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The role of cognitive control in bilingual language comprehension: An event-related potential study of dense code-switching sentences

Research Article

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Abstract

This study investigated the engagement of domain-general cognitive control during the comprehension of dense code-switching sentences. Stimulus-locked event-related potentials (ERPs) were measured while L1-dominant Chinese–English bilinguals read switch and non-switch sentences. The results of the reading task revealed language dominance effects on the N400, left anterior negativity (LAN) and late positive component (LPC). The language dominance effects at lexical level (i.e., on the N400 and LAN) were modulated by individual differences in monitoring capacity. In contrast, inhibition capacity predicted code-switching costs at the sentence level (i.e., for the LPC component). The results suggest that proactive monitoring and reactive inhibition affect different processing stages during the comprehension of dense code-switching sentences. These findings partially align with processing models of code-switching incorporating a dual control mode perspective and contribute new insight into the dynamic interplay between reactive and proactive control processes.

1. Introduction

Bilinguals are constantly faced with the challenge of controlling their two languages to avoid interference from the language not in use. There is an ongoing debate on whether and how the language control mechanisms recruit domain-general cognitive control processes (Green, 1998; Jiao et al., 2022a). Though it has been repeatedly observed that language control during production engages domain-general inhibition (Green, 1998; Jiao et al., 2022a; Kang et al., 2020; Linck et al., 2012; Liu et al., 2014; but see Calabria et al., 2012, 2015; Prior & Gollan, 2013; Segal et al., 2019), the association between domain-general cognitive control and language control during comprehension is relatively under-researched, and the relevant studies have yielded inconsistent findings.

In the following paragraphs, we begin by describing difference types of intra-sentential code-switching. Next, we review the existing research on the relationship between cognitive control and bilingual language control, focusing on comprehension studies. We further review previous research on the modulating role of intra-sentential code-switching types in control processes during comprehension. Finally, we present the research questions of this study.

So far to our knowledge, there have been two studies (Hofweber et al., 2020a; Jiang et al., 2023) examining whether the relationship between cognitive control and bilingual language control during comprehension is modulated by intra-sentential code-switching types – that is, alternation, insertion and dense code-switching (Muysken, 2000). It has been proposed that different types of intra-sentential code-switching engage proactive versus reactive control to differing degrees (Hofweber et al., 2020a, 2020b). However, the evidence supporting the modulating role of this contextual factor during comprehension is far from conclusive. More specifically, the research particularly on dense code-switching, which is characterized by intra-sentential code-switching type involving frequent code-switches, is sparse, and more research is needed.

Thus, using the ERP technique, the present study extends this line of research by further investigating whether and which aspects of domain-general cognitive control mechanisms are recruited during the comprehension of dense code-switching.

1.1 Bilingual language control during comprehension

Bilingual language production studies have provided convincing evidence for a relationship between domain-general inhibition and language control using switching paradigms, where bilingual speakers are asked to name digits or pictures in their L1 or L2 (Kang et al., 2020; Linck et al., 2012; Liu et al., 2014, 2016). The findings are in line with the Inhibitory Control (IC) model (Green, 1998), which posits that during successful language control, the non-target language schema has to be suppressed by the cognitive control system, and the previously inhibited schema must be reactivated after switching.

The cognitive mechanisms for production might not necessarily apply to comprehension, as production is top-down processing from concept to utterance where the language of the output must be specified early in the process, while comprehension is mostly a bottom-up process where the language tag/node (e.g., "English") encoding language membership information is activated reactively by input (Dijkstra & van Heuven, 1998, 2002). So far, however, relatively little is known about the relationship between cognitive control and bilingual language comprehension. Moreover, the available evidence has been largely inconsistent concerning whether cognitive control is recruited in comprehension and which aspects of cognitive control get involved.

According to the Bilingual Interactive Activation (BIA) model (Dijkstra & van Heuven, 1998), bilingual word comprehension entails top-down control from language nodes within the language system. Specifically, the activation of a particular language node allows selection of words in that language while inhibiting words in the other languages. Using lexical decision and semantic categorization paradigms with stimuli in different languages, most single-word studies have failed to find the engagement of domain-general inhibition in comprehension (Alvarez et al., 2003; Blanco-Elorrieta & Pylkkänen, 2016; Chauncey et al., 2008, 2011; Declerck et al., 2019a; Geyer et al., 2011; Jiao et al., 2019, 2020, 2022b; Jylkkä et al., 2018; Ong et al., 2019; Struck & Jiang, 2022; Struys et al., 2019; Timmer et al., 2021a, 2021b). Instead these findings suggest that bilinguals inhibit lexical representations in the non-target language mainly through the language node in the lexicon (Alvarez et al., 2003; Chauncey et al., 2008, 2011; Geyer et al., 2011), as specified in the Bilingual Interactive Activation (BIA) model (Dijkstra & van Heuven, 1998). Yet, several studies have observed that bilingual language control during single-word comprehension recruited domain-general inhibition as during production (Jackson et al., 2004; Jiao et al., 2021; Orfanidou & Sumner, 2005; Thomas & Allport, 2000; von Studnitz & Green, 1997; Wu & Thierry, 2013). Meanwhile, some single-word studies have found that monitoring, another essential process of cognitive control, was involved in bilingual language comprehension (Jiao et al., 2019, 2020, 2021, 2022b; Jylkkä et al., 2018; Struys et al., 2019; Timmer et al., 2021a, 2021b).

A similar heterogeneity exists in the literature on sentence comprehension regarding the association between cognitive control and bilingual language comprehension. Though some studies did not observe an overlap between domain-general inhibition and bilingual language comprehension (Blanco-Elorrieta & Pylkkänen, 2017; Bultena et al., 2015a, 2015b), there is also evidence for an overlap between cognitive control (and, more specifically, domain-general inhibition) and bilingual language comprehension in sentence context (Abutalebi et al., 2007; Adler et al., 2020; Bosma & Pablos, 2020; Faroqi-Shah & Wereley, 2022; Gross et al., 2019; Ibáñez et al., 2010; Liao & Chan, 2016; Litcofsky & Van Hell, 2017; Moreno et al., 2002; Pérez & Duñabeitia, 2019; Ratiu & Azuma, 2017; Stasenko et al., 2020).

Notably, more recent work has shown that the relationship between cognitive control and bilingual language control during comprehension depends on a wide variety of individual factors, such as bilinguals' language proficiency (Gross et al., 2019; Wu & Struys, 2022), and contextual factors, such as the semantic constraints from the preceding context (Pivneva et al., 2014). Following this line of research, several studies have examined the role of intra-sentential code-switching types in modulating control processes during comprehension (Hofweber et al., 2020a; Jiang et al., 2023).

1.2 The effects of intra-sentential code-switching types on control processes during comprehension

According to Muysken (2000), there are three main intra-sentential code-switching patterns dominating different bilingual communities: insertion, alternation, and dense code-switching. In the insertion pattern, a word or a constituent from one language is inserted into a structure from the other language, as in (1), where English determines the overall structure, and the Chinese noun 新年 (*Xinnian,* Chinese new year) is inserted into the English grammatical frame. Alternation involves switching between loosely connected stretches of language halfway through the sentence, as in (2). In dense code-switching, different languages mix and interweave, so there is no clearly identifiable switch point, as in (3).

(1) *My favorite time of the year is* 新年.
"My favorite time of the year is Chinese New Year." (Kang, 2017, p. 9)

(2) 我觉得活不下去了*if anything happened.*
"I would never survive if anything happened." (Liu, 2018, p. 746)

(3) 她 *make* 那个 *toys* 给我玩。
"She made the toys for me to play." (Goh, 2016, p. 167)

It has been proposed that intra-sentential code-switching types adaptively alter the processing demands on cognitive control processes (Green & Wei, 2014; Hofweber et al., 2020a, 2020b; Treffers-Daller, 2009). Incorporating the hypothesis of the Dual Mechanisms of Control in the study of attention (Braver, 2012), Hofweber et al. (2020a, 2020b) argued that dense CS and the other two code-switching types (i.e., insertion and alternation) differ in terms of the frequency of intra-sentential switches, such that they vary with regard to their positions on a control mode continuum from more proactive to more reactive. Specifically, alternation and insertion involve infrequent code-switching and thus use local inhibition infrequently. Therefore, both types of code-switching induce a reactive control mode, where task schema exerts inhibition on non-target language after the cross-language conflict is detected. However, since the reactive inhibition is cognitively effortful, bilinguals would operate in proactive control mode when there is frequent switching and thus higher demand for local inhibition (i.e., in dense code-switching contexts). Under the proactive control mode, bilinguals mainly employ continuous goal maintenance and monitoring to carefully adjust the relative activation levels of languages and prevent any potential interference before it occurs.

The application of Hofweber et al. (2020a, 2020b)'s hypothesis about a dual control involvement to bilingual language comprehension research could account for at least some of the existing inconsistencies. Specifically, the existing evidence for the engagement of domain-general inhibition during comprehension mainly derives from studies of alternational and insertional code-switching sentences (Adler et al., 2020; Bosma & Pablos, 2020; Faroqi-Shah & Wereley, 2022; Gross et al., 2019; Liao &

Chan, 2016; Litcofsky & Van Hell, 2017; Stasenko et al., 2020). Nevertheless, several studies that failed to find the involvement of domain-general inhibition during comprehension used stimuli involving dense code-switching sentences (Blanco-Elorrieta & Pylkkänen, 2017). Moreover, most of the evidence supporting the involvement of monitoring, rather than inhibition, in bilingual language comprehension comes from single-word studies (Jiao et al., 2019, 2020, 2021, 2022b; Jylkkä et al., 2018; Struys et al., 2019; Timmer et al., 2021a, 2021b), where the mixed language blocks resemble the dense code-switching context because of frequent switches (Jiang et al., 2023; Jylkkä et al., 2018).

