et al. (2019) demonstrated using a longitudinal design that individuals immersed in and continually using a second language showed a reshaping of the caudate nucleus. The caudate nucleus is a brain region involved in adaptive learning, and modifying future behaviors based on past experiences (Packard & Knowlton, 2002). In line with their results, the present study found smaller congruency effects with more L2 usage, suggesting that more L2 usage is associated with more adaptive and efficient learning.

The neural data for the N2 and the conflict SP further demonstrate the importance of second-language experiences in adaptations to brain processing of conflict and contextual cues. The N2 was larger for incongruent than congruent trials, reflecting increased attention to the conflicting, but irrelevant, words, as expected (review in Larson et al., 2014). This effect was contextualized by an interaction with context, such that the congruency effect was only present for the LPC, but not the more difficult HPC condition. In the HPC context, participants likely start paying attention to task-irrelevant features (i.e. the words) of the trials, given that these features usually benefit performance. Importantly, greater L2 proficiency was associated with more consistent N2 amplitudes across contexts. Individuals with lower L2 proficiency showed greater (more negative) N2 brain responses during a Stroop task when the task was in the more difficult HPC context compared to the LPC context. However, N2 amplitudes did not change based on context for those high in L2 proficiency. Within the present framework, this pattern is consistent with more efficient early control engagement for highly proficient individuals, insofar as comparable behavioral performance is achieved with reduced need for context-dependent modulation of the N2 – less proficient bilinguals might adjust more on-the-fly when entering a high-conflict context.

Related work supports the idea that specific bilingual experiences map onto distinct neural control profiles. For example, Carter et al. (2023) reported that individual differences in bilingual experience were linked to systematic variation in conflict-related ERPs (including N2 and later components), and that neural control architecture helped explain experience–behavior associations. This converges with the present findings that different experience dimensions relate to different stages of control, and helps contextualize why effects can differ across samples and measures.

Given that bilinguals frequently engage in language switching and conflict resolution from non-target languages, these experiences may contribute to enhanced neural efficiency in handling contextual cues (Abutalebi et al., 2012; Grundy et al., 2017). The observed effects on the N2 and conflict SP suggest that different aspects of bilingual experience – such as proficiency, usage, switching frequency, and L2 age of acquisition – play distinct roles in shaping both early conflict monitoring and later-stage attentional control adjustments. While previous work has primarily focused on how bilingualism influences executive function at the behavioral level, our results provide neurophysiological evidence that bilingual experiences shape neural responses to conflict monitoring and attentional control dynamically across time. Future research should continue to disentangle how different bilingual experiences modulate attentional control across various executive function tasks and neural markers. These findings are also in line with our previous work with different paradigms and samples showing that bilingualism contributes to more rapid disengagement of attention from irrelevant information (Grundy & Bialystok, 2018; Grundy et al., 2017b; Grundy et al., 2020). While traditional models of attentional control suggest that larger conflict adaptation effects indicate stronger cognitive control (Botvinick et al., 2001; Egner, 2007; Kerns et al., 2004), recent findings challenge this assumption. Egner (2008) demonstrated that with experience, individuals shift toward a more stable control strategy that reduces the need for transient adaptation effects. Consistent with this, Grundy et al. (2017) found that bilinguals exhibit smaller sequential congruency effects (SCEs), which they interpreted as evidence of a more efficient control process that does not rely as heavily on trial-level adjustments. The present findings support this view, as bilinguals with greater L2 proficiency showed reduced context sensitivity in N2 amplitudes (i.e., a smaller N2 context effect), suggesting that they may engage a more stable form of conflict resolution rather than relying on transient control mechanisms. Being able to rapidly disengage attention from the previous (and no-longer-relevant) stimulus allows more consistent and efficient responses over time. The present study extends this by showing that L2 proficiency was associated with this pattern of more consistent responses, suggesting a possible efficiency pattern.

