Neuropsychologia 142 (2020) 107441

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: http://www.elsevier.com/locate/neuropsychologia

Language context modulates executive control in bilinguals: Evidence from language production

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ARTICLE INFO

Keywords:
Bilingualism
Language context
Language switching
Executive control

ABSTRACT

The effect of language context on bilingual language control has been widely studied, but research examining how these contexts affect executive control is relatively limited. In the present study, we used EEG to examine how language context in production influences executive control in bilinguals. A single group of unbalanced Chinese-English bilinguals completed a modified Flanker task interleaved with a picture-naming task, such that executive control performance was measured in three contexts: Chinese, English, and mixed-language. Event-related potentials (ERPs) revealed larger N2 amplitudes and smaller P3 and LPC (late positive component) amplitudes for the mixed-language context than the single-language context across both congruent and incongruent trials. Moreover, during the language production task, LPC amplitudes in mixed-language context were smaller than in the single-language contexts. These findings suggest that language contexts modulate both bilingual language control and domain-general executive control.

1. Introduction

What is the relationship between language control and domain-general executive control in bilinguals? This is a highly debated topic (see reviews in Bialystok, 2017; Lehtonen et al., 2018). However, there is increasing evidence that language contexts in comprehension modulate executive control systems in bilinguals (Adler et al., 2019; Jiao et al., 2019; Wu and Thierry, 2013). Given the distinct language control processes in production and in comprehension, the present study aimed to explore whether language context in *production* modulates executive control.

1.1. The relationship between bilingual language control and executive control

It is widely accepted that control is necessary for bilinguals to resolve competition between two languages due to parallel activation of competing representations (Kroll et al., 2015). Comprehending or speaking of a target language in a language switching environment requires monitoring of the critical features of the language and inhibition of interference from the other language.

Evidence supporting the relationship between bilingual language control and executive control comes from two main lines of research. One approach is to examine executive control performance of different bilinguals as a function of their interactional experience (Beatty-Martínez et al., 2019; Hartanto and Yang, 2016; Hofweber et al., 2016). For example, Hartanto and Yang (2016) compared task-switching performance between two groups of bilinguals who lived in single-language or mixed-language contexts, to examine whether disparate language contexts modulated executive control performance. Bilinguals in the single-language context group lived in an environment in which only one language was used in a given context, with rare language switching. Bilinguals in the mixed-language context were those who lived in an environment where two languages were often used simultaneously, with frequent language switching. The behavioral results showed that bilinguals who lived in a mixed-language context had smaller switch costs than the other group, suggesting that language context modulates bilinguals' executive control system.

The second line of research supporting the relationship between bilingual language control and executive control comes from studies that manipulate language demands within the same bilinguals (Adler et al., 2019; Jiao et al., 2019; Wu and Thierry, 2013). For instance, Jiao et al. (2019) created single- and mixed-language contexts by using a picture-word matching task interleaved within a Flanker task and

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https://doi.org/10.1016/j.neuropsychologia.2020.107441
Received 9 October 2019; Received in revised form 18 March 2020; Accepted 18 March 2020
Available online 19 March 2020

showed that bilinguals performed best in the mixed-language context. The two approaches are widely adopted in the bilingualism literature. However, the first approach is used to investigate the stable effect of long-term bilingual experience on executive control by comparing different bilinguals, and the second approach focuses on the instant effect of task-induced language contexts by the same bilinguals.

The present study used the task-induced approach to explore whether language context in *production* modulates executive control. The main benefits for using task-induced approach is that this approach can examine the language context effect on language control and executive control at the same time (Beatty-Martínez et al., 2019). Furthermore, the within-subjects design allows us to rule out any potential between-group differences, such as socioeconomic status that might influence group performance in other studies (Hsu and Novick, 2016; Jiao et al., 2019).

1.2. The modulation effect of language context

The language-mode continuum framework (Grosjean, 2012) and the adaptive control hypothesis (Green and Abutalebi, 2013) both emphasize that language context affects language control processes in bilinguals. Specifically, Grosjean (2012) proposed a language-mode continuum to represent the activation level of two languages in different language modes (i.e., language contexts). When bilinguals interact with other bilinguals who share the same languages, and switch between languages in communication, both languages are candidates in this mixed-language context. Conversely, bilinguals in a single-language context communicate with others only in one of the two languages. In this case, the non-target language is deactivated to prevent a language switch. Grosjean emphasized that the language context where bilinguals are exposed could affect their language control behavior.

Similarly, Green and Abutalebi (2013) put forward the adaptive control hypothesis, a more specific framework about the language control processes in different interactional contexts (i.e., language contexts). This hypothesis proposed that language control processes could adaptively change their expression and cooperate with other control processes differentially as a function of language context. Both theories provide theoretical motivation for several studies to explore the effect of language context on language control (Beatty-Martínez and Dussias, 2017; Beatty-Martínez et al., 2019; Blanco-Elorrieta et al., 2018). For example, Blanco-Elorrieta and colleague (2018) recorded magnetoencephalography (MEG) from American Sign Language-English bilinguals and examined bilingual picture naming in unilingual context and bilingual contexts. The MEG study revealed that during language switching in a mixed-language context, disengaging from the previous language led to increased activity in the anterior cingulate cortex (ACC) and dorsolateral prefrontal cortex (dlPFC) associated with executive control. This study suggests that when simultaneously producing two languages in mixed-language context, the brain regions related with executive control are engaged to exert sufficient top-down control in order to manage language-switching behavior of bilingual individuals.

Importantly, language context has also been shown to influence executive control (Adler et al., 2019; Jiao et al., 2019; Wu and Thierry, 2013). Jiao et al. (2019) used a task-induced approach to examine the effect of language comprehension context on the executive control system. In the first two experiments of this behavioral study, the Flanker task was interleaved with a picture-word matching task, and a group of Chinese-English bilinguals made responses to both tasks. There were three language contexts, including Chinese (L1), English (L2), and mixed-language contexts. Compared with L1 and L2 single-language contexts, the participants performed better in the mixed-language context for both congruent and incongruent Flanker trials. Moreover, the findings of Experiment 3 and 4 excluded the potential confounding effect of an individual's alertness. Jiao et al. (2019) provide preliminary behavioral evidence that language context in word comprehension affects executive control.