However, Hofweber et al. (2020a) failed to observe the expected effects of intra-sentential code-switching types during comprehension. Using the cross-task conflict adaptation paradigm, they asked a group of L1-dominant German–English bilinguals to perform the flanker task in four bilingual reading contexts (i.e., alternation of English and German, insertion of English into German, insertion of German into English, and dense code-switching of English and German) and in the monolingual English reading context that were created by interleaving whole sentences with flanker trials. The whole sentences were displayed on the screen. According to Hofweber et al. (2020a, 2020b)'s hypothesis about a dual control involvement, the researchers expected that alternational and insertional sentences would induce reactive control modes and thus exert high levels of load to reactive inhibition, which would transfer to subsequent flanker trials and result in better inhibitory performance (i.e., smaller conflict effect) in the flanker task. On the contrary, dense code-switching sentences might trigger a proactive control mode, thus exerting high load to proactive monitoring and leading to better monitoring performance (i.e., shorter overall RTs) in the flanker task. The RTs and accuracy data, however, did not show any significant difference in cognitive control performance across the four bilingual contexts. There might be several reasons for the absence of significant effects in Hofweber et al. (2020a). For example, the subtle fast-modulation effects of language contexts on the subsequent cognitive control processes may be hard to detect by behavioral measures (Hofweber et al., 2020a; Jiang et al., 2023). Moreover, the German–English bilinguals the researchers tested were habitual code-switchers. Thus, when processing the code-switches that are congruent with their usual mode of language use, bilinguals may expend a small amount of cognitive control (Hofweber et al., 2020a; Jiang et al., 2023), leaving little room for the effects of intra-sentential code-switching types.

A subsequent study by Jiang et al. (2023), however, has provided preliminary evidence for the modulating role of intra-sentential code-switching types during comprehension. Taking a correlational approach, which has been shown to be sensitive to behavioral effects (Jylkkä et al., 2018), the study investigated whether bilinguals' cognitive control skills predict language switching performance in different manners due to intra-sentential code-switching types (i.e., alternation and dense code-switching) during comprehension. L1-dominant Chinese–English bilinguals from a non-habitual codeswitching community were administered a flanker task and a self-paced reading task, which were used to measure cognitive control skills and language switching performance, respectively. The RTs data showed that bilinguals' inhibition capacity predicted the marker for reactive language control (i.e., L2 switch cost, referring to the performance difference between L2 switch and non-switch trials in mixed language blocks) in an alternation context, while monitoring skills were marginally related to the index for proactive language control (i.e., language dominance effect, referring to the performance difference between L1 and L2 trials in mixed language blocks) in dense code-switching context. The results suggested that alternation exerted high load to reactive inhibition, while dense code-switching tended to trigger proactive monitoring during comprehension.

Yet, Jiang et al. (2023) observed only a marginal association between monitoring and the language dominance effect. It may be the case that monitoring is mainly recruited in certain subprocesses before the behavioral response is realized. Thus, it may be more likely to detect the recruitment of monitoring by the ERP technique of high temporal resolution than the behavioral measures that reflect the cumulative sum of different cognitive processes (Kang et al., 2020). To this end, the present study seeks further evidence for the involvement of domain-general monitoring during dense code-switching comprehension using ERP.

Moreover, in dense code-switching context, Jiang et al. (2023) did not observe a reversed dominance effect. The reversed dominance effect refers to when processing in the dominant language is more costly than the weaker language in the context of mixed language blocks. This effect has been frequently observed in production studies and it is assumed to be a marker of proactive language control (Declerck, 2020). Thus, its absence in dense code-switching context seems inconsistent with Hofweber et al. (2020a, 2020b)'s hypothesis that this particular code-switching type should induce a proactive control mode, and prevent us from drawing on strong conclusions regarding the role of intra-sentential code-switching types during comprehension.

A possible explanation for the absence of the reversed language dominance effect in Jiang et al. (2023) could be the relatively low sensitivity of the behavioral measures (Kang et al., 2020). Another possibility is that the proactive control mechanism may operate differently than previously assumed. Specifically, it has been proposed that a proactive control mechanism works by de-activating L1 and/or by favoring L2 to achieve more similar L1 and L2 activation, which will prevent the potential interferences on the weaker L2 and improve the overall processing in mixed language blocks (Christoffels et al., 2007, 2016; Mosca & Clahsen, 2016; Mosca & de Bot, 2017). Nevertheless, the results in Jiang et al. (2023) demonstrated that participants with better monitoring skills de-activated L2 to a greater extent. Thus, for the bilingual sample in their study, the most efficient way to facilitate overall performance in the mixed language block might be de-activating the weaker L2 rather than giving an advantage to it. However, as mentioned above, the correlation between monitoring capacity and language dominance effect in Jiang et al. (2023) is only marginal; thus, more studies (for example, ERP studies) are needed to examine this proposal for the way proactive control mechanism functions. Using the ERP technique, the current study seeks to find the prominent marker for the proactive control mode, the reversed language dominance effect, in a dense code-switching context and further examine how the proactive control mechanism functions.

Taken together, to provide strong support for the modulating role of intra-sentential code-switching types during comprehension in conjunction with Jiang et al. (2023), the current study investigates the control processes that specifically underlie sentence comprehension in the dense code-switching context using the ERP technique. Many single-word studies (e.g., Jiao et al., 2019, 2020, 2021, 2022b) and several sentential comprehension studies (Blanco-Elorrieta & Pylkkänen, 2017; Hofweber et al., 2020a; Jiang et al., 2023) have shed light on the comprehension of the dense code-switching type. This study, nevertheless, is unique among previous studies in at least three respects. First, compared with prior single-word studies, where the mixed language block can be regarded as a dense code-switching context (Jiang et al., 2023; Jylkkä et al., 2018), we examine the sentence-level language switching that is more ecologically valid (Blanco-Elorrieta & Pylkkänen, 2018) and includes switching of morpho-syntax in addition to lemma switching at the word level (Liu et al., 2017). Second, we recruit bilinguals from the same non-habitual codeswitching community as Jiang et al. (2023). Thus, relative to studies of dense code-switching sentences that test habitual code-switchers (Blanco-Elorrieta & Pylkkänen, 2017; Hofweber et al., 2020a), effortful cognitive control processes are more likely to be applied during the comprehension of code-switches in the current study. Finally, we use the ERP technique rather than the behavioral experiment used by Jiang et al. (2023). The ERP dynamically measures the millisecond-by-millisecond neural response to the stimulus, thus allowing to provide more reliable evidence for the use of proactive language control mechanism and the engagement of domain-general cognitive control (e.g., monitoring) in dense code-switching sentences comprehension.

1.3 The neural markers associated with the switch cost and language dominance effect in comprehension literature

Regarding the neural markers associated with the switch cost, the comprehension studies have largely reported that relative to non-switched words, code-switched words enhanced the magnitude of the N400, the Left Anterior Negativity (LAN), and the Late Positive Complex (LPC) (Chauncey et al., 2008, 2011; Fernandez et al., 2019; Geyer et al., 2011; Kaan et al., 2020; Liao & Chan, 2016; Litcofsky & Van Hell, 2017; Midgley et al., 2009; Moreno et al., 2002; Ng et al., 2014; Pellikka et al., 2015; Phillips et al., 2006; Ruigendijk et al., 2016; Valdés Kroff et al., 2020; Van Der Meij et al., 2011; Yacovone et al., 2021; Zeller, 2020).

The N400 and LAN have been associated with initial lexical processing (Yacovone et al., 2021). Specifically, the N400, a negative-going wave peaking about 400 ms post-stimulus onset over centro-parietal electrode sites, is sensitive to lexical-semantic processing (Grainger & Holcomb, 2010). In contrast, the LAN, an anterior negativity that is often left-lateralized occurring in the same time window as the N400, has been associated with difficulties in morphosyntactic processing (Friederici, 2002). The N400/LAN effect in response to code-switches during comprehension has been associated with difficulties in the lexical access to the switched word (Alvarez et al., 2003; Liao & Chan, 2016; Ruigendijk et al., 2016; Van Der Meij et al., 2011) and the semantic or morphosyntactic integration (Chauncey et al., 2008, 2011; Fernandez et al., 2019; Moreno et al., 2002; Ng et al., 2014; Van Der Meij et al., 2011), which could be caused by the inhibition sent from the language nodes to all lexical representations of the other language (including the up-coming target word representation) (Alvarez et al., 2003; Chauncey et al., 2008, 2011). Moreover, the switch-related N400/LAN effect has also been related to efforts to overcome word-level inhibition in the previous trial (Fernandez et al., 2019; Pellikka et al., 2015).

The interpretations of the switch-related modulations of LPC, a positive-going deflection typically peaking around 600 ms post-stimulus onset over the parietal electrode sites, were rather mixed in comprehension literature. Most relevant to the present study are the task-set reconfiguration and sentence-level restructuring accounts. Specifically, the LPC has been related to task-set reconfiguration, i.e., inhibiting the currently irrelevant task set and activating the new one, in task-switching literature (Nicholson et al., 2005, 2006). Thus, the LPC elicited by the comprehension of intra-sentential code-switching could index the language-set reconfiguration process involving the inhibition of the current language and re-activation of the target language (Litcofsky & Van Hell, 2017; Moreno et al., 2008). Alternatively, the LPC effect could reflect a general kind of reprocessing triggered by a conflict between, for example, two sentence interpretations, or a lack of information (Kolk & Chwilla, 2007). In this interpretation, switch-related LPC effects would reflect the costs associated with sentence-level restructuring due to the change to the construction of sentence-level representations (Litcofsky & Van Hell, 2017).