Certain bilingual experiences were associated with conflict SP amplitudes as well. For all participants, incongruent trials elicited larger conflict SP amplitudes than congruent trials. This pattern is consistent with more attentional control being applied to conflicting trials after initial detection at the N2 (review in Larson et al., 2014). The conflict slow potential (SP) is a late-stage neural marker of post-conflict control, reflecting the sustained engagement of attentional resources to resolve conflict (Larson et al., 2014; West, 2003). Studies have found that diminished conflict SP amplitudes are linked to attentional control deficits. For example, individuals with traumatic brain injury (TBI) exhibit reduced conflict SP amplitudes, suggesting an impaired ability to sustain attentional control following conflict detection (Larson et al., , 2009). This aligns with findings from other late-stage ERP components, such as the Late Positive Component (LPC), which also shows reduced amplitudes in individuals with fewer available cognitive resources (Raynal et al., 2024). Given the similarities between the conflict SP and LPC as indices of sustained attention, combined with the fact that individuals with worse attentional control show smaller conflict SPs, our interpretation is that larger conflict SP amplitudes reflect greater available attentional resources. More support for this claim comes from Liu et al. (2016), showing that individuals with higher IQ had larger conflict SP amplitudes than those with lower IQ, as well as smaller conflict adaptation effects on a flanker task. Although the switching-frequency by context interaction in the conflict SP was modest (one-tailed significance), the direction was consistent with our a priori prediction; we therefore interpret it cautiously as preliminary evidence.

Both language-switching frequency and L2 AoA moderated conflict SP amplitudes. More frequent language-switching predicted smaller differences between LPC and HPC contexts for the conflict SP. In other words, people who frequently switch between their first and second languages showed less adjustment in attentional control based on contextual cues compared to those who switch rarely between their languages. This finding is in line with our predictions based on the dense-code switching environmental demands that Green and Abutalebi introduced (2013). People who switch often between languages are usually immersed in environments in which contextual cues are not as necessary (i.e. dense code-switching environments), given that everyone (or most) in the environment know both languages, and adjustments to control are not needed. Our study demonstrates that this pattern was borne out on a domain-general executive function task. We argue that language switching frequency contributes to domain-general changes to cues signaling a need for changes to attentional control.

On the other hand, earlier L2 AoA led to greater conflict SP amplitudes, regardless of trial type. This result suggests that people differ in their baseline levels of conflict SP resources depending on the age at which they learned a second language. Those who acquired their second language earlier seem to have more attentional resources available for all types of trials. A pure cost account would predict either (a) a behavioral cost (e.g., larger conflict effects or slower responses) or (b) selective increases in conflict-related activity (i.e., larger conflict SP effects). Neither pattern was observed: performance was unchanged and the SP increase was not specific to conflict. This pattern is therefore more consistent with a difference in baseline sustained engagement (i.e., available attentional resources) than with compensatory effort. This pattern was reflected in larger SP amplitudes that did not differ across trial types, suggesting increased sustained engagement rather than changes in conflict-specific processing. Within the framework of Table 1, this configuration aligns with an overall-amplitude pattern (comparable behavior, no change in N2, increased SP) and is interpreted here as reflecting capacity rather than inefficiency because it lacks the behavioral or conflict-specific signatures expected under a cost-based account. Given that the brain is more malleable in early development (review in Huttenlocher, 2009), our findings suggest that learning a second language at a younger age enhances neural plasticity and increases the resources available for attentional control during early development.