In line with these behavioral findings, an ERP study by Wu and Thierry (2013) revealed the modulatory effect of language context on executive control in a group of Welsh-English bilinguals. In this study, every Flanker trial was preceded by a word stimulus, creating Welsh (L1), English (L2) and Welsh-English mixed-language contexts. Participants were asked to respond to the Flanker task trials and ignore the words. Results revealed that bilinguals performed more accurately on the incongruent Flanker trials in the mixed-language context than in both single-language contexts; the ERP data revealed that P3 amplitudes for incongruent Flanker trials were smaller for the mixed-language context than both single-language contexts. These findings suggest that language contexts in word comprehension modulate executive control.

Adler et al. (2019) went beyond word comprehension and examined Flanker/sentence reading performance in bilinguals. In this study, Spanish-English bilinguals performed a cross-task adaptation paradigm that tested whether a code-switch sentence during real-time comprehension triggers executive control engagement that affects subsequent performance on the Flanker task. This study discovered that compared to reading sentences that did not contain a code-switch, reading code-switched sentences facilitated ensuing conflict resolution of Flanker trials. These findings suggest that integrating a code-switch during real-time comprehension may recruit domain-general executive control, providing new insight on the modulatory effect of language context on domain-general executive control.

In sum, there is some evidence that language context in passive comprehension modulates ensuing executive control processes. When bilinguals are immersed in a mixed-language context, the language control demands for resolving the cross-linguistic competing representation may trigger executive control engagement, which regulates subsequent executive control performance moment-by-moment on other tasks. Meanwhile, the language context effect also provides novel insight into the debate over whether or not there is a bilingual advantage compared to monolinguals on executive function tasks. Linguistic context may influence whether or not bilinguals will show an advantage over monolinguals.

1.3. Language contexts in production

Behavioral and electrophysiological evidence gathered so far has provided support for the modulatory role of language contexts in comprehension on executive control (Adler et al., 2019; Wu and Thierry, 2013), but it is still not clear whether language contexts in *production* affect executive control.

There are similarities between bilingual language control in comprehension and in production contexts. The two languages are active in parallel during speaking or perceiving the intended language. This means that language control mechanisms are necessary to coordinate languages in comprehension and in production contexts (Kroll et al., 2015; Nozari and Novick, 2017). Furthermore, language control mechanisms can adaptively change in accordance with language context (Green and Abutalebi, 2013). Hence, like comprehension, we expect that language production context will modulate executive control, a hypothesis tested in our study.

Importantly, however, the language control processes in comprehension and in production recruit distinct neural circuitry (Blanco-Elorrieta and Pylkkänen, 2016; Declerck and Philipp, 2018; Mosca and de Bot, 2017). One MEG study explored the overlap between language control and executive control both in production and comprehension and discovered a clear dissociation of language control between production and comprehension (Blanco-Elorrieta and Pylkkänen, 2016). In addition, Declerck and Philipp (2018) recruited German-English-French trilinguals to examine the role of inhibition in production and in comprehension. Two language production tasks (picture naming task and reading aloud task) and two language comprehension tasks (picture categorization task and written word categorization task) were used in this study. The dependent variable, reflecting language inhibition, was n-2 language repetition costs, which was measured by the difference between AB*A* trials and CB*A* trials (A, B, and C referred to the three languages in this study). In the production tasks, n-2 language repetition costs were observed, with slower responses during AB*A* trials than during CB*A* trials; but in the comprehension tasks, n-2 language repetition costs were only found in the picture categorization task, not in the written word categorization task. These results indicate that there are distinct language control processes in comprehension and in production. For example, the language control in production is related to the Inhibitory Control (IC) model (Green, 1998), emphasizing that inhibitory control is necessary to suppress interference from non-target language during bilingual language production. However, the Bilingual Interactive Activation plus (BIA+) model surrounding bilingual language comprehension proposes that visual input activates sublexical/lexical orthographic and phonological representations then accesses a particular language during word identification, relying less on inhibitory control mechanisms (Dijkstra and van Heuven, 2002).

During language production in bilinguals, there are two loci of language control, including local control and global control. Specifically, local control refers to the language control on a specific item, mainly engaged in a mixed-language context or language switching context. Global control refers to the whole-language control, an effective locus for competition resolution in a single-language context. Under different language contexts, bilinguals can adjust and engage local/global control in accordance to the language control demand (Guo et al., 2011; Timmer et al., 2019). The effects of local and global language control on executive control tasks can be examined separately by comparing single-language and mixed-language contexts and by comparing the two single-language contexts (Guo et al., 2011), respectively. In a mixed-language context, bilinguals have to rely on local control of lexical items given that both languages are potential candidates. In single-language contexts, bilinguals rely on global control at the level of the whole-language in order to inhibit the non-target language. Based on previous work, long-lasting inhibitory control is required on the more dominant L1 when planning speech in the less dominant L2 (Misra et al., 2012). Thus, global control could be reflected by comparing the two single-language contexts.

In sum, given the distinct language control processes in comprehension and in production, it is necessary to explore whether language contexts in production affect executive control.

1.4. The present study

The present study aimed to explore whether language contexts in production modulate executive control. Given two loci of language control involved in language production, another focus of the present study was to determine the source of facilitation on executive control in the mixed-language context.

The present study adopted a cross-task-adaptation paradigm, in which a Flanker task was interleaved with a picture-naming task. By using this paradigm, we could examine whether on the fly adjustments in executive control are modulated by language contexts in production, and eliminate any potential confounding variables between different bilinguals, such as socioeconomic status (Hsu and Novick, 2016; Jiao et al., 2019). The picture naming task was used to create language production contexts, including Chinese (L1), English (L2) and mixed-language contexts. A group of bilinguals were asked to perform the Flanker task in each language context. The logic behind cross-task-adaptation paradigm is if there is a modulation effect of language context in production on executive control system, the language control processes triggered by the different language production contexts would adaptively affect the ensuing Flanker trials.

Using high temporal resolution EEG technique, we simultaneously recorded behavioral and event-related potential data in both the Flanker and picture naming tasks. The advantage of EEG is that it gives us an opportunity to examine the effect of language context on language ability and executive control ability at the same time (Beatty-Martínez and Dussias, 2017). Bilingualism is about language experience, but regrettably, few studies examining the cognitive consequence of bilingualism have examined language ability, and have not provided a comprehensive framework about the consequences of bilingualism for both language and cognition. Hence, the current study examined behavior and electrophysiological responses on both language (i.e., picture naming) and cognition (i.e., Flanker) tasks. For picture naming, the P2 and LPC (late positive component) were analyzed to explore where the effect of language context on executive control comes from. For the Flanker task, the N2, P3, and LPC components were analyzed to examine the language context effect on executive control.