To the best of our knowledge, there has been no direct ERP evidence for the reversed language dominance effect in comprehension literature. However, the existing ERP work using the semantic or syntactic violation paradigm in sentence context has systematically observed the language dominance effect during comprehension in the form of differential latencies of the ERP components (Moreno et al., 2008). Specifically, in pure language blocks, the peak latencies of the LAN/N400 and LPC effects have been repeatedly found to be delayed for the nondominant L2 compared to the dominant L1 (Elston-Gúttler & Friederici, 2005; Hahne, 2001; Kutas & Kluender, 1994; Moreno et al., 2008; Moreno & Kutas, 2005; Rossi et al., 2006; van Heuven & Dijkstra, 2010; Weber-Fox & Neville, 1996). This pattern held for both (semantically or syntactically) incorrect and correct sentences (Hahne, 2001). Moreover, the onset latencies of the N400 effects were also delayed for the L2 than L1 (Moreno & Kutas, 2005; Newman et al., 2012). The delays in the latencies of these components might be attributed to different degrees of automaticity (Hahne, 2001) with respect to the early lexical-semantic and morphosyntactic (as indexed by N400 and LAN) and the sentence-level reanalysis and syntactic integration (as indexed by LPC) processing stages in sentence comprehension (Rossi et al., 2006). Therefore, we predict that when the language dominance effect is reversed in mixed language blocks, the latencies of the N400/LAN and LPC effects will be delayed for the dominant L1 when compared to the nondominant L2. Notably, the modulations of ERP amplitude were not equally consistent across previous studies on the language dominance effect (Martin et al., 2015; Moreno et al., 2008); thus, we did not use the amplitude of the ERP component as the index of reversed language dominance effect.

1.4 The present study

The primary goal of the present study is to investigate the role of domain-general inhibition and monitoring during the comprehension of dense code-switching sentences. Taking a correlational approach (Jiang et al., 2023; Linck et al., 2012), we asked L1-dominant Chinese–English bilinguals to complete a flanker task and a reading task. Individuals' inhibition (and more specifically, reactive inhibition) and monitoring capacities were indexed by the conflict effect (i.e., the performance difference between incongruent and congruent trials) (Jylkkä et al., 2018; Morales et al., 2013) and the global response times (Jiao et al., 2019; Struys et al., 2019) in the flanker task, respectively. In the reading task, we presented the sentences one word at a time using the rapid serial visual presentation (RSVP) procedure that has been frequently used in ERP studies of reading comprehension (Tanner, 2018).

According to Hofweber et al. (2020a, 2020b)'s hypothesis about a dual control perspective, dense code-switching should trigger a proactive control mode; thus, it should exercise high levels of load to proactive monitoring to adjust the activation levels of languages before the cross-language interferences occur but engage little or no reactive inhibition to resolve the interferences.

Therefore, two specific research questions are addressed in the present study: (1) whether the dense code-switching sentences predominantly involve proactive language control mechanism; (2) whether and how domain-general inhibition and monitoring play a role in the comprehension of dense code-switching sentences. We tested for the presence of switch costs as a marker of reactive control and the presence of a reversed dominance effects as a marker of proactive control. Switch cost is a prominent index of reactive language control, reflecting the efforts to overcome the reactive inhibition exerted on the non-target language after its activation (Declerck et al., 2019b; Green, 1998). On the contrary, reversed language dominance effect has been taken as a marker of proactive language control, as it may reflect sustained de-activation of L1 and/or increase of L2 activation (Declerck, 2020). This mechanism should result in more similar L1 and L2 activation levels, thus preventing the great L1 interference during L2 processing (which is attributed to the high resting-level activation of L1) before it occurs and improving overall performance in mixed language blocks (Declerck, 2020).

On the basis of Hofweber et al. (2020a, 2020b)'s hypothesis about a dual control perspective, we formulate two hypotheses. (1) The dense code-switching will predominantly recruit the proactive language control mechanism, thus showing a reversed language dominance effect (i.e., delayed latencies of the N400/LAN and LPC for L1 relative to L2). In contrast, there will be little to no use of reactive language control. The presence of switch costs has been taken as evidence in favor of the implementation of a reactive language control mechanism (Declerck et al., 2019b); thus, there should be little to no switch cost (i.e., increase in the magnitude of the N400/LAN and LPC for switch compared to non-switch trials). (2) The monitoring skills should be related to the marker of proactive language control (that is, the [reversed] language dominance effect) but the association between inhibition skills and the marker for reactive language control (that is, switch cost) should be small or even absent.

2. Method

2.1 Participants

Sixty Chinese (L1)–English (L2) bilinguals were recruited from Beijing Normal University in China. All participants signed the written informed consent and were paid for their participation. Ethical approval was obtained from the Committee of Protection of Participants at Beijing Normal University. All participants were right-handed with normal or corrected-to-normal vision. None of the participants had neurological or psychological impairments or had used psychoactive medication. Eight participants were excluded because of excessive EEG artifacts. The final sample comprised 52 participants (42 females; average age: 21.0 years; *SD* = 2.20).

All participants were from the same language community as those in Jiang et al. (2023). They were born in China without immigration experience or overseas education, and were exposed to L1 from birth and learned L2 at a mean age of 8.16 years old (*SD* = 1.95) in a classroom setting. Language switching frequency was assessed using the Chinese version of the Bilingual Switching Questionnaire (BSWQ) (Rodriguez-Fornells et al., 2012), the larger values on the scores of which indicate more frequent switching (the highest total score is 60). The relatively low overall score (*M* = 29.7; *SD* = 5.1) indicated that these bilinguals seldom engaged in code-switching in their daily lives.

In addition, all participants were administered the Oxford Placement Test (OPT) and self-rated their language proficiency on a 7-point scale (1 = not proficient at all; 7 = very proficient) to obtain the objective and subjective indicators of language proficiency, respectively. The higher the OPT score is, the higher the English proficiency of the participant (the highest total score is 50). The mean score of OPT of all participants was 39.26 (*SD* = 4.37). The average proficiency ratings of L1 listening, speaking, reading, and writing of all participants were 6.66 (*SD* = .55), 6.51 (*SD* = .70), 6.57 (*SD* = .67), 6.40 (*SD* = .77), respectively, and of L2 were 4.13 (*SD* = 1.11), 3.70 (*SD* = 1.07), 5.00 (*SD* = 1.00), 4.38 (*SD* = 1.06), respectively. Self-reported language proficiency comparison was performed with Cumulative Link Mixed-effect Models in R using the package ordinal (Christensen, 2022). The results revealed significant differences between the subjective proficiency scores of the first and second languages for all skills [listening, $z = -5.88$, $p < .001$; speaking, $z = -6.01$, $p < .001$; reading, $z = -5.83$, $p < .001$; writing, $z = -5.83$, $p < .001$], indicating that the participants were Chinese (L1)-dominant bilinguals.

2.2 Materials

The stimuli consisted of 120 sentences, including all the 40 sentences in Jiang et al. (2023)'s dense code-switching block and 80 newly generated sentences. All sentences contained subordinate clauses. All the critical words were nouns and acted as the subject of the main clause. Non-switch sentences were presented in single languages, whereas critical words were preceded by a different language in switch sentences. The switch sentences were created following the definition of dense code-switching in Hofweber et al. (2020a, 2020b). Specifically, the switch sentences consisted of two switches occurring at the noun in the subordinate clause and within the noun phrase in the main clause, respectively. In this way, the dense code-switching sentences involve frequent switching. The switch and non-switch sentences contained the same critical words but differed with respect to the sentence meaning. Thus, participants read switch and non-switch sentences that shared the same critical words, which enabled us to obtain ERP responses to critical words in switch and non-switch conditions from the same participants, and thus minimized the confounding effects of individual differences in critical word processing. The switch cost was indexed by the difference between ERP responses to the critical words preceded by Chinese and English. Table 1 shows a set of example sentences.

Ten students (7 females; average age: 22.4 years; *SD* = 1.51) rated the processing difficulty for the sentences on a 7-point scale (1 = extremely simple; 7 = extremely difficult). Their average English proficiency ratings of L2 listening, speaking, reading, and writing were 4.40 (*SD* = .97), 4.20 (*SD* = .63), 5.60 (*SD* = .84), 4.90 (*SD* = .88), respectively, which were close to participants in the formal experiment [listening, $t = -.77$, $p = .45$; speaking, $t = -2.03$, $p = .05$; reading, $t = -1.93$, $p = .07$; writing, $t = -1.64$, $p = .12$]. The results revealed that the overall difficulty for sentences

Table 1. A set of example sentences.

Language of critical words	Trial type	Example sentences
English	Switch	当 *darkness* 降临时，所有 ***wolves*** 对着月亮大声嚎叫。 (“When darkness fell, all the wolves howled at the moon loudly.”)
English	Non-switch	*With the desire for freedom, the* ***wolves*** *often despise domestic dogs.*
Chinese	Switch	*To kill* 时间 *on vacation, that* 男孩 *threw stones into the river.* (“To kill time on vacation, that boy threw stones into the river.”)
Chinese	Non-switch	在走廊到栅栏之间，几个男孩来回跑了十次。 (“Between the corridor and the fence, several boys ran back and forth ten times.”)

Note. Critical words were those in bold. In the formal experiment, the words were not bolded. English switched word: *wolves*; Chinese switched word: 男孩 “boy/boys”.

in both switch and non-switch conditions was quite low ($M = 1.98$, $SD = .55$), indicating that they were easy to comprehend.

To reduce the predictability of switches, forty filler sentences (10 English switch sentences, 10 English non-switch sentences, 10 Chinese switch sentences, and 10 Chinese non-switch sentences) were added. The syntactic structure of filler sentences was the same as that of critical sentences, whereas the second switch in filler sentences was located at the final word in the main clause.