Studies have shown that L2 AoA leads to structural changes to the brain (Anderson et al., 2024; DeLuca et al., 2019; Mechelli et al., 2004), and our study adds to this body of evidence by showing that L2 AoA is related to domain-general *functional* processing changes to the brain as well. In particular, the conflict SP component, which reflects later-stage sustained attentional control, was enhanced in individuals with earlier L2 acquisition – suggesting more attentional resources available in those with early bilingual experience. This aligns with cognitive reserve frameworks proposing that lifelong cognitively demanding experiences, including bilingualism, help preserve executive functioning despite aging or neuropathology. Bialystok (2021) outlines evidence that bilinguals exhibit delayed onset of dementia symptoms, preserved cognition despite neuropathology, and slower decline in late-stage aging than monolinguals. Several meta-analyses support these conclusions (Anderson et al., 2020; Brini et al., 2020; Paulavicius et al., 2020). Neuroimaging work further supports this idea; bilinguals show increased gray matter density in regions tied to attentional control (e.g., Abutalebi et al., 2015) and even volumetric renormalization of the hippocampus, a critical memory center, following a U-shaped pattern with extended L2 engagement (Gallo et al., 2025). Gallo et al. (2022) report that high L2 proficiency and L2 AoA both predict executive performance beyond traditional reserve-enhancing factors like education or physical activity. Our data extend this literature by identifying specific ERP signatures – namely, larger conflict SP amplitudes – that may reflect greater attentional capacity in individuals with earlier and more intense bilingual experience. These neurophysiological markers provide evidence that the timing and nature of bilingual experience shape the efficiency and flexibility of attentional control systems across the lifespan. Some may argue that the data presented in the present manuscript, and any cross-sectional studies, do not speak to causality and that confounds (SES, IQ, etc.) may be driving the observed effects. However, there are now several longitudinal studies that support the view that bilingualism enhances executive functions. For example, Bak et al. (2016) conducted a randomized controlled trial (RCT) in which older adults were assigned to either a second-language learning program or a control condition. Results demonstrated that those in the language-learning group showed significant improvements in executive functions. Other training-based studies also provide evidence that second-language learning induces changes to executive functions. For example, Pfenninger and Polz (2018) showed that older adults engaging in foreign language learning exhibited improvements in executive function, autonomy, and communicative skills, suggesting that bilingual engagement may support cognitive resilience. Wong et al. (2019) demonstrated that six months of foreign language learning boosted cognitive performance, and that this boost was maintained three months later. Meltzer et al. (2023) provided evidence that app-based second-language learning yielded similar executive function benefits to traditional brain-training programs, further supporting the role of bilingual engagement in maintaining cognitive function. In an ERP study, Sullivan et al. (2014) demonstrated that even early-stage second-language learning leads to enhanced executive control, aligning with our findings regarding the modulation of the N2 and conflict SP responses. Our results align with frameworks that differentiate an early conflict monitoring stage and a later compensatory control stage – and show that bilingual experiences can uniquely fine-tune each of these stages independently.

Potential limitations

A reviewer of a previous version of this paper noted that patterns we characterize as efficient (e.g., smaller CSPC or SCE effects in experienced bilinguals) are also observed in clinical populations (e.g., brain injury, developmental disorders). However, multiple studies challenge the assumption that larger conflict “adaptation” effects are indicative of superior attentional control.

Most research on conflict adaptation (SCE) examines whether or not an effect is present rather than its magnitude. For instance, theories based on cognitive control (Botvinick et al., 2001), feature integration (Hommel et al.,2004), contingency learning (Schmidt & De Houwer, 2011), and repetition expectancy (Duthoo et al., 2014) explore the conditions that either elicit or eliminate conflict adaptation by modifying task parameters to support their respective frameworks. Control-based theories argue that conflict adaptation reflect top-down control adjustments in response to conflict signals (e.g., Botvinick et al., 2001), while feature integration theories propose that stimulus-response bindings are episodically retrieved across trials (e.g., Hommel et al., 2004). For example, Botvinick et al. (2001) suggest that “conflict monitoring serves to translate the occurrence of conflict into compensatory adjustments in control” (p. 625), meaning that conflict adaptation-related processes are engaged contextually as needed. However, research on the relative *magnitude* of conflict adaptation rather than its presence or absence suggests that smaller conflict adaptation effects develop over time with more efficient processing.

