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THE IMPACT OF LANGUAGE CONTEXT ON PROACTIVE CONTROL IN BILINGUALS

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Abstract: With the acceleration of globalization, frequent cross-linguistic communication has emerged as a defining cognitive feature of modern society. This phenomenon has shifted scholarly focus from single-language contexts to mixed-language, emphasizing how varying language environments modulate the bilingual advantage. Guided by the Adaptive Control Hypothesis, this study operationalized three distinct language contexts (Chinese, English, and Mixed-language). It employed the AX-Continuous Performance Task (AX-CPT) with event-related potential (ERP) recordings to investigate context-dependent modulations of proactive control in bilinguals. The results revealed that compared to single-language contexts, mixed-language contexts demonstrate superior behavioral efficiency, manifested as faster response time specifically in BX and BY trials, along with distinct neurophysiological profiles: (1) augmented N2 amplitudes during cue B processing, and (2) attenuated late positive component amplitudes throughout picture processing stage. These findings suggest that mixed-language enhances proactive control through increased task complexity, demonstrating differential neural resource allocation patterns across language environments.

Keywords: Language environment; Proactive control; AX-Continuous Performance Task; Event-related potential

1 INTRODUCTION

The human brain exhibits remarkable adaptability, dynamically reorganizing in response to individual experiences. Language, as a manifestation of cognitive capacity, is a critical factor in shaping neural architecture. Extensive cross-linguistic research indicates that bilingual experience modulates both linguistic functions and domain-general cognitive control—the ability to process goal-relevant information while suppressing interference flexibly [1]. The Dual Mechanisms of Control (DMC) framework provides a theoretical foundation for understanding the inherent variability in cognitive control. This framework proposes two distinct regulatory modes: proactive control and reactive control [2].

Proactive control operates through an "early selection" mechanism. During the task preparation phases, this mode selectively processes task-relevant cue information and actively maintains these cue representations in working memory throughout the cue-to-probe interval. This sustained maintenance facilitates anticipatory response preparation, allowing cue information to predict subsequent responses. By optimizing attentional, perceptual, and action systems in advance, proactive control enhances goal-directed behavior, improves task performance, and mitigates cognitive interference. In contrast, reactive control functions as a "late correction" mechanism. This mode resolves conflicts during response execution by dynamically accessing task-relevant information and reactivating prior cue representations through retrieval processes as needed to guide responses and correct erroneous tendencies.

The AX-Continuous Performance Task (AX-CPT), a well-established paradigm for studying attention and working memory, effectively dissociates these control mechanisms. This paradigm consists of cue stimuli followed by probe stimuli, separated by a temporal delay (blank screen). Enhanced proactive control is evidenced by reduced reaction times or error rates in BX trials. At the neural level, larger N2 amplitudes (negative deflection) during cue processing reflect greater cognitive control demands or neural resource allocation, with enhanced N2 amplitudes for B cues indicating superior proactive control [3].

The Adaptive Control Hypothesis emphasizes that language, as fundamentally collaborative behavior[4], necessitates the minimization of "joint cognitive effort." Insufficient language control can lead to reduced interaction efficiency (e.g., switching errors and comprehension failures), potentially resulting in social or functional costs (e.g., professional risks and communication breakdowns).To maintain effective communication in complex interactions, language control processes dynamically adapt to contextual demands through three mechanisms: neural efficiency optimization, control process coordination, and network connectivity adjustments. This adaptation induces enduring neurobehavioral changes in bilingual individuals. The hypothesis identifies three interactional contexts: 1) Single-language Context (utilizing different languages in distinct environments), 2) Dual-language Context (the co-activation of both languages within a single environment, necessitating language selection based on interlocutor identity), and 3) Dense Code-switching Context (the intra-utterance blending of lexical and grammatical elements from different languages).