The Bilingual Anterior to Posterior and Subcortical Shift (BAPSS, Grundy et al., 2017a) model states that learning a second language is initially cognitively demanding and requires many frontal resources. Life-long use of these demanding cognitive processes may lead to more efficient resource allocation and enhance more early, automatic processes to prepare the control system for potential conflict. Hence, in ERP components, Grundy et al. (2017a) proposes that bilinguals tend to have a larger amplitude at the conflict-sensitive N2 component but reduced amplitudes in the late time-windows (i.e., P3 and LPC) than monolinguals in domain-general executive control tasks. The N2 is a negative-going wave peaking between 200 and 350 ms after stimulus onset, with an anterior scalp distribution (Folstein and Van Petten, 2008). The N2 is a reflection of conflict monitoring, with larger N2 amplitudes signifying more resources allocated to conflict processing. The P3 component, a positive-going wave with the latency of about 300–400 ms, mainly reflects response inhibition and stimulus categorization (Kousaie and Phillips, 2012). In addition, based on the BAPSS model, we also examined the later LPC. The larger N2 amplitude but smaller P3/LPC amplitude proposed in the BAPSS model might indicate that more neural resources have been devoted at the early stage of cognitive processing for bilinguals than monolinguals, reducing the requirement for stimulus categorization at later stages of cognitive processing (Grundy et al., 2017a).

The present study used a picture-naming task interleaved with a Flanker task and hypothesized that language contexts in production would influence executive control processes. We hypothesized that mixed-language contexts would cue the bilingual experience and enhance cognitive resources more generally, resulting in larger N2 amplitudes on the Flanker task than single-language contexts. This would reflect more resource allocation to conflict monitoring early in the time course. In turn, smaller P3/LPC amplitudes should be observed because cognitive processing in earlier time windows should reduce the need for additional categorization/response suppression processing in later time windows.

2. Methods

2.1. Participants

Twenty-two Chinese (L1) – English (L2) bilinguals participated in the study for monetary compensation. All participants were students recruited from Beijing Normal University. They were all born in China with no background of immigration or overseas education. The participants were sequential bilinguals, who were exposed to Chinese from birth and learned English at a mean age of 8.6 ± 1.8 years in a classroom setting. In addition, all participants had attended some courses in English, but they spend most of the time in dominant Chinese, e.g., home environment. They were right-handed bilinguals with normal or corrected-to-normal vision. None of the participants had neurological or psychological impairments or had used psychoactive medication. Ethical approval was obtained from the Committee of Protection of Subjects at Beijing Normal University. All participants signed the written informed consent. Data from three participants were eliminated because of excessive EEG artifacts. The final sample consisted of nineteen participants (12 female), aged from 18 to 26 years old (20.5 ± 2.2).

The language proficiency of participants was measured by the Oxford Placement Test (OPT) and a self-report questionnaire (see Table 1). Firstly, the score of OPT is an objective indicator for L2 proficiency (Liu et al., 2016). The total score of OPT was 50, consisting of 25 multiple choice questions and a cloze test. The higher the score, the higher the English proficiency of the participant. Then, the subjective indicator of language proficiency was measured by a self-rating questionnaire. Participants were asked to indicate how well their L2 were compared with their L1 in listening, speaking, reading, and writing skills. Language proficiency was rated on a six-point scale, in which 6 suggests comparable skill between L1 and L2, and 1 suggests much lower L2 skills than L1 skills. The average proficiency of L1 and L2 in four aspects were reported in Table 1. Paired-samples *t*-test revealed a significant difference between the subjective proficiency scores of L1 and L2 for all skills [listening, $t(18) = 8.9$, $p < 0.001$; speaking, $t(18) = 9.0$, $p < 0.001$; reading, $t(18) = 8.9$, $p < 0.001$; writing, $t(18) = 6.6$, $p < 0.001$]. Based on this background information, the group of participants were unbalanced, sequential bilinguals with dominant L1.

2.2. Design and procedure

In order to examine the effect of language context in production on executive control, the present study interleaved a picture naming task with a Flanker task, resulting in a 2 (congruency: congruent, incongruent) × 3 (context: L1, L2, and mixed) within-subjects design. The Flanker task was used to measure executive control, including congruent and incongruent trials; the picture naming task was used to create three language production contexts, including Chinese (L1), English (L2), and mixed-language contexts. The presentation of picture naming trials was pseudo-randomized such that there were no more than five consecutive naming trials in the same language during the mixed-language context.

2.2.1. Flanker task

The Flanker task stimuli consisted of one target central arrow and two flanking arrows on each side (Eriksen and Eriksen, 1974). All participants were asked to respond as quickly as possible to the pointing direction of the target arrow by pressing the left or the right button. There were two types of trials, congruent and incongruent trials, according to the congruency between the pointing direction of target arrow and flanking arrows. On congruent trials, the central target arrow pointed to the same direction of the four flankers (e.g., < < < < <), but the central target arrow pointed to the opposite direction of the flanking arrows on incongruent trials (i.e., < < > < <). The incongruent flankers provide conflicting information to the correct response, leading to increased conflict resolution demand in comparison to congruent trials.

2.2.2. Picture naming task

Language contexts in production were created by a picture-naming task. There were three language contexts – L1, L2, and mixed-language contexts, depending on the naming languages. Before the formal ERP experiment, participants were allowed to familiarize themselves with the L1 and L2 picture names in order to reduce naming error.

Table 1
Means (and SDs) of AoA and language proficiency in four language skills.

	L1 (Chinese)	L2 (English)
AoA	–	8.6 (1.8)
OPT	–	38.8 (4.8)
Listening	5.7 (0.5)	3.4 (1.3)
Speaking	5.3 (0.6)	3.0 (1.1)
Reading	5.2 (1.1)	2.8 (1.2)
Writing	5.2 (1.1)	2.7 (1.5)

Note: SD represents standard deviation; AoA represents the age of L2 acquisition; OPT represents the score of the Oxford Placement Test.