Conflict adaptation effects get smaller with practice, suggesting that smaller effects may reflect increased cognitive efficiency rather than impairment (Mayr & Awh, 2009; van Steenbergen et al., 2015). Egner et al. (2010) found that conflict adaptation effects get smaller as response-to-stimulus intervals lengthen, allowing more time for performance adjustments – contrary to the expectation that larger conflict adaptation effects indicate greater adaptability. Individuals with higher intelligence show smaller conflict adaptation effects, implying that more stable control strategies may be characteristic of higher-functioning individuals, not just clinical populations (Liu et al.2016). Thus, rather than mirroring cognitive deficits, the smaller conflict adaptation effects observed in bilinguals may reflect a more stable attentional strategy (Grundy & Bialystok, 2018).

While larger sample sizes generally offer increased power for detecting higher-order interactions, the present sample (N = 50) is on the higher end of what is typical for ERP studies of cognitive control, as documented in large-scale meta-analyses showing that many ERP investigations use substantially smaller samples and are often underpowered for similar effects (Clayson et al., 2019; Szűcs & Ioannidis, 2017). Importantly, the theoretical motivation of our analyses constrains interpretation rather than compensating for limited statistical power; accordingly, we emphasize effect sizes, pattern consistency, and transparency regarding limitations, while acknowledging that larger samples will be important for improving precision and replication. Future research should seek to replicate these effects with larger samples to further confirm the robustness of these findings. An important direction for future research will be to examine interactions among bilingual experience dimensions, as different combinations of proficiency, usage, acquisition timing, and switching may give rise to distinct control profiles.

Conclusions

The present study examined how different bilingual experiences relate to neural and behavioral indicators of attentional control in a context-specific proportion congruency (CSPC) Stroop paradigm (Crump et al., 2006). We found that individual differences in bilingual experience – specifically L2 usage, L2 proficiency, L2 age of acquisition, and language switching frequency – each showed unique associations with performance and ERPs. In sum, more frequent L2 usage predicted smaller behavioral conflict effects; higher L2 proficiency was linked to more stable (context-invariant) N2 responses; earlier L2 AoA was associated with larger conflict SP amplitudes (greater sustained attentional resources); and frequent language switching was associated with reduced context-based modulation of the conflict SP.

These results extend our understanding of how bilingualism influences attentional control by demonstrating that not all bilinguals exhibit the same pattern of cognitive and neural adaptation. Instead, specific facets of bilingual experience play distinct roles. Frequent L2 use was related to a general performance boost (reduced Stroop interference), suggesting that active engagement in a second language may strengthen domain-general conflict resolution skills. High L2 proficiency was associated with a refined neural control strategy at early processing stages: proficient bilinguals did not need to up-regulate conflict monitoring (N2) in the high-conflict context to the same extent as less proficient bilinguals did. One interpretation is that greater proficiency confers a flexibility or efficiency in engaging control – proficient bilinguals might maintain a moderate level of monitoring that is effective across contexts, whereas less proficient bilinguals must adjust more when entering a high-conflict context. Early L2 AoA was linked to a generally more robust conflict SP, indicating greater overall attentional resources available during conflict resolution. This could reflect long-term neuroplastic effects of early bilingual exposure on frontal–parietal control networks. This contrasts with the pattern seen for proficiency, where reduced N2 modulation suggests greater efficiency in early conflict monitoring. In combination, these findings indicate that different bilingual experiences may fine-tune control mechanisms through distinct neural strategies – some emphasizing economy of engagement, others emphasizing the amount of attentional resources developed. In line with these observations, several resting-state fMRI studies show enhanced functional connectivity between frontal and parietal regions in bilinguals – and importantly, this connectivity is greater in those who acquired their L2 earlier, even when matched for proficiency (Berken et al., 2016). Finally, frequent language switching was associated with an attenuated context effect in the SP, suggesting that those who habitually switch languages apply a more uniform level of sustained control regardless of context. This fits with our hypothesis that constant context switching in language could reduce sensitivity to contextual cues on non-linguistic attentional control tasks. Together, these findings highlight how individual bilingual experiences fine-tune neural mechanisms of control in distinct and interpretable ways.

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Competing Interests

The authors declare no conflicts of interest.

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