Differential bilingual experiences across these contexts reshape linguistic demands and modify language-executive control dynamics. Environmental pressures may alter the difficulty of lexical retrieval during speech production, thereby influencing the timing and mechanisms of cognitive control engagement. Researchers compared three groups of highly proficient Spanish-English bilinguals: 1) Single-language context bilinguals in Spain (using English as L2 in specific settings such as school or work with minimal switching), 2) Dual-language context bilinguals in Puerto Rico (who frequently utilize both languages), and 3) Varied context bilinguals in the U.S. (living in an English-dominant environment with occasional code-switching). Participants completed lexical production tasks (picture naming) and an

AX-CPT variant. Results demonstrated context-dependent relationships between lexical accessibility and cognitive control: the single-language context group exhibited minimal reliance on contextual processing with a predominant reactive control strategy, whereas mixed-language context bilinguals displayed stronger context-dependent tendencies coupled with proactive control [5].

Although existing studies demonstrate language context effects on proactive control, correlational designs comparing group performance differences have inherent limitations. Such approaches merely assess associations between bilingual cognitive advantages and context, without establishing causal relationships. The present study addresses this through a dual-task paradigm that manipulates language control demands while observing subsequent impacts on proactive control tasks.

2 METHOD

2.1 Participants

Sample size estimation was conducted using G*Power 3.1.9.7 with the following parameters: repeated-measures ANOVA (within-subjects factors), effect size $f = 0.25$, $\alpha = 0.05$, power $(1-\beta) = 0.80$, number of groups = 1, and number of measurements = 12. The analysis indicated a required sample size of 13 participants. We ultimately recruited 27 right-handed university students (unbalanced Chinese-English bilinguals), with normal or corrected-to-normal vision, good health, and no history of neurological or psychiatric disorders. All participants had passed the College English Test Band 4 (CET-4). All participants provided informed consent and received monetary compensation upon completion.

2.2 Design and Procedure

The study employed a 3 (Language Context: Chinese, English, and mixed-language) × 4 (Trial Type: AX, AY, BX, BY) within-subjects design. Language contexts served as the independent variable, while AX-CPT performance metrics (reaction times [RTs] and error rates) functioned as dependent variables. Participants completed a dual-task paradigm comprising sequential picture-naming and AX-CPT tasks per trial. The experiment included 300 trials divided into 6 counterbalanced blocks (2 blocks/condition), separated by self-paced rest periods. Condition presentation order followed a Latin square randomization protocol, Figure 1 provides a detailed depiction of the procedure..

2.2.1 Picture naming task

The picture-naming task incorporated three language contexts (Chinese, English, and mixed-language), manipulated through language switching. In a mixed-language context, participants first viewed a 500ms white fixation cross at the screen center. A 250ms language cue followed: red squares signaled Chinese naming, and blue squares English naming (color-language mapping counterbalanced). After a 1000ms line drawing presentation, "*****" symbols prompted vocal responses per cue instructions. Chinese context and English context required constant L1 or L2 naming without switching demands. All picture stimuli consisted of 60 black-and-white line drawings selected from Snodgrass and Vanderwart's photo gallery Snodgrass and Vanderwart, standardized by Zhang and Yang [6]. The Chinese word for each picture was a two-character word and the English equivalents ranged from 3 to 8 letters in length.

2.2.2 Continuous performance task

In the Continuous Performance Task, a cue stimulus (A and B), a blank screen, and a probe stimulus (X and non-Y) were presented sequentially in the center of the screen, and the subject's task was to press the "F" key (i.e., the AX sequence) for the probe X that appeared after the cue A, and the "J" key (i.e., the AY, BX, and BY sequences) for the rest. The task was to press the "F" key (i.e., the AX sequence) for probe X following cue A, and the "J" key (i.e., the AY, BX, and BY sequences) for all other cases, with the AX sequence accounting for 70% of the total, and the other three sequences accounting for 10% of the total. Each cue appeared for 250 ms, followed by a blank interval (1,000 ms), after this interval, the probe stimulus appeared for 250 ms, followed by a trial interval (1,000 ms).