In mixed-language context, the target picture was presented on the center of computer screen, accompanied by the naming cue. A red cue indicated naming in L1, and a blue cue indicated naming in L2 (Fig. 1). The color-language association was counterbalanced across participants. Participants were instructed to name the target picture in the correct language, switching between two languages in mixed-language context. In the L1 and L2 single-language contexts, participants always named the target picture in one language (L1 or L2), with no language switching demand.

All picture stimuli consisted of 60 black-and-white line drawings selected from the Snodgrass and Vanderwart's photo gallery Snodgrass and Vanderwart, 1980standardized by Zhang and Yang (2003). The Chinese word for each picture was a two-character word and the English equivalents ranged from 3 to 8 letters in length. A separate group of 25 students, that are similar to the participants in L2 proficiency [listen: $t(42) = 1.09$, $p = 0.28$; speaking: $t(42) = 0.15$, $p = 0.88$; reading: $t(42) = -1.08$, $p = 0.29$; writing: $t(42) = 0.91$, $p = 0.37$], assessed the familiarity of L1 and L2 names for the pictures on a 7-point scale (1 = very unfamiliar, 7 = very familiar). Paired samples t-tests showed that there was no significant difference in the average familiarity between L1 names (6.56 ± 0.27) and L2 names (6.59 ± 0.23), $t(59) = -0.79$, $p = 0.43$. Thus, L1 and L2 names for the pictures are similar in word familiarity.

2.2.3. Interleaved picture naming-to-flanker sequence

The current study interleaved a picture naming task with a Flanker task by the cross-task-adaptation paradigm. Each language context appeared in a separate block, and the order of three blocks was counterbalanced among participants. There were 120 trials of picture naming task and 120 trials of Flanker task in each language context (i.e., L1, L2, and mixed-language blocks). In L1 and L2 blocks, each picture was presented twice, and named in the same language (i.e., L1 or L2). In the mixed-language block, each picture was also presented twice but named in L1 and L2 respectively. For the Flanker task, half the trials were congruent trials and the other half were incongruent trials.

Fig. 1 provides a detailed depiction of the procedure. First, a fixation appeared in the center of the computer screen for 400 ms; after a 200 ms blank screen, the target picture accompanied with a colored cue presented for 1000 ms. The symbol "*****" then appeared, signaling participants to name the picture as quickly and accurately as possible. The delayed naming instruction aimed to avoid contamination of the EEG signal with myoelectric artifacts of language articulation (Christoffels et al., 2007; Liu et al., 2016). There was a 500 ms blank screen followed the picture naming task. Then, five arrows of the flanker task appeared on the screen, and remained until the participant pressed the response key or for a maximum duration of 1500 ms. Finally, an inter-trial interval of 2000 ms occurred. In each context block, participants were instructed of the target language. Before the experimental portion of the study, participants were provided with 16 Flanker task practice trials with feedback.

2.3. Electrophysiological recordings

Continuous EEG was recorded from 64 Ag/AgCl electrodes placed according to the extended 10–20 positioning system. The signal was recorded with a 1 kHz sampling rate and referenced online to the right mastoid (M2). Vertical and horizontal eye movements were recorded by electrodes placed on the supra- and infra-orbital ridges of left eye (VEOG), and the outer canthi of the left and right eye (HEOG). Impedances were kept below 5 kΩ. Electroencephalographic activity was filtered online with a bandpass between 0.05 and 100 Hz. The reference electrode was converted to bilateral mastoid (M1 and M2), and some artifacts were rejected manually. The data were re-filtered offline with a 30 Hz low-pass, zero-phase shift digital filter. Based on the record of eye movements, eye blinks were corrected for each subject by a regression-based algorithm (Semlitsch et al., 1986). Continuous recordings were cut into epochs ranging from −200 to 1000 ms relative to the onset of

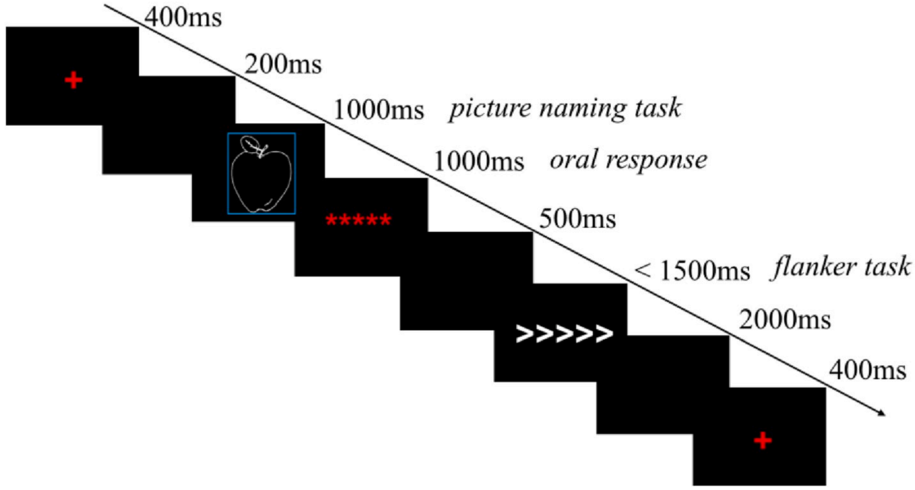

Fig. 1. Experimental procedure for the interleaved presentation of picture naming task and Flanker task.

the arrow stimulus during the Flanker task, and from −200 to 800 ms relative to the onset of picture stimulus during the picture naming task. Baseline correction was performed in reference to the pre-stimulus activity (−200 to 0 ms). Signals exceeding ±80 μV in any given epoch were automatically discarded. In total, 88% of the data in Flanker task were kept after artifact rejection; 92% of the data in picture naming task were kept after artifact rejection.

2.4. Behavioral data analysis

Picture naming accuracy was at ceiling (>97%), thus, the current study only analyzed behavioral data for the Flanker task. For response times (RTs), data from incorrect responses (2.5%) and RTs beyond M±3SD or less than 150 ms (1.5%) were excluded. For accuracy, all data entered analyses. Analyses were conducted using mixed-effects models with crossed random effects for subjects and items in the R environment (version 3.4.3) (lme4 and lmerTest package, Bates et al., 2007; Kuznetsova et al., 2017). The reason for using mixed-effects models was to allow random effects of subjects and items to be considered simultaneously, making the data modelling more appropriate and the results generalizable to other subjects and items.