In total, each participant read 120 critical sentences (60 switch and 60 non-switch sentences) and 40 filler sentences. Half of the sentences contained critical Chinese words, while the other half contained critical English words. The critical words in Chinese were different from that in English. All the sentences were pseudo-randomized such that there were no more than three consecutive sentences of the same type, and sentences with the same critical word did not appear consecutively. To ensure participants actively read the sentences, 20 yes/no comprehension questions were presented in Chinese randomly behind the sentences. For example, the comprehension question “Did the thieves escape punishment?” followed the sentence, “After the crime was exposed, no doubt that thieves were punished.” Half of the questions required a “yes” response, and half required a “no” response.

2.3 Procedure

Stimuli were presented using E-Prime 2.0. Participants completed the flanker task first and then completed the sentence reading task while the brain’s responses to critical words were recorded. After the formal experiment, participants were asked to complete the background questionnaires.

Flanker task

Two types of trials, congruent and incongruent trials, were included in the flanker task. The congruent (i.e., <<<< < or > >>>>) and incongruent trials (i.e., <<>< < or > ><>>) differed in terms of the consistency of the pointing directions of the central target arrow and the flanking arrows. Each trial began with a white fixation cross “+” presented in the center of the black screen for 500 ms. Following this, the flanker trials appeared. If participants did not respond within 1500 ms, the stimulus disappeared. After a blank screen with a duration of 500 ms, the next trial started. Participants were asked to respond as quickly as possible to the pointing direction of the target arrow by pressing the left or right button (i.e., “F” or “J” button on the keyboard). Time spent on each trial (RTs) and accuracy for each response were recorded. The task consisted of 96 trials, half of which were consistent, and the other half were inconsistent.

Sentence reading task

Before the reading task, participants received Chinese instructions on the computer screen and were encouraged to read the sentences carefully. The instructor emphasized that three types of sentences – that is, Chinese sentences, English sentences, and sentences that included both Chinese and English – were presented in this task. Then, participants read 5 practice sentences, which were different from the experimental sentences, but were identical in structure.

Each trial was preceded by a fixation cross for 500 ms. After the blank screen with 1000 ms, the sentence was presented word-by-word using rapid serial visual presentation (RSVP). Each word of the sentence appeared on the screen for 400 ms, followed by a 400 ms inter-stimulus interval. Each word was displayed at the center of the screen using a white 32-point Courier New font on a black background. A yes/no comprehension question followed some sentences, and participants were required to respond by pressing the “F” or “J” button on the keyboard (“F” for “yes” and “J” for “no”). A blank screen of 600–1000 ms appeared after each sentence or the comprehension question following the sentences, and then the next trial started. To avoid motion artifacts, participants were instructed to keep their eyes focused on the center of the screen during the reading process and move as little as possible. Participants were encouraged to blink as little as possible.

2.4 EEG recording and analysis

Electrophysiological data were recorded using 64 Ag/AgCl electrodes placed according to the extended 10–20 positioning system. The signal was recorded at a 500 Hz sampling rate and referenced online to the tip of the nose. Vertical and horizontal eye movements were recorded by electrodes placed on the supra- and infra-orbital ridges of the left eye (VEOG) and the outer canthi of the left and right eyes (HEOG). Impedances were maintained below 5 kΩ. The electroencephalographic activity was filtered online with a bandpass between 0.05 and 100 Hz.

We pre-processed our EEG data using both EEGLAB (Delorme & Makeig, 2004) and ERPLAB (Lopez-Calderon & Luck, 2014) toolboxes in Matlab (MathWorks, Inc.). To begin with, we re-referenced offline to the average of the left and right mastoids. The EEG signals were then low-pass filtered offline at 30 Hz. Next, we identified and corrected eye blink artifacts using an Independent Component Analysis (ICA). Subsequently, we divided continuous recordings into epochs ranging from −200 ms to 800 ms relative to stimulus onset. Baseline correction was performed in reference to pre-stimulus activity (−200 to 0 ms). A two-step artifact rejection process was then performed. Specifically, we firstly subjected all epochs to an automatic rejection procedure where epochs containing deviations larger than 90 µV were automatically discarded. This procedure rejected

191 epochs, and the mean rejection rate per participant was 3.06% (*SD* = .04). Secondly, we visually inspected each electrode to check the quality of the EEG recording, looking for eye motion artifacts, electrocardiographic and muscular artifacts, and instances of power line noise, channel noise, and channel pop-off effects. If a single electrode had multiple artifacts that were not removed or corrected using the above methods, we interpolated the entire electrode channel. On average, approximately 1 electrode was interpolated across all participants. All participants' remaining data consisted of at least 24 trials in each condition (80%).

Based on previous literature and visual inspection of the waveforms, two time windows were selected to examine components of interest. First, a 300–500 ms time window was chosen to capture the N400 and LAN components. Second, a 500–800 ms time window was chosen to correspond to the LPC component. Mean amplitudes, peak latencies, and onset latencies of critical words were measured from these two time windows after stimulus onset for each channel location. Onset latencies were measured as the 20% fractional area latency, representing the time at which 20% of the total mean amplitude was obtained within a time window (Newman et al., 2012). All scalp electrodes were included in the analysis. The scalp electrodes were grouped into nine scalp regions along the anteriority (3 levels: frontal, central, and parietal) and laterality (3 levels: left, medial, right) dimensions (see Figure 1).

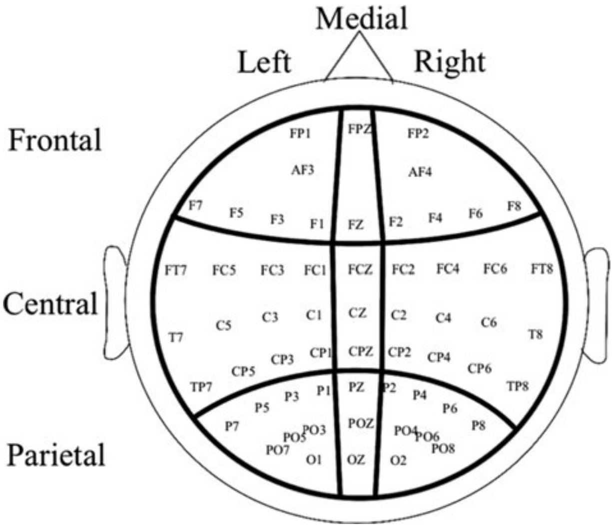

Figure 1. Scalp regions that resulted from dividing electrodes along the dimensions anteriority (3 levels) and laterality (3 levels).

2.5 Mixed-effects model analyses

Analyses were conducted in R using the package lme4 (Bates et al., 2015). RTs data, single-trial mean amplitude and single-trial latency were submitted to linear mixed-effects model, and the accuracy data were submitted to the logistic mixed-effects model. Reaction times were log-transformed to better approximate a normal distribution.

The flanker analyses included sum coded fixed effects for Trial type (congruent = −1, congruent = 1) and random effects for participants. We started with a full model including the maximal random effects structure (Barr et al., 2013), i.e., random intercepts for participants and random slopes for Trial type. If the model failed to converge, we used a backwards-stepping procedure until the model could be fitted. Model comparisons were conducted to determine the best-fitting model. Specifically, we compared the models to a random-intercepts-only model. If likelihood-ratio tests did not show a significant effect favoring the models with larger random effects structures, the random-intercepts-only model was preferred; otherwise, the models with larger random effects structures were preferred. The decision to include random slope effects was also based on Akaike Information Criterion (AIC) model comparisons of the models with and without these random slope effects. The model with the smallest AIC value (small indicates a better fit) was selected as the final model. The same selection procedures of the best-fitting model were applied to the subsequent analyses. R code used in all the analyses can be seen in Appendix S1 in Supplementary Material.

Our ERP data analyses started with the reversed language dominance effect and switch cost to address the first research question. For analyses of the reversed language dominance effect, language, laterality, anteriority and their interaction were included in models as fixed effects. Language, laterality, and anteriority were sum coded (L1 = −1, L2 = 1; left = 1/0, medial = 0/1, right = −1; central = 1/0, frontal = 0/1, parietal = −1). The initial models included random intercepts for participants, items, and channels and random slopes for language, laterality, anteriority and their interaction (see endnote 1). According to previous studies on the language dominance effect (Moreno et al., 2008; van Heuven & Dijkstra, 2010), we used the latencies as the dependent variable. For analyses of the switch costs, mean amplitudes were subjected to models (Litcofsky & Van Hell, 2017) with Trial type, laterality, anteriority and their interaction as fixed effects. We chose not to include the variable language in the models because we used the mere presence of switch cost as evidence for the reactive language control mechanism (Declerck et al., 2019b). Trial type, laterality, and anteriority were sum coded (non-switch = −1, switch = 1; left = 1/0, medial = 0/1, right = −1; central = 1/0, frontal = 0/1, parietal = −1). The initial models included random intercepts for participants, items and channels, and random slopes for Trial type, laterality, anteriority and their interaction. For statistically significant interactions involving the factor language or Trial type, follow-up pairwise comparisons were computed using the emmeans function of the package emmeans (Lenth et al., 2022), with *p* values corrected for multiple comparisons using Bonferroni.