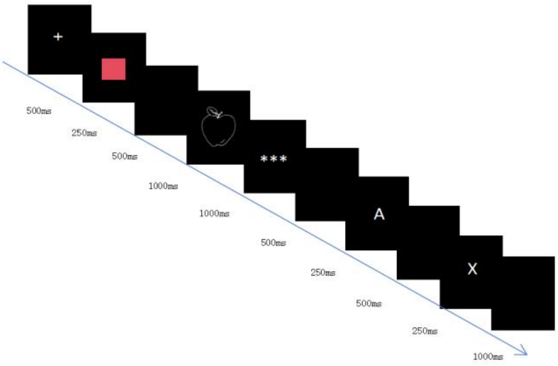

Figure 1 Experimental Procedure for the Interleaved Presentation of Picture Naming Task

2.3 Electrophysiological Recordings

The experiments were conducted using Brain Product's EEG equipment, selecting 64 conductive electrode caps and Recorder software to record EEG data. The signal sampling rate was 500 Hz, the filter bandwidth was 0. 1-100 Hz, the reference electrode was the FCz point, the grounding point was the AFz point, the electrode was placed in the lower part of the right eye to record the vertical EEG, and the contact resistances between the scalp and the electrodes were all less than 10 kΩ. The raw data were analyzed offline using Analyzer 2.0 software. The specific steps were as follows: the reference electrode was converted to the average reference of TP9 and TP10, the independent component analysis (ICA) was used to remove the electrooculographic artifacts, the band-pass 0.1-30Hz was used for filtering, and the N2 and LPC waveforms were segmented using the criteria of 200ms before stimulus presentation to 800ms after stimulus presentation. The N2 and LPC waves were segmented from 200ms before to 800ms after the stimulus presentation, and the EEG of 200ms before the stimulus presentation was used as the baseline correction. Artifacts such as blinks were automatically corrected, EEG waves with voltages exceeding ±100 μV were rejected before EEG events were superimposed, and finally, data time courses were categorized and averaged.

2.4 Behavioral Data and Event-related Brain Potential Analysis

The data were analyzed using SPSS 21, and since the percentage of AX trials was much higher than the other trials, only the correct rate and reaction time of AY, BX, and BY were analyzed; the raw data were chosen to analyze the error rate, and the reaction time of the correct response was chosen only for the reaction time of the correct response. The shorter the reaction time of BX trials, the higher the correct rate indicating that the subject was biased toward using proactive control, and the longer the reaction time of AY trials, the lower the correct rate indicating that the subject favored the use of reactive control.

For the ERP analysis of the persistence manipulation test, the mean N2 amplitude of the cue letters was used as the dependent variable, and the time window for analysis was from 200 ms before the appearance of the cue letters to 800 ms after the appearance of the cue letters. Due to the inconsistency in the latency of N2 amplitude of cues A (250 ms-350 ms) and B (300 ms-400 ms), they were subjected to a one-way repeated-measures ANOVA, respectively.

For the ERP analysis of the language switching task, a one-way repeated measures ANOVA was conducted with the average LPC (450ms-650ms) amplitude of the pictures as the dependent variable, and the time window of analysis was from 200ms before the appearance of the pictures to 800ms after the appearance of the pictures.