2.5. Event-related brain potential analysis

Given our theoretical interest of language context on executive control, we analyzed both Flanker and picture-naming ERP data. ERP components in the Flanker task were defined on the basis of the grand average and analyzed in time-windows typically used to examine the N2 (250–350 ms), P3 (350–500 ms) and late positive component (LPC, 500–700 ms) (Grundy et al., 2017b; Morales et al., 2015). Consequently, the mixed-effects models were performed on the mean amplitudes of N2 (FZ, FCZ, CZ), P3 and LPC (FCZ, CZ, CPZ, PZ) (Grundy et al., 2017b; Moreno et al., 2014). Similar to the behavioral data analysis, linear mixed-effects models for the Flanker task were separately fitted on the amplitude data of each ERP component, including context, congruency, and their interaction as fixed effects, and by-subjects and by-items as random effects. The trials entering analysis were correct in both the preceding picture-naming task and in the corresponding Flanker task, in order to avoid error detection in picture-naming influencing subsequent processes on the Flanker task. Following this, we analyzed time-windows typically used to examine P2 (200–240 ms) and LPC (450–650 ms) (Jackson et al., 2001; Jin et al., 2014) based on the grand average waveforms. The mixed-effects models of the picture-naming task were performed on the mean amplitude of three electrodes (P3, PZ, P4) (Jackson et al., 2001), including context as a fixed effect, with crossed random effects for subjects and items. Based on our hypothesis, we compared the Flanker task in mixed-language and in single-language contexts (average of L1 and L2 contexts), reflecting the effect of local language control on executive control. We then compared processing during the Flanker task in the L1 context compared to the L2 context, reflecting the effect of global language control on executive control. The absence of a language context effect would be reflected by comparable Flanker task processing among the three language contexts.

3. Results

3.1. Behavioral results in flanker task

3.1.1. RTs

Flanker task reaction times are presented in Fig. 2. We fit a linear mixed-effects model with congruency (congruent vs. incongruent), context (L1 vs. L2 vs. mixed-language), and their interaction as fixed effects. The model included by-subject and by-item random intercepts. Because the model with maximal random slopes did not converge, we used a backward-fitting procedure to identify a model with the largest random effects that would converge (Barr et al., 2013). Thus, the fitted model included the by-subject random slope for congruency and context, and the by-item random slope for congruency.

Given the theoretical interest of current study, the context variable was coded with orthogonal contrasts. Specially, if the local control of mixed-language context plays a role, the Flanker task performance in mixed-language context would be different from that in single-language contexts without local control demand. Thus, the first contrast compared single-language contexts (average of L1 and L2 contexts) to mixed-language context and the second contrast compared the Flanker performance in L1 context and that in L2 context in order to examine the role of global control. Congruency was sum coded (congruent = −0.5, incongruent = 0.5). The fixed effects structure of the best-fitted model was summarized in Table 2. As seen in Table 2, there was a significant effect of congruency, indicating the incongruent trials (M = 538 ms) were responded to more slowly than congruent trials (M = 444 ms). However, there was no significant difference between single-language and mixed-language contexts, and no difference between L1 and L2 context. Neither interaction reached significance.

3.1.2. Accuracy

Based on each participant's mean accuracy, the accuracy of Flanker task was presented in Fig. 3.

For accuracy, we fit a logistic mixed-effects model with congruency, context, and their interaction as fixed effects. The model included by-

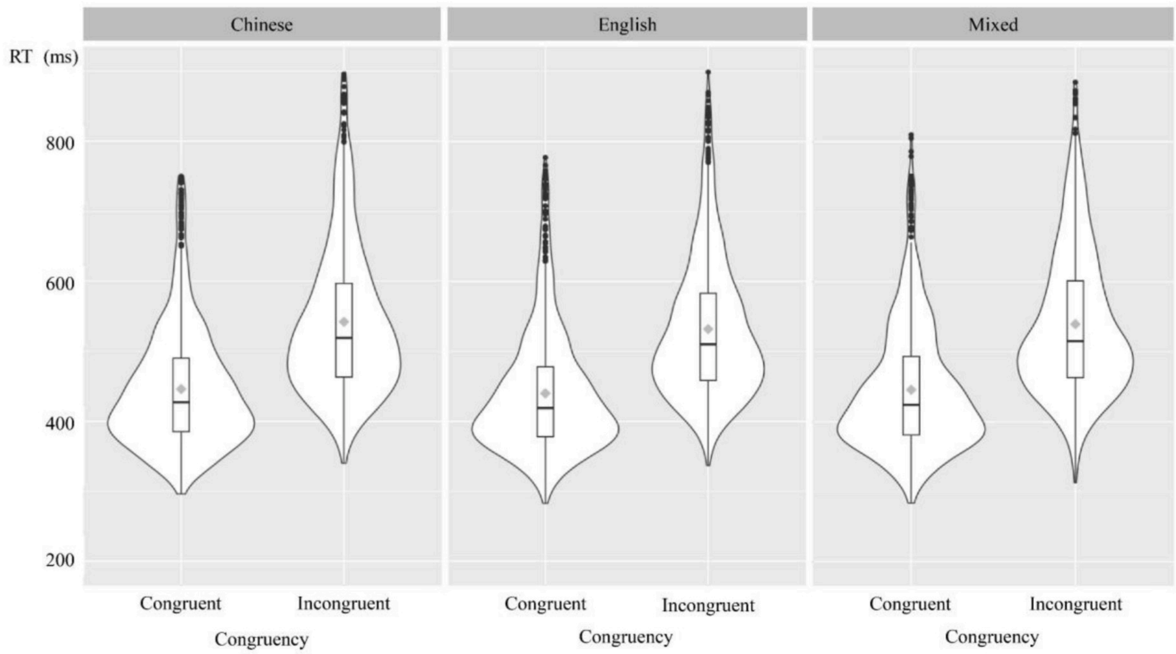

Fig. 2. Violin plots showing the RTs of the Flanker task for each language context [left: Chinese (L1) context; center: English (L2) context; right: Mixed-language context] for each trial type (congruent and incongruent trial). The gray dot represents the mean value, while the thin horizontal black line represents the median. The violin plot outline shows the density of data points for different RTs, and the boxplot shows the interquartile range with the 95% confidence interval represented by the thin vertical black line.

Table 2
Fixed effects estimates of mixed-effects model for RTs in Flanker task.