To address the second research question, we inserted each cognitive control measure (conflict effect, global RTs in the flanker task) into the models of language switching performance separately. Importantly, it has been repeatedly found that the engagement of domain-general inhibition in reactive language control was modulated by switching direction (i.e., switching from L1 into L2 or switching from L2 into L1) (Abutalebi et al., 2007; Bosma & Pablos, 2020; Jiang et al., 2023; Pérez & Duñabeitia, 2019). Thus, language and Trial type were simultaneously included in Conflict Effect models examining the association between inhibition skills and reactive language control to uncover any associations between these two control processes – for example, involved in a particular switching direction. Meanwhile, to keep the statistical models simple, we focused on the anteriority dimension and did not include laterality as a factor. The initial models included random intercepts for participants, items, and channels and random slopes for language, Trial type, anteriority, conflict effect and their interaction in the conflict effect model, and language, anteriority, global RTs and their interaction in the global RTs model. Cognitive control measures were treated as continuous predictors and centered. When the interactions with the distributional factor anteriority were significant, we conducted simple effects models by performing treatment coding for anteriority with frontal, central, and parietal taken as the reference values, respectively.

For models with significant fixed effects, *p* values were provided by the ANOVA/summary function of the package LmerTest (Kuznetsova et al., 2017). Cohen's *d* effect sizes were calculated using the lme.dscore function from the package EMAtools (Kleiman, 2021) for each fixed effect of the best-fitted models, and the cohen.d function from the package psych (Revelle, 2022) for each pairwise comparison. Partial Eta-squared (η_p^2) effect sizes were obtained from the model ANOVA tables using the effectsize package (Ben-Shachar et al., 2022). Given the aims of the study, we only present the effects involving the factor language and/or Trial type.

3. Results

The participants achieved an average accuracy of 90% ($SD = .07$) on the comprehension questions during the reading task. Thus, no participant was excluded from the analyses.

3.1 Behavioral results of the flanker task

For the RTs analysis of the flanker task, incorrect trials and the RT on a trial beyond Mean ± 3 standard deviations (*SD*) were removed (3.05%). For accuracy in the flanker task, all available data were analyzed.

The results of the flanker task are reported in Table 2. The conflict effects of flanker task were significant and were in the expected direction in reaction times ($t = 21.23$, $p < .001$, $d = 5.94$) and in the accuracy rates ($z = -6.91$, $p < .001$, $d = -.24$).

3.2 ERP results

Switch cost and reversed language dominance effect

Figure 2 shows the ERP waveforms across the switch and non-switch conditions and the distribution of the switch-related effects. Figure 3 presents the ERP waveforms across L2 and L1 conditions. Notably, following most of the studies on language dominance effects (Moreno et al., 2008; van Heuven & Dijkstra, 2010), analyses of reversed language dominance were carried out on peak latencies in the 300–500 ms time window. However, in the 500–800 ms time window, onset and not peak latencies were subjected to the analysis since the LPC waves for L1 did not have a single clear peak in the present data (Newman et al., 2012) and thus would result in low quality of peak latency (Liesefeld, 2018).

Table 2. Mean reaction times (RT, ms, standard deviations) and accuracy (%) (standard deviations) in the flanker task.

	RT	Accuracy
Congruent	469 (88)	99 (.07)
Incongruent	528 (92)	96 (.19)
Conflict effect	**58 (22)**	**-3 (.04)**
Global performance	**497 (63)**	-

Time window between 300–500 ms

The omnibus switch cost model failed to detect significant main effect of Trial type [$F(1) = .08$, $p = .78$]. Trial type interacted significantly with anteriority [$F(2) = 12.68$, $p < .001$, $\eta_p^2 = .0007$], but pairwise comparisons did not reveal any statistically significant switch-related effect (all *ps* > .31). Additional analyses were conducted on a set of left-anterior channels (i.e., AF3, F7, F5, F3) and central channels (i.e., FZ, CZ, PZ) where the LAN and N400 switch-related effects have been reported, respectively (Vaughan-Evans et al., 2020; Yacovone et al., 2021). However, the analyses did not reveal any significant switch-related effect (all *ps* > .70).

The omnibus reversed language dominance effect model revealed a marginally significant main effect of language [$F(1) = 3.65$, $p = .06$, $\eta_p^2 = .03$] with earlier peak latencies for L1 ($M = 395.27$ ms, $SD = 56.60$) than L2 trials ($M = 399.72$ ms, $SD = 57.25$), indicating a typical language dominance effect. Moreover, there were a significant language by laterality interaction [$F(2) = 9.33$, $p < .01$, $\eta_p^2 = .0005$]. Pairwise comparisons following these significant interactions revealed earlier peak latencies for L1 than L2 in bilateral sites (left: L1: $M = 394.33$ ms, $SD = 57.25$; L2: $M = 399.38$ ms, $SD = 56.92$; right: L1: $M = 396.09$ ms, $SD = 56.02$; L2: $M = 400.57$ ms, $SD = 57.49$) [left: $t = -2.40$, $p < .05$, $d = .09$; right: $t = -2.19$, $p < .05$, $d = .08$].

Time window between 500–800 ms

Once again, the omnibus switch cost model did not detect significant main effect of Trial type [$F(1) = .30$, $p = .58$]. There were a significant Trial type by anteriority interaction [$F(2) = 4.52$, $p < .05$, $\eta_p^2 = .0002$] and a marginally significant Trial type by anteriority by laterality interaction [$F(4) = 2.04$, $p = .09$, $\eta_p^2 = .0002$], but pairwise comparisons did not show any statistically significant switch-related effect (all *ps* > .16). We performed additional analyses on a set of parietal channels (i.e., PZ/1/2/3/4/5/6, CPZ/1/2/3/4/5/6) where the LPC switch-related effect has been reported (Kaan et al., 2020), but did not observe significant switch-related effect [$F(1) = .92$, $p = .34$].

The omnibus reversed language dominance effect model revealed marginally significant difference in onset latencies across L1 ($M = 578.74$ ms, $SD = 58.81$) and L2 trials ($M = 582.75$ ms, $SD = 58.62$) [$F(1) = 2.81$, $p = .10$, $\eta_p^2 = .03$]. Moreover, there were significant two-way interactions of language and anteriority [$F(2) = 15.18$, $p < .001$, $\eta_p^2 = .29$], and language and laterality [$F(2) = 8.93$, $p < .001$, $\eta_p^2 = .22$]. Follow-up pairwise comparisons showed a significant main effect of language at left ($t = -2.50$, $p < .05$, $d = .09$) and parietal sites ($t = -3.52$, $p < .001$, $d = .14$), with earlier onset latencies for L1 compared to L2 trials (left: L1: $M = 577.53$ ms, $SD = 58.08$; L2: $M = 582.94$ ms, $SD = 58.20$; parietal: L1: $M = 573.18$ ms, $SD = 56.82$; L2: $M = 581.36$ ms, $SD = 60.97$). Moreover, there was significant three-way interaction of language, anteriority, and laterality [$F(4) = 4.51$, $p < .05$, $\eta_p^2 = .00005$]. Follow-up pairwise comparisons showed a significant main effect of language at left central ($t = -2.18$, $p < .05$, $d = .08$), left parietal ($t = -4.66$, $p < .001$, $d = .18$), medial parietal ($t = -2.72$, $p < .01$, $d = .11$), and right parietal ($t = -2.81$, $p < .01$, $d = .11$) sites, with earlier onset latencies for L1 compared to L2 trials (left central: L1: $M = 579.14$ ms, $SD = 58.45$; L2: $M = 583.77$ ms, $SD = 57.16$; left parietal: L1: $M = 571.53$ ms, $SD = 55.64$; L2: $M = 582.13$ ms, $SD = 61.38$; medial parietal: L1: $M = 575.75$ ms, $SD = 57.87$; L2: $M = 582.28$ ms, $SD = 60.67$; right parietal: L1: $M = 573.89$ ms, $SD = 57.53$; L2: $M = 580.25$ ms, $SD = 60.66$). Overall, the results suggest a left and parietally distributed language dominance effect.