3 RESULTS

3.1 Behavioral Results in Continuous Performance Task

3.1.1 RTs

Continuous Performance Task reaction times are presented in Table 1. A 3×3 repeated measures ANOVA was conducted on reaction times, with a significant main effect of language context, $F(2,104)=7.132$, $p<0.05$, $\eta^2=0.215$, and shorter reaction times in the Mixed-language context(M=375.41ms) than in Chinese context (M=420.26ms) and English context (M=416.79ms). The main effect of sequence type was significant, $F(2,104)=138.845$, $p<0.001$, $\eta^2=0.842$, with longer reaction times in the AY condition (M=544.92ms) than in BX (M=326.81ms) and BY (M=340.73ms). The interaction was significant, $F(2,104) = 2.872$, $p < 0.05$, $\eta^2 = 0.099$. Simple effects analyses revealed that the reaction time of AY (M = 536.53ms) trials in the mixed-language context was not significantly different from that of AY trials in the Chinese context (M = 546.95ms), $p = 0.554$, and from that of AY trials in the English context (M = 551.29ms) was not significantly different, $p = 0.448$. The response time of the BX (M = 293.91ms) trial in the mixed-language context was significantly different from that of the BX trial in the Chinese context (M = 340.20ms), $p < 0.05$, and from that of the BX trial in the English context (M = 346.32ms), $p < 0.05$. The response time of the BY (M=295.78ms) trial was significantly different from that of the BX trial in the Chinese context (M=373.64ms), $p<0.01$, and significantly different from that of the BX trial in the English context (M=352.77ms), $p<0.01$.

Table 1 Mean Proportion RTs(ms) by Trial and Different Language Contexts in the Continuous

Condition	Mixed-Language	Chinese	English
AY	536.53	546.95	551.29
BX	293.91	340.20	346.32
BY	295.78	373.64	352.77

3.1.2 Accuracy

Continuous Performance Task accuracy is presented in Table 2 Mean proportion errors by trial and different language contexts in the continuous performance task. A 2×3 repeated measures ANOVA was conducted on correctness, and the main effect of context was not significant, $F(2,104)=0.159$, $p>0.05$. The main effect of the condition was significant, $F(2,104)=7.011$, $p<0.05$, $\eta^2=0.219$. Correctness was lower in AY (M=0.842) than in BX (M=0.928) vs. BY (M=0.922) trials. The interaction was not significant, $F(2,104)=2.341$, $p=0.06$.

Table 2 Mean Proportion Errors by Trial and Different Language Contexts in the Continuous Performance Task

Condition	Mixed-Language	Chinese	English
AY	0.92	0.81	0.95
BX	0.91	0.87	0.92
BY	0.94	0.84	0.92

3.2 ERP Results in Continuous Performance Task

Figure 2 shows N2 waveforms of cue B(left panel) and A(right panel) in different language contexts. A one-way repeated measures ANOVA within the N2 mean wave amplitude (300ms-400ms) for cue B showed significant differences between contexts, $F(2,78)=3.791$, $p<0.05$, $\eta^2=0.127$, and the results of multiple comparisons showed that the N2 mean wave amplitude of mixed-language context (M=-2.09) was significantly greater than that of Chinese context (M=-1.08) vs. English context (M= -0.791), with no significant difference between Chinese context and English context. One-way repeated-measures ANOVA within the N2 mean amplitude (250ms-350ms) of cue A showed no significant difference, $F(2,78) = 0.459$, $p = 0.635$.

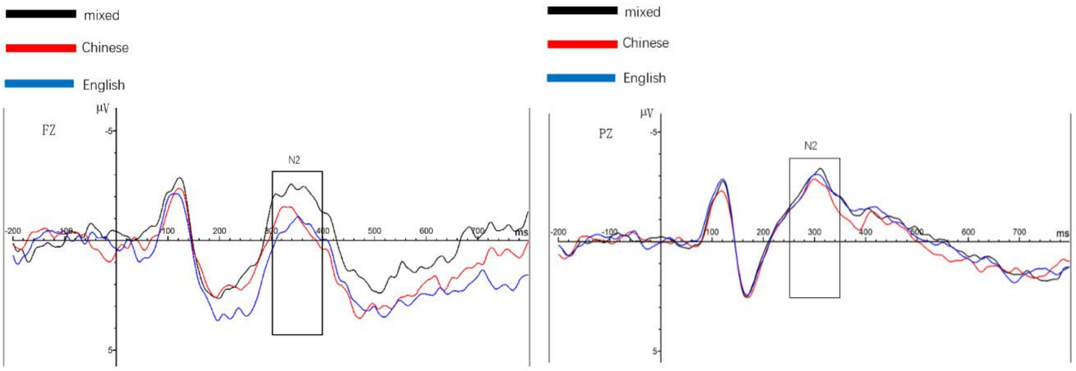

Figure 2 N2 Waveforms of Cue B(Left Panel) and A(Right Panel) in Different Language Contexts