	Estimated	SE	t	p
(Intercept)	**491.31**	**14.06**	**34.95**	**< .001**
Context (M vs. S)	2.36	5.28	0.45	0.66
Context (L1 vs. L2)	−8.34	4.91	−1.70	0.10
Congruency (C vs. I)	**92.44**	**6.61**	**13.98**	**< .001**
Context (M vs. S): Congruency (C vs. I)	−2.77	4.09	−0.68	0.50
Context (L1 vs. L2): Congruency (C vs. I)	−3.51	5.24	−0.68	0.50

Note: M = Mixed-language context; S = Single-language context (average of L1 and L2 context); C = congruent; I = incongruent. The bold items represent the significant effects in Flanker task.

subject and by-item random intercepts. And the fitted model included the by-subject random slope for congruency. As with RTs, the context variable was coded with orthogonal contrasts, and congruency variable was sum coded.

As Table 3 showed, there was a significant effect of congruency, indicating the accuracy of incongruent trials (M = 96%) was lower than congruent trials (M = 99%). However, there was no significant difference between single-language and mixed-language contexts, and no difference between L1 and L2 contexts. Neither interaction reached significance.

3.2. ERP results in flanker task

3.2.1. N2 time window (250–350 ms) in flanker task

Fig. 4 shows the grand-averaged event-related potential waveforms elicited by congruent and incongruent trials in three different contexts.

For the mean amplitude of N2 (FZ, FCZ, CZ), the mixed-effects model was conducted with congruency, context, and their interactions as fixed effects. As random-effects, the mixed-effects model included by-subject and by-item random intercepts, and by-subject random slope for context. As with the behavioral data analysis, language context was coded with orthogonal contrasts. Specially, the first contrast compared single-language contexts to the mixed-language context and the second contrast compared the amplitude in L1 context and that in L2 context. Congruency was sum coded (congruent = −0.5, incongruent = 0.5). The fixed effects structure of the best-fitted model was summarized in Table 4.

As shown in Table 4, there was a significant effect of congruency, with larger N2 amplitude for incongruent trials in comparison to congruent trials across all contexts. The difference between mixed-language context and single-language contexts (the average amplitude of L1 and L2 contexts) was significant, with larger amplitudes in the mixed-language context than the single-language contexts across congruent and incongruent trials. In order to examine the comparison between the mixed-language context and the two single-language contexts separately, we fit another mixed-effects model for N2 amplitude with the same fixed effects and random effects, but used the treatment coding for context variable (mixed-language context as a baseline). Congruency was still sum coded (congruent = −0.5, incongruent = 0.5). The mixed-effects model with treatment coding examined the contrast comparing mixed-language and L1 context, and the contrast comparing mixed-language and L2 context. The results revealed larger N2 amplitudes in the mixed-language context across both congruent and incongruent trials (mixed-language vs. L1: estimated = 0.66, SE = 0.27, t = 2.44, p = 0.01; mixed-language vs. L2: estimated = 1.18, SE = 0.27, t = 4.44, p < 0.001).

3.2.2. P3 time window (350–500 ms) in flanker task

For P3 amplitude (FCZ, CZ, CPZ, PZ), the mixed-effects model was conducted with congruency, context, and their interaction as fixed effects. As random-effects, the mixed-effects model included by-subject and by-item random intercepts, by-subject random slope for context. Congruency was sum coded (congruent = −0.5, incongruent = 0.5), and context was coded with orthogonal contrasts. The fixed effects structure of the best-fitted model was summarized in Table 5.

As shown in Table 5, the context effect (single-language vs. mixed-language contexts) reached significance, showing smaller amplitudes for mixed-language context than single-language contexts. In line with N2 model, we then fit the other mixed-effects model for P3 amplitude

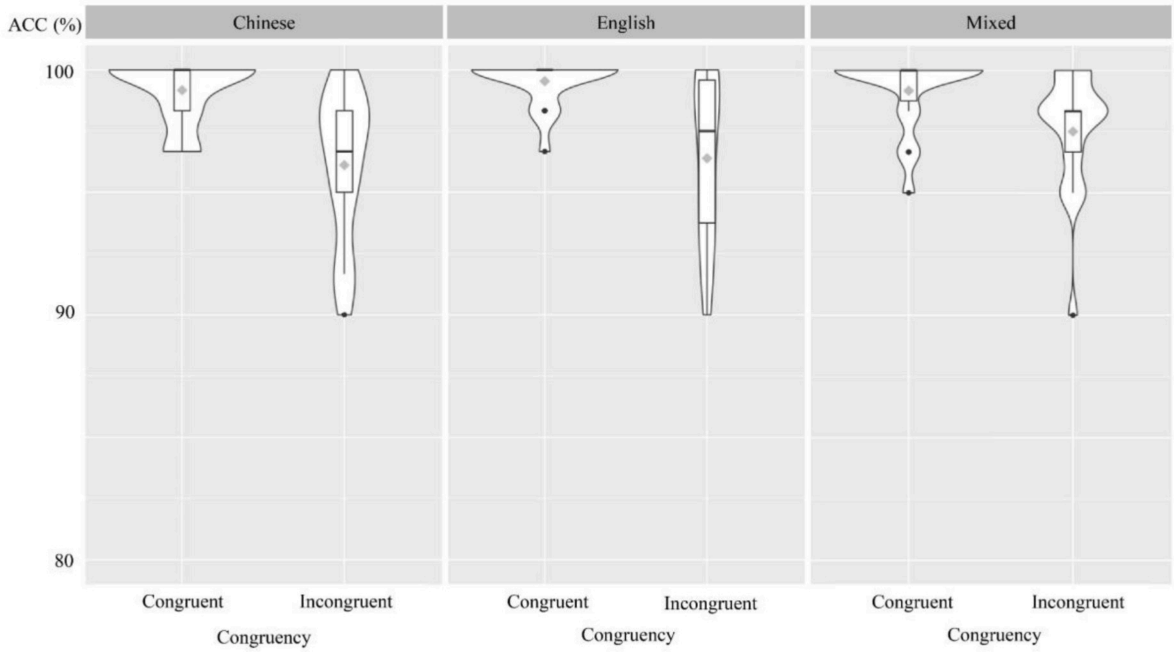

Fig. 3. Violin plots showing the accuracy of the Flanker task for each language context [left: Chinese (L1) context; center: English (L2) context; right: Mixed-language context] for each trial type (congruent and incongruent trial). The gray dot represents the mean value, while the thin horizontal black line represents the median. The violin plot outline shows the density of data points for different RTs, and the boxplot shows the interquartile range with the 95% confidence interval represented by the thin vertical black line.