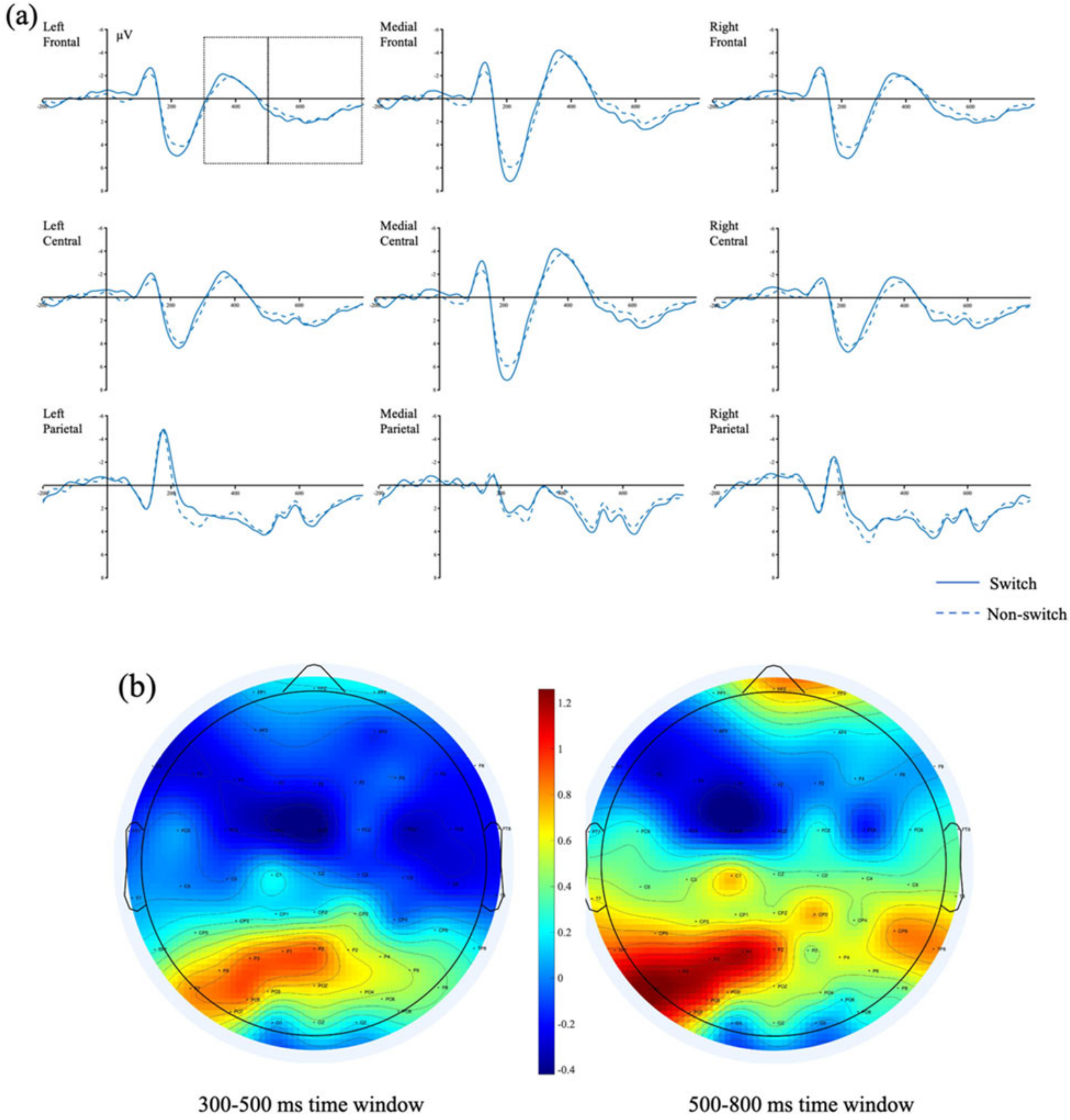

Figure 2. (a) Grand average waveforms time-locked to stimulus onset comparing non-switch to switch trials in the mixed block. (b) The topographic plot shows the distribution of the switch cost in the 300-500 ms (left) and 500-800 ms (right) time windows collapsed cross language. Cool colors indicate larger negativity for switch than for non-switch trials.

In sum, we did not find any switch cost in the 300–500 ms time window or 500–800 ms time window. In the 300–500 ms time window, we found a language dominance effect broadly distributed over the whole scalp, including a centro-parietal N400 effect and a left anterior negativity (LAN) effect. During the LPC component, we found a left and parietally distributed language dominance effect.

Switch cost and reversed language dominance effect and the cognitive control measures.

Time window between 300–500 ms

All the correlations between the cognitive control measures and the language control measures in the 300–500 ms time window are summarized in Table 3. The omnibus global RTs model revealed a significant two-way language × global RTs interaction $[F(1) = 5.39, p < .05, \eta_p^2 = .10]$, suggesting that the monitoring capacity predicted language dominance effects over the whole scalp (i.e., the LAN and N400). As observed in Figure 4, the monitoring capacity mainly modulated the peak latency for L1 trials: the peak of the ERP response to L1 trials was later for participants with better monitoring skills (i.e., faster global RTs). The omnibus conflict effect model did not reveal any significant effect (all $ps > .18$).

Time window between 500–800 ms

All the correlations between the cognitive and language control measures in the 500–800 ms time window are summarized in

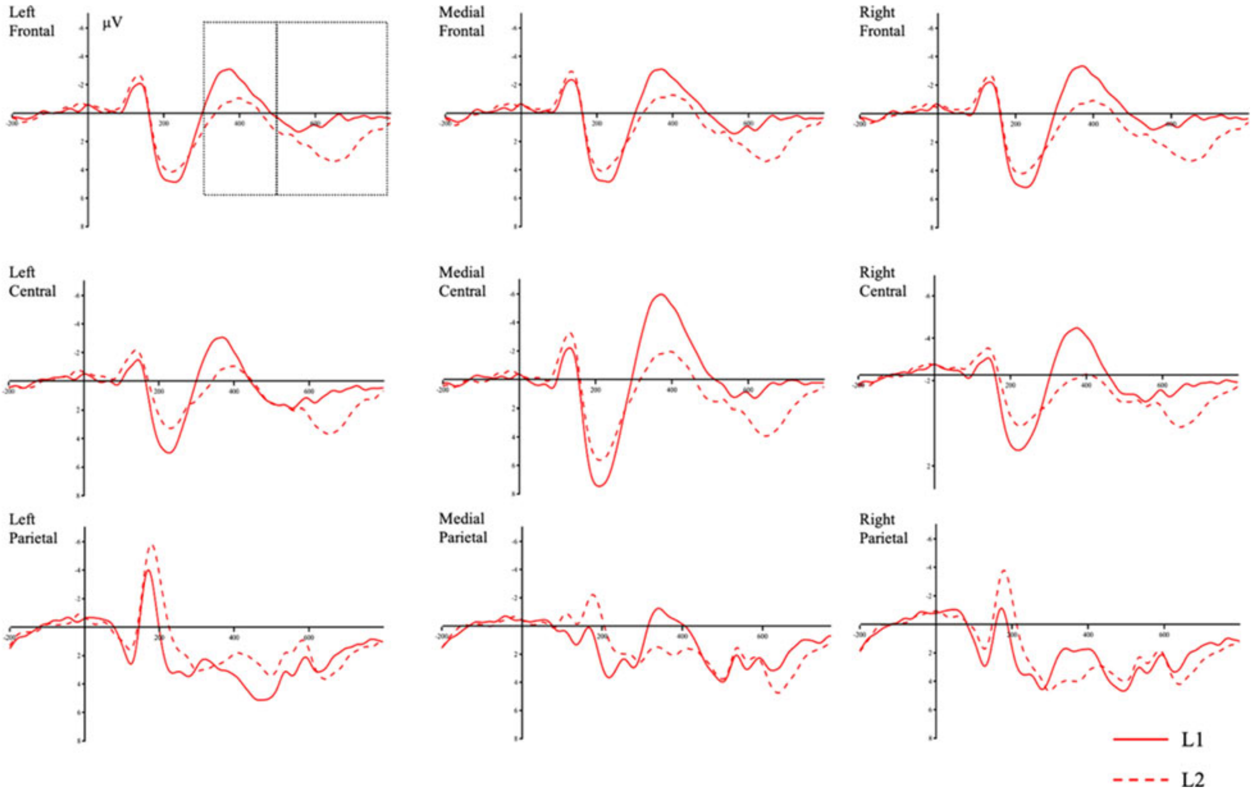

Figure 3. Grand average waveforms time-locked to stimulus onset comparing L2 to L1 trials in the mixed block.

Table 4. In the omnibus global RTs model, the two-way language × global RTs interaction was insignificant [$F(1) = .17$, $p = .68$]. The three-way language × global RTs × anteriority interaction was significant [$F(2) = 9.59$, $p < .001$, $\eta_p^2 = .0006$]. However, the simple effects analyses following the significant three-way interaction did not reveal any significant language × global RTs interactions over frontal, central or parietal sites (all $ps > .25$).

The omnibus conflict effect model revealed a significant three-way language × Trial type × Conflict Effect interaction [$F(1) = 4.45$, $p < .05$, $\eta_p^2 = .00001$]. However, simple effects models failed to reveal any significant interactions with treatment coding for language (all $ps > .73$) or Trial type (all $ps > .20$). From Figure 5(a), we see that the extent to which L2 switch costs were larger than L1 switch costs became smaller as the inhibition capacity decreased (i.e., larger conflict effect). As shown

Table 3. Outcome of the linear mixed-effects models examining the correlations between cognitive control measures and language control measures in the 300–500 ms time window.

	df	MeanSq	F
Omnibus Global RTs model			
Language × Global RTs	1	16782.70	5.39*
Language × Global RTs × anteriority	2	4349.50	1.40
Omnibus Conflict Effect model			
Language × Conflict Effect	1	25.90	.40
Trial type × Conflict Effect	1	.11	.00
Language × Trial type × Conflict Effect	1	14.58	.23
Language × Conflict Effect × anteriority	2	12.57	.20
Trial type × Conflict Effect × anteriority	2	20.89	.32
Language × Trial type × Conflict Effect × anteriority	2	110.00	1.71

Note. ∗ $p < .05$.