3.3 ERP Results in Picture Naming Task

Figure 3 shows LPC waveforms of picture naming task in different contexts. A one-way repeated measures ANOVA within the mean LPC amplitude (450-650ms) of the pictures showed significant differences between contexts, $F(2,78)=14.151$, $p<0.01$, $\eta^2=0.352$. Results of multiple comparisons showed that the LPC amplitude of the mixed-language context (M=2.20) was significantly smaller than that of the Chinese context (M=3.89) vs the English context (M=4.20), with no significant difference between the Chinese context and the English context.

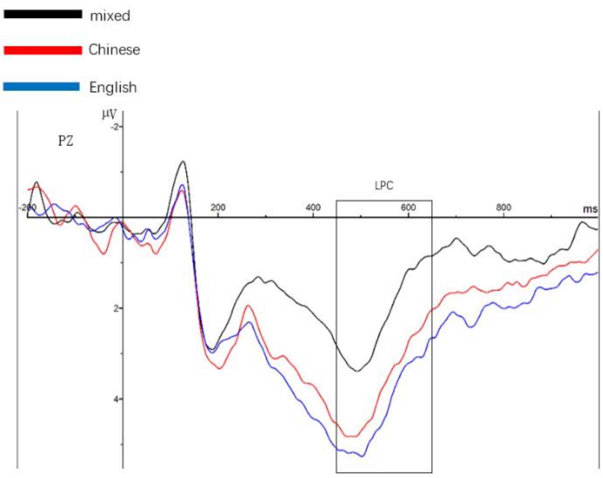

Figure 3 LPC Waveforms of Picture Naming Task in Different Contexts

4 DISCUSSION

This study investigates whether different language contexts influence cognitive control patterns in bilinguals. The results reveal that, compared to single-language contexts, bilingual contexts elicit shorter reaction times (RTs) for BX and BY trials, along with larger N2 amplitudes triggered by cues, demonstrating enhanced proactive control implementation during these trials. The behavioral results indicate a significant main effect of trial type, with longer RTs and lower accuracy in AY trials compared to BX and BY trials, suggesting that participants predominantly employ proactive control strategies, which aligns with previous research that shows a preference for proactive control in young adults [7]. Consistent with earlier studies [8], proactive control delays AY responses while accelerating BX responses, whereas reactive control produces the opposite pattern [9]. The shorter RTs for BX and BY trials in mixed-language contexts, with no significant difference between them, suggest that participants pre-establish response mappings based on cue information, which is a hallmark of proactive control. Cue-related ERP findings in the AX-CPT task demonstrated significantly larger N2 amplitudes for cue B in mixed-language contexts compared to both Chinese context and English context. The N2 component, which is associated with cognitive control processes such as cue monitoring, conflict resolution, and inhibition, reflects an increased allocation of attentional resources to cues in mixed-language contexts. The absence of N2 differences for cue A, which is a high-frequency cue requiring minimal conflict monitoring, indicates selective proactive engagement.

In picture-naming tasks, mixed-language context elicited significantly smaller late positive component (LPC) amplitudes compared to single-language contexts. The LPC, characterized as a broad, parietal-distributed positive waveform, is linked to deep semantic processing and memory retrieval[10]. Its amplitude is inversely correlated with processing demands: greater difficulty results in reduced LPC magnitude. Jiao similarly observed diminished LPC amplitudes in bilingual contexts during picture naming [11], attributing this pattern to the heightened language control demands faced by unbalanced bilinguals. Thus, the contextual advantages observed in this study may be due to different task demands in different linguistic contexts.