Table 3
Fixed effects estimates of mixed-effects model for accuracy in Flanker task.

	Estimated	SE	*z*	*p*
(Intercept)	**4.54**	**0.27**	**16.67**	**< .001**
Context (M vs. S)	0.10	0.24	0.40	0.69
Context (L1 vs. L2)	0.36	0.30	1.19	0.23
Congruency (C vs. I)	**−2.01**	**0.45**	**−4.45**	**< .001**
Context (M vs. S): Congruency (C vs. I)	0.65	0.48	1.34	0.18
Context (L1 vs. L2): Congruency (C vs. I)	−0.71	0.59	−1.19	0.23

Note: M = Mixed-language context; S = Single-language context (average of L1 and L2 context); C = congruent; I = incongruent. The bold items represent the significant effects in Flanker task.

with treatment coding for context (mixed-language context as a baseline). Results of treatment-coding model revealed a significant difference across congruent and incongruent Flanker trials between the mixed-language context and the L1 context (estimated = 1.49, SE = 0.61, $t = 2.46$, $p = 0.03$), and between the mixed-language context and the L2 context (estimated = 1.88, SE = 0.69, $t = 2.73$, $p = 0.01$).

3.2.3. LPC time window (500–700 ms) in flanker task

For LPC amplitude (FCZ, CZ, CPZ, PZ), the mixed-effects model was conducted with congruency, context, and their interaction as fixed effects. As random-effects, the LPC model included by-subject and by-item random intercepts, by-subject random slope for context and congruency. Congruency was sum coded (congruent = −0.5, incongruent = 0.5), and context was coded with orthogonal contrasts. Table 6 showed the fixed effects structure of the best-fitted model for LPC during Flanker task.

For the LPC amplitude, there was a significant effect of congruency. Moreover, the comparison between mixed-language context and single-language context revealed a significant difference with smaller LPC amplitudes in the mixed-language context. Hence, we fit the other mixed-effects model for LPC amplitude with treatment coding for context (mixed-language context as a baseline). Results of the treatment-coding model revealed a significant difference across congruent and incongruent Flanker trials between the mixed-language context and the L1 context (estimated = 1.31, SE = 0.59, $t = 2.23$, $p = 0.04$), and between the mixed-language context and the L2 context (estimated = 1.60, SE = 0.66, $t = 2.41$, $p = 0.03$).

3.3. ERP results in picture naming task

3.3.1. P2 time window (200–240 ms) in picture naming task

The grand-averaged event-related potential waveforms elicited by picture naming task is presented in Fig. 5. For the mean amplitude of P2 (P3, PZ, P4), the mixed-effects model was conducted with context as fixed effects. As random-effects, the mixed-effects model included by-subject and by-item random intercepts, by-subject random slope for context. Context variable was coded with orthogonal contrasts. The mixed-effects models for P2 showed that neither the difference between single-language and mixed-language contexts (estimated = −0.20, SE = 0.51, $t = -0.40$, $p = 0.70$), nor the difference between two single-language contexts (estimated = 0.06, SE = 0.37, $t = 0.17$, $p = 0.87$) reached significant level.

3.3.2. LPC time window (450–650 ms) in picture naming task

The mixed-effects model for the LPC in the picture-naming task was performed on the mean amplitude of P3, PZ, and P4 electrodes (Jackson et al., 2001). In line with the P2 analysis, the mixed-effects model for the LPC during the picture-naming task was conducted with a fixed effect of context (L1, L2 and mixed-language), and random-effects, including by-subject and by-item random intercepts. The context variable was coded with orthogonal contrasts. The mixed-effects models showed that there was a significant contrast between single-language and mixed-language contexts (estimated = −0.51, SE = 0.23, $t = -2.20$, $p = 0.03$), with smaller LPC amplitudes in the mixed-language naming condition than in the single-language naming condition. However, there was no significant difference between L1 and L2 contexts (estimated = 0.22, SE = 0.29, $t = 0.74$, $p = 0.46$).