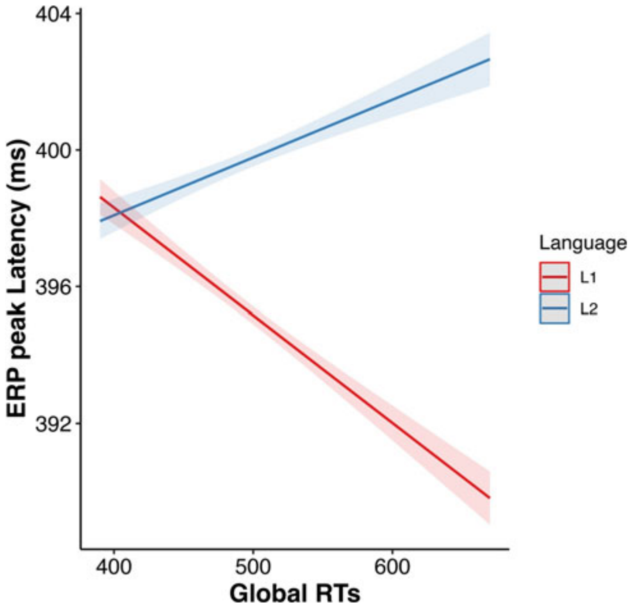

Figure 4. Peak latency of ERP response to L1 and L2 trials (in ms), and global RTs (in ms) in the 300-500 ms time window. Shared areas represent standard errors

Table 4. Outcome of the linear mixed-effects models examining the correlations between cognitive control measures and language control measures in the 500–800 ms time window.

	df	MeanSq	F	Estimate	Standard Error	t
Omnibus Global RTs model						
ANOVA						
Language × Global RTs	1	575.00	.17			
Language × Global RTs × anteriority	2	31725.00	9.59***			
Simple effects models following the language × Global RTs × anteriority interaction						
Intercept: frontal				582.84	1.53	381.05***
Language × Global RTs				.01	.01	1.16
Intercept: central				582.27	1.43	408.02***
Language × Global RTs				.01	.01	.60
Intercept: parietal				577.42	1.56	369.31***
Language × Global RTs				-.01	.01	-.55
Omnibus Conflict Effect model						
ANOVA						
Language × Conflict Effect	1	98.40	1.15			
Trial type × Conflict Effect	1	.25	.00			
Language × Trial type × Conflict Effect	1	379.45	4.45*			
Language × Conflict Effect × anteriority	2	103.24	1.21			
Trial type × Conflict Effect × anteriority	2	7.75	.09			
Language × Trial type × Conflict Effect × anteriority	2	80.27	.94			
Simple effects models following the Language × Trial type × Conflict Effect interaction						
Intercept: L1				.67	.25	2.69**
Trial type × Conflict Effect				-.00	.00	-.35
Intercept: L2				1.53	.27	5.60***
Trial type × Conflict Effect				.00	.00	.25
Intercept: Non-switch				1.00	.25	4.08***
Language × Conflict Effect				-.01	.01	-1.29
Intercept: Switch				1.20	.29	4.15***
Language × Conflict Effect				-.00	.01	-.73

Note. * $p < .05$; ** $p < .01$; *** $p < .001$.

in Figure 5(b), this association was mainly attributed to the negative correlation of the inhibition capacity with the L2 switch cost.

In sum, we found that the peak of the LAN/N400 to L1 was later for participants with better monitoring skills. Furthermore, the inhibition capacity predicted the difference in switch cost on the LPC across the two languages, which was mainly attributed to the negative correlation between inhibition capacity and the L2 switch cost.

4. Discussion

Results regarding whether and which aspects of domain-general cognitive control processes are recruited in bilingual language comprehension remain largely inconsistent. To reconcile the mixed findings, several studies (Hofweber et al., 2020a; Jiang et al., 2023) have examined the modulating role of intra-sentential code-switching types during comprehension on the basis of Hofweber et al. (2020a, 2020b) processing model of code-switching about a dual control perspective. Yet, the studies to date did not provide conclusive evidence for the effects of this contextual factor during comprehension. Specifically, though the alternation context has been found to exert high requirement to reactive inhibition during comprehension, there was no reliable evidence that the comprehension of dense code-switching type exerted high load to proactive monitoring (Jiang et al., 2023). Following this line of research, the present study uses the ERP technique to further investigate the control processes specifically involved in the comprehension of dense code-switching sentences. In general, the findings are partially in line with our predictions.

Firstly, regarding the language control mechanisms involved during the comprehension of dense code-switching, the reversed language dominance effect and switch costs were absent in the

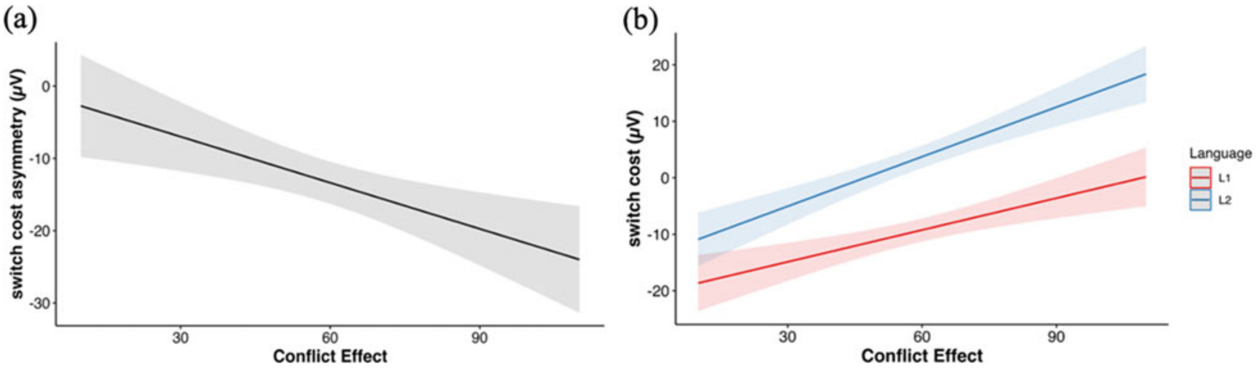

Figure 5. (a) Difference in the switch cost across L1 and L2 (in µV, L1 switch cost – L2 switch cost), and conflict effect (in ms) over the whole brain; (b) L1 and L2 switch cost (in µV), and conflict effect (in ms) over the whole brain in the 500-800 ms time window. Shared areas represent standard errors.

reading task, which at first appeared to be against the use of proactive language control (Declerck, 2020) and reactive language control (Declerck et al., 2019b) mechanisms. However, there were robust associations between monitoring capacity and language dominance effects in the 300–500 ms time window, where there was no association between inhibition capacity and language switch cost (to be discussed below). Nevertheless, in the 500–800 ms time window, inhibition capacity was significantly related to language switch cost, whereas monitoring capacity did not predict the language dominance effects (to be discussed below). Thus, dense code-switching sentences might predominantly involve a proactive language control mechanism in the 300–500 ms time window, which is consistent with our prediction. However, in the 500–800 ms time window, these sentences predominantly involve reactive language control mechanisms, which is inconsistent with our hypothesis.

Secondly, concerning the relationship between cognitive control and bilingual language control, we observed that proactive monitoring and reactive inhibition were both engaged during the comprehension of dense code-switching sentences. Specifically, participants' monitoring skills robustly predicted the language dominance effects on the N400 and LAN, indicating that bilinguals mainly employ proactive monitoring to adjust the activation of different languages at the lexical level (Yacovone et al., 2021). The inhibition capacity, on the contrary, was related to language switch cost (and more specifically, the difference in switch cost across the two languages) on the LPC, suggesting a role of domain-general reactive inhibition in sentence-level processing (Litcofsky & Van Hell, 2017).

Thus, our findings partially corroborate Hofweber et al. (2020a, 2020b)'s hypothesis about a dual control involvement, which posits that the dense code-switching type involving frequent switches exerts higher load to proactive monitoring than reactive inhibition. One plausible account for the absent association between monitoring capacity and the language dominance effect on the LPC is that the dynamic interplay between reactive inhibition and proactive monitoring would be influenced by factors other than intra-sentential code-switching types, such as the processing stages involved in sentence comprehension. That is, during certain processing stages (e.g., sentence-level processing), the influence of the frequency of intra-sentential switches (Hofweber et al., 2020a, 2020b; Jiang et al., 2023) might be mitigated by, for example, the difficulty in processing (to be discussed below). Hence, the existing processing model of code-switching about a dual control perspective (Hofweber et al., 2020a, 2020b) may be revised to accommodate the fluctuation of the relative engagement of each cognitive control mechanism (Braver, 2012; Gross & Kaushanskaya, 2015; Morales et al., 2013; Peeters & Dijkstra, 2018; Wu & Struys, 2022) across different processing stages.

Another possible explanation for not observing a more profound engagement of domain-general proactive monitoring than reactive inhibition during the comprehension of dense code-switching sentences is that onset and not peak latency in the 500–800 ms time window was used. It has been found that the onset latency might be less robustly related to language proficiency than peak latency (Newman et al., 2012). Therefore, the involvement of proactive monitoring during sentence-level comprehension (i.e., in the 500–800 ms time window) may have been masked by the insensitivity of the onset latency to changes in activation levels of the two languages.

Importantly, the discrepant associations between cognitive control and language control at lexical and sentence levels indicate that processing stages (i.e., lexical and sentence-level processing stages) may modulate the control processes during comprehension. This novel finding could explain at least some of the existing inconsistencies in the comprehension literature. That is, inconsistencies across studies could be due to the fact that they examined different processing stages. Indeed, most single-word studies did not observe the engagement of domain-general inhibition in comprehension (e.g., Struys et al., 2019), and some single-word studies have observed the engagement of domain-general monitoring in comprehension (e.g., Jiao et al., 2020). Nevertheless, most sentential comprehension studies have found that domain-general inhibition was involved in language control (e.g., Adler et al., 2020). Future studies should further investigate the modulating role of processing stages to gain a comprehensive understanding of language control during comprehension.

Notably, previous studies have examined the control processes involved in the comprehension of dense code-switching sentences, but they failed to detect the engagement of proactive monitoring or reactive inhibition (Blanco-Elorrieta & Pylkkänen, 2017; Jiang et al., 2023). The discrepancy between the previous work and this study could be explained by the fact that we used the time-sensitive ERP technique rather than the behavioral measures of relatively low sensitivity (Jiang et al., 2023). In addition, we tested non-habitual code-switchers, whereas some previous studies (Blanco-Elorrieta & Pylkkänen, 2017) tested bilinguals from habitual codeswitching communities. The non-habitual code-switchers may find it challenging to process the code-switches that contrast with their usual mode of language use (Litcofsky & Van Hell, 2017; Valdés Kroff et al., 2020). Thus, they may activate high levels of cognitive control during the comprehension of code-switches (Hofweber et al., 2020a; Jiang et al., 2023). However, the habitual code-switchers may find it cognitive effortless to process the code-switches that are congruent with their usual mode of language use (Litcofsky & Van Hell, 2017; Valdés Kroff et al., 2020); therefore, they may invest a small amount of cognitive control during the comprehension of code-switches (Hofweber et al., 2020a; Jiang et al., 2023).