Bialystok proposed an attentional control framework that extends beyond traditional conceptualizations of cognitive control components, offering a comprehensive explanation applicable to diverse tasks. While bilinguals typically outperform monolinguals in conflict-laden tasks, their performance converges with that of monolinguals in simple, verbal, or non-conflict conditions. This pattern suggests that the cognitive advantages of bilinguals originate not from isolated inhibitory mechanisms but from lifelong experience in managing dual languages—continuously coordinating goals, suppressing interference, and flexibly switching between linguistic systems.

Such experiences enhance the efficiency and adaptability of attentional systems. Consequently, the advantages of bilingualism remain undetectable in automated tasks or those requiring minimal attentional control, such as simple cognitive tasks performed by young adults. This is analogous to the performance of mathematicians and high school students on elementary arithmetic problems, where the test fails to differentiate their mathematical capabilities. Bilingual advantages emerge exclusively in high-demand tasks that involve substantial working memory loads.

Marttune investigated whether increased working memory demands induce flexible shifts in cognitive control strategies in young, healthy adults [13]. Using an adapted AX-CPT paradigm that manipulated cognitive load through contextual cue maintenance demands, the study demonstrated that low working memory loads enable effortful proactive strategies, whereas high loads promote stimulus-driven reactive control. Behavioral data from web-based experiments and MRI-validated replications confirmed that increased cognitive load correlated with reactive responding. Neuroimaging revealed distinct neural substrates: proactive control engaged the right dorsolateral prefrontal cortex (dlPFC) during cue processing, whereas reactive control activated the same region during probe processing. Crucially, task difficulty operates differently across populations - the AX-CPT may be a challenging task for monolinguals, predisposing them to reactive strategies. In high-stress variants of the AX-CPT, requiring the maintenance of 3-5 simultaneous cues, bilinguals' superior attentional control reduces cognitive load, allowing proactive engagement even under heightened demands. This contrasts with monolinguals' tendency to adopt resource-conserving reactive strategies at higher levels of difficulty, which is consistent with evidence from numerous studies suggesting that bilinguals tend to rely more heavily on proactive control.

The present results show proactive control dominance under high task demands, seemingly contradicting Marttunen's findings. However, both studies fundamentally illustrate the role of task difficulty in modulating cognitive resource allocation: Marttunen enhanced reactive control via AX-CPT working memory overload, whereas the present study enhanced proactive control via mixed-language context complexity. These complementary findings establish that task difficulty regulates control mode selection through bidirectional resource redistribution, which either enhances or attenuates proactive engagement. Maintaining AX-CPT accuracy required strategic enhancement of proactive control for BX/BY trials while avoiding overcommitment to AY trials, which required flexible attentional optimization. The mixed-language context, characterized by reduced LPC amplitudes and increased complexity, required simultaneous AX-CPT performance and language selection (via cue-dependent inhibition). According to Bialystok's framework, this dual demand optimizes global attentional control, explaining superior AX-CPT performance through three mechanisms: (1) enhanced cue monitoring (increased N2 amplitudes), (2) efficient conflict resolution (accelerated BX/BY responses), and (3) adaptive neural resource allocation (reduced LPC amplitudes reflecting controlled lexical access) [12].

5 CONCLUSION

The present study sheds light on the cross-talk between language control and domain-general executive control in bilinguals by showing that proactive control is affected by language contexts in production.

Compared to single-language contexts, mixed-language contexts demonstrate superior behavioral efficiency, manifested as faster response time specifically in BX and BY trials, along with distinct neurophysiological profiles: (1) augmented N2 amplitudes during cue B processing, and (2) attenuated late positive component amplitudes throughout picture processing stages. In other words, control demands cued by language contexts affect subsequent proactive control processes.

CONFLICTING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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