Moreover, the present study explored the control processes at the sentence level. Thus, compared to the large amount of single-word comprehension literature, where the mixed language block can be seen as a dense code-switching context (Jiang et al., 2023; Jylkkä et al., 2018), the present study sheds light on the control processes engaged in more natural settings, which could be more intricate than what the prior single-word studies have found. Specifically, previous single-word comprehension studies have repeatedly observed the recruitment of monitoring (e.g., Jiao et al., 2019, 2020, 2021, 2022b) rather than domain-general inhibition (e.g., Timmer et al., 2021a, 2021b) in bilingual language control. Their findings are basically in agreement with the proposal that the dense code-switching type context exerts higher load to proactive monitoring than reactive inhibition during comprehension (Hofweber et al., 2020a; Jiang et al., 2023). Indeed, this is what we found in the earlier lexical processing stage in the course of sentence comprehension. That is, the monitoring capacity predicted the language dominance effects on the LAN and N400, but the inhibition capacity was not associated with switch cost on the LAN or N400. However, interestingly, we observed that reactive inhibition, rather than proactive monitoring, was recruited during the sentence-level processing stage. That is, the inhibition ability predicted the switch cost on the LPC over the whole scalp, but the monitoring capacity was not related to the language dominance effect on the LPC.

In the following paragraphs, we will explain some of our findings in more detail. The first finding that may be worth discussing is the absence of switch costs and the reversed language dominance effect. Because dense code-switching involves switching and mixing at both lexical and grammatical levels (Hofweber et al., 2016), one might have reasonably expected it would generate an increase in the amplitude of ERP components associated with lexical-semantic and morphosyntactic (i.e., N400, LAN) (Yacovone et al., 2021) and syntactic processing (i.e., LPC) (Rossi et al., 2006). There are several possible reasons for the absence of these effects. Firstly, it might be argued that the absence of these effects reflects little to no use of language control (Declerck, 2020; Declerck et al., 2019b) during the comprehension of dense code-switching sentences. However, we did observe significant correlations between monitoring capacity and language dominance effect on the LAN and N400, and significant correlations between inhibition capacity and switch costs on the LPC, which provided convincing evidence for the use of top-down control processes.

Thus, it would be more plausible to account for the nonsignificant switch costs on the LAN/N400 and the absent reversed language dominance effect on the LPC by adopting a dual control mode perspective (Braver, 2012; Hofweber et al., 2020a, 2020b). Specifically, in the 300–500 ms time window, the proactive control mechanism might play a major role and resolve most language interference before they occur, leaving little room for the use of reactive language control and resulting in little to no switch costs. In the 500–800 ms time window, on the contrary, language control processes were mainly implemented reactively when the non-target language disrupted the selection of the target language. Thus, the relative activation levels of languages were less likely to be adjusted proactively, and the reversed language dominance effect did not occur.

Notably, better monitoring capacity has been found to correlate with a later peak latency of LAN and N400 for L1. This finding indicates that participants with higher monitoring skills are more ready to proactively de-activate the L1 lexical representation, which converges with the prominent way proactive control has been found to improve overall performance (Declerck, 2020). Yet, the reversed language dominance effect for the LAN/N400 was still absent. These seemingly contradictory findings could be reconciled by assuming that the reversed language dominance effect is an extreme case on a continuum from better L1 than L2 performance to better L2 than L1 performance (Declerck, 2020). Its absence might relate to other factors, such as a low number of trials, rather than no use of proactive language control (Declerck, 2020). Furthermore, though inhibition capacity significantly correlated with switch cost on the LPC, which suggests the implementation of reactive control processes, the switch cost for the LPC component was still absent. A plausible explanation for the nonsignificant switch cost on the LPC is that the processing speed during language comprehension tasks is quite fast (Declerck et al., 2019b). It has been proposed that the language control processes might adjust to the context and speed up accordingly; thus, bilinguals would spend less time returning to pre-switch activation levels, leading to little to no (behavioral) switch costs in comprehension tasks (Declerck et al., 2019b). Likewise, we speculate that the language control mechanism during comprehension might also sharpen itself (i.e., improve efficiency) to adjust to the processing speed. That is, bilinguals may more rapidly deploy control processes, thereby limiting the activation of the non-target language (Linck et al., 2012). In turn, they may require less effort to resolve the interference (Linck et al., 2012), leading to little to no switch costs on ERP components.

The second finding we would like to discuss is that the relative engagement of each cognitive control mechanism fluctuates across the early and late time windows. Though proactive monitoring is exclusively recruited in the 300–500 ms time window, the relative contribution of this mechanism reduces between 500 ms and 800 ms, during which reactive inhibition dominates bilingual language control. Notably, it has been found that the balance between the proactive and reactive control processes could be influenced by factors such as language dominance (Gross & Kaushanskaya, 2015; Wu & Struys, 2022), daily experience in language switching (Peeters & Dijkstra, 2018), and cognitive development (Gross & Kaushanskaya, 2015). For example, Wu and Struys (2022) has found that as L2 proficiency increased, bilinguals switched from relying on both domain-general inhibition and monitoring to relying exclusively on monitoring during single-word comprehension. The researchers argued that bilinguals with higher L2 proficiency had experienced more demanding contexts where two languages with equal degrees of activation interfered significantly with each other; thus, they could have been trained to apply the proactive monitoring mechanism to address the language competition efficiently. Therefore, we speculate that the dominant involvement of inhibition during the LPC component could be attributed to the increased difficulty in processing.

Specifically, the LPC has been associated with difficulty in sentence-level processing, such as syntactic integration (Hahne & Friederici, 2001; Rossi et al., 2006). Furthermore, previous studies have repeatedly observed L2 processing and/or acquisition difficulty, particularly in complex syntax (Clahsen & Felser, 2006). Then, it might be the case that the difficulty in processing L2 syntax yielded low levels of the co-activation and competition of sentence-level representations in daily life. Thus, bilinguals did not receive sufficient training to apply proactive monitoring efficiently during the sentence-level processing phase, resulting in great reliance on inhibition to resolve cross-language interference after it occurs in the late time window. In contrast, the N400 and LAN have been related to lexical processing (Yacovone et al., 2021). There is a large set of data on cross-language lexical activation (Van Hell & Tanner, 2012; Van Hell & Witteman, 2009). In this case, there might be high levels of competition of lexical representations in daily life, which could train bilinguals to employ proactive monitoring efficiently during the lexical processing stage.

The third finding that should be addressed is the negative correlation between inhibition capacity and the extent to which L2 switch cost is larger than L1 switch cost during the LPC component. This association was mainly due to the negative correlation between inhibition capacity and L2 switch cost. Notably, task-switching literature has repeatedly observed that the neural activity during the LPC components decreased with training, which was thought to result from a neural sharpening process improving efficiency (Najberg et al., 2021). Thus, we infer that the bilinguals with higher inhibition capacity could resolve the language competition more efficiently, thus showing decreased switch cost on the LPC. Moreover, the stronger association between inhibition and L2 switch cost than L1 switch cost is in line with some studies on language switching during comprehension (Abutalebi et al., 2007; Bosma & Pablos, 2020; Jiang et al., 2023; Pérez & Duñabeitia, 2019). One reason for this connection could lie in the strong bottom-up activation of language node from L1 words before switching, which may result in increased demand for activating the non-dominant L2 and inhibiting the dominant L1 when switching from the L1 to L2 (Abutalebi et al., 2007; Bosma & Pablos, 2020; Jiang et al., 2023; Pérez & Duñabeitia, 2019).

One limitation of the present study is that onset and not peak latency in the 500–800 ms time window was used since the LPC wave did not have a single clear peak in the present data. It has been found that the onset latency might be less robustly related to language proficiency than peak latency (Newman et al., 2012). Thus, the association between monitoring capacity and language dominance effect on the LPC might have been stronger than we have observed. Another limitation is that the study lacks a direct comparison across different types of intra-sentential code-switching, so limited conclusions can be drawn as to whether the observed effects are specific to dense code-switching only. Moreover, it can be predicted that insertion and alternation involving lexical switching would generate an increase in N400 that is more associated with lexical-semantic processing, while dense code-switching involving switching and mixing at both lexical and grammatical levels would trigger increased N400, LAN, or LPC amplitudes. Future research could examine the ERP components associated with different code-switching types further, even though our findings did not confirm this prediction.

5. Conclusion

To conclude, the present study, using the ERP technique, investigates the control processes underlying the comprehension of dense code-switching sentences. The results revealed the engagement of both proactive monitoring and reactive inhibition. Moreover, proactive monitoring dominates the early lexical processing phase, while reactive inhibition dominates the sentence-level processing stage. The findings are partially consistent with the prediction of Hofweber et al. (2020a, 2020b)'s hypothesis about a dual control involvement – that is, the dense code-switching type should exert higher load to proactive monitoring than reactive inhibition. The novel finding of the discrepant associations between cognitive control and language control at lexical and sentence levels provides new insights into the dynamic interplay between reactive inhibition and proactive monitoring and helps to deal with the inconsistencies in comprehension literature regarding the relationship between cognitive control and bilingual language control.

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Data availability. The data that support the findings of this study are openly available in the Mendeley repository, Jiang, Siyi (2023), "The role of cognitive control in bilingual language comprehension: An event-related potential study of dense code-switching sentences", Mendeley Data, v1 http://dx.doi.org/10.17632/gn8wjw7yyv.1

Note

[1] When the models with channels as a random effect resulted in singular fits, and the models with channels as a control variable did not improve model fit compared with the model collapsing across the channels, we would not include it in the models.

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