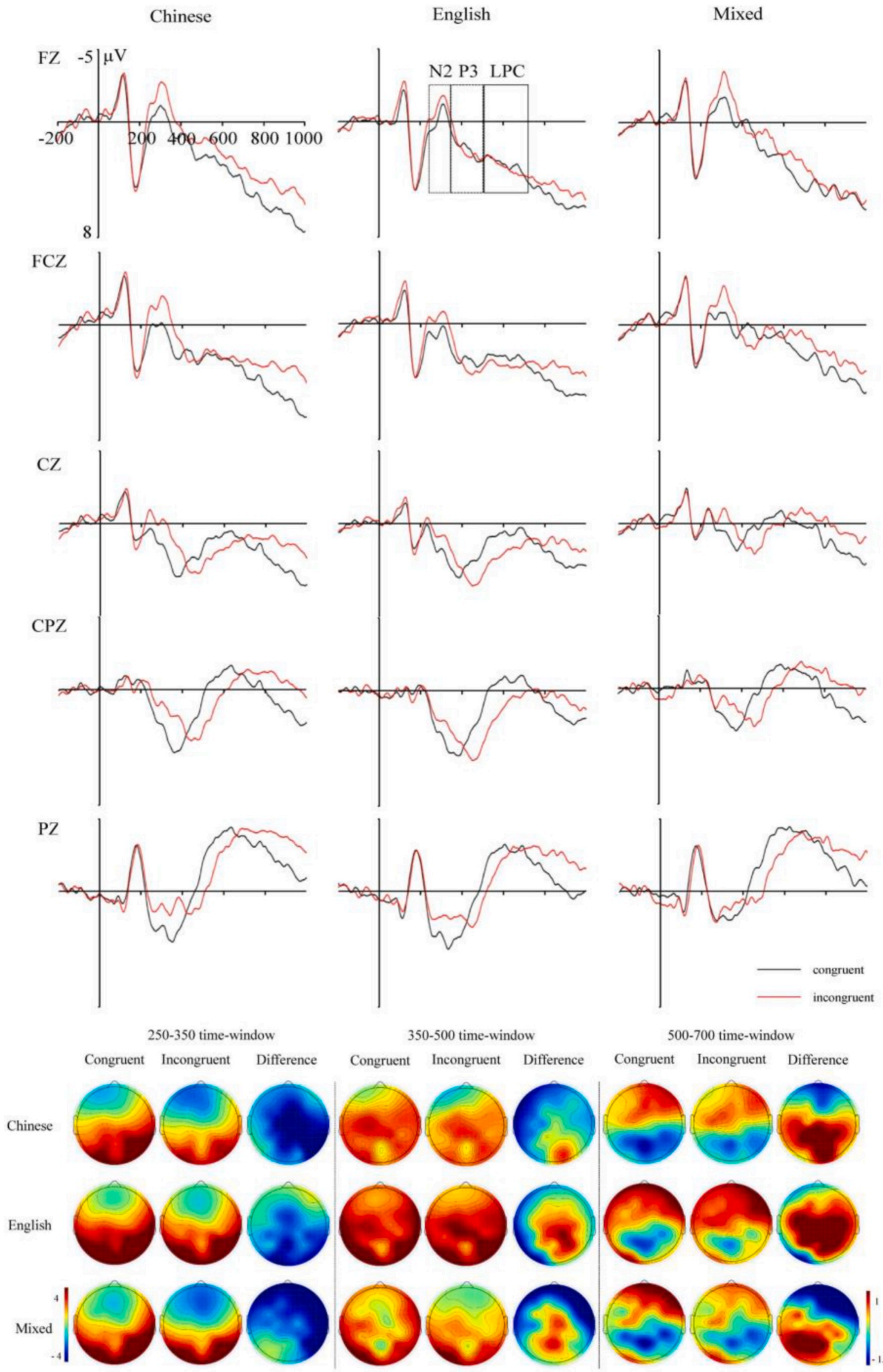

Fig. 4. Grand average waveforms (upper panel) and topographic maps (lower panel) of congruent and incongruent Flanker trials in L1, L2 and mixed-language contexts. The topographic maps in the Difference column represent the congruency effect by subtracting congruent trials from incongruent trials.

Table 4
Fixed effects estimates of mixed-effects model for N2 in Flanker task.

	Estimated	SE	*t*	*p*
(Intercept)	−0.07	0.66	−0.11	0.91
Context (M vs. S)	**−1.07**	**0.44**	**−2.41**	**0.03**
Context (L1 vs. L2)	−0.94	0.22	0.99	0.34
Congruency (C vs. I)	**1.25**	**0.22**	**−4.35**	**< 0.001**
Context (M vs. S): Congruency (C vs. I)	−0.41	0.46	−0.88	0.38
Context (L1 vs. L2): Congruency (C vs. I)	0.33	0.53	0.61	0.54

Note: M = Mixed-language context; S = Single-language context (average of L1 and L2 context); C = congruent; I = incongruent. The bold items represent the significant effects in Flanker task.

Table 5
Fixed effects estimates of mixed-effects model for P3 in Flanker task.

	Estimated	SE	*t*	*p*
(Intercept)	**2.32**	**0.73**	**3.19**	**0.005**
Context (M vs. S)	**−1.68**	**0.61**	**−2.77**	**0.01**
Context (L1 vs. L2)	0.39	0.44	0.88	0.39
Congruency (C vs. I)	0.17	0.21	0.80	0.42
Context (M vs. S): Congruency (C vs. I)	0.16	0.44	0.37	0.32
Context (L1 vs. L2): Congruency (C vs. I)	0.51	0.51	1.00	0.32

Note: M = Mixed-language context; S = Single-language context (average of L1 and L2 context); C = congruent; I = incongruent. The bold items represent the significant effects in Flanker task.

Table 6
Fixed effects estimates of mixed-effects model for LPC in Flanker task.

	Estimated	SE	*t*	*p*
(Intercept)	0.34	0.66	0.51	0.62
Context (M vs. S)	**−1.45**	**0.58**	**−2.50**	**0.02**
Context (L1 vs. L2)	0.30	0.46	0.64	0.53
Congruency (C vs. I)	**1.26**	**0.39**	**3.20**	**0.005**
Context (M vs. S): Congruency (C vs. I)	−0.58	0.49	−1.19	0.23
Context (L1 vs. L2): Congruency (C vs. I)	0.45	0.56	0.79	0.43

Note: M = Mixed-language context; S = Single-language context (average of L1 and L2 context); C = congruent; I = incongruent. The bold items represent the significant effects in Flanker task.

4. Discussion

In the current study, we explored the modulatory effect of language production contexts on executive control in a group of unbalanced bilinguals. We created three types of language production contexts, namely L1, L2, and mixed-language contexts, and compared the behavioral and electrophysiological data during a modified Flanker task that interleaved a picture-naming task. There were two main findings. First, despite no behavioral differences between languages contexts, the modulatory effect of language production context on executive control was evident in the ERP data. Compared to the single-language contexts, the mixed-language context elicited larger N2 amplitudes and smaller P3 and LPC amplitudes across congruent and incongruent trials of the Flanker task. Secondly, for the picture-naming task, a smaller LPC amplitude was observed for the mixed-language context than the single-language contexts.

4.1. The effect of language context on executive control

Language context has been widely emphasized and examined in the bilingualism literature, as exemplified by the language-mode continuum framework (Grosjean, 2012) and the adaptive control hypothesis (Green and Abutalebi, 2013). While language context studies typically concentrate on the bilingual language control domain (Liu et al., 2019), others have begun to examine how these contexts affect domain-general executive control (Adler et al., 2019; Jiao et al., 2019). In the present study, we provide ERP evidence for the modulatory effect of language production context on executive control.

As mentioned in the Introduction, there are two approaches commonly used to examine the cross-talk between bilingual language control and executive control. One approach is to examine the short-term effect of task-induced language contexts on executive control within a group of bilinguals (Adler et al., 2019; Jiao et al., 2019; Wu and Thierry, 2013), and the other is to examine the long-term effect of bilingual experience on executive control by comparing different groups of bilinguals (Beatty-Martínez et al., 2019; Hartanto and Yang, 2016). Using the first approach, our findings not only reveal the effect of language context on the Flanker task, but also reveal how contexts affect language control. In line with previous studies examining the short-term effect of language context, the facilitative effect of mixed-language context on executive control was evident in the ERP results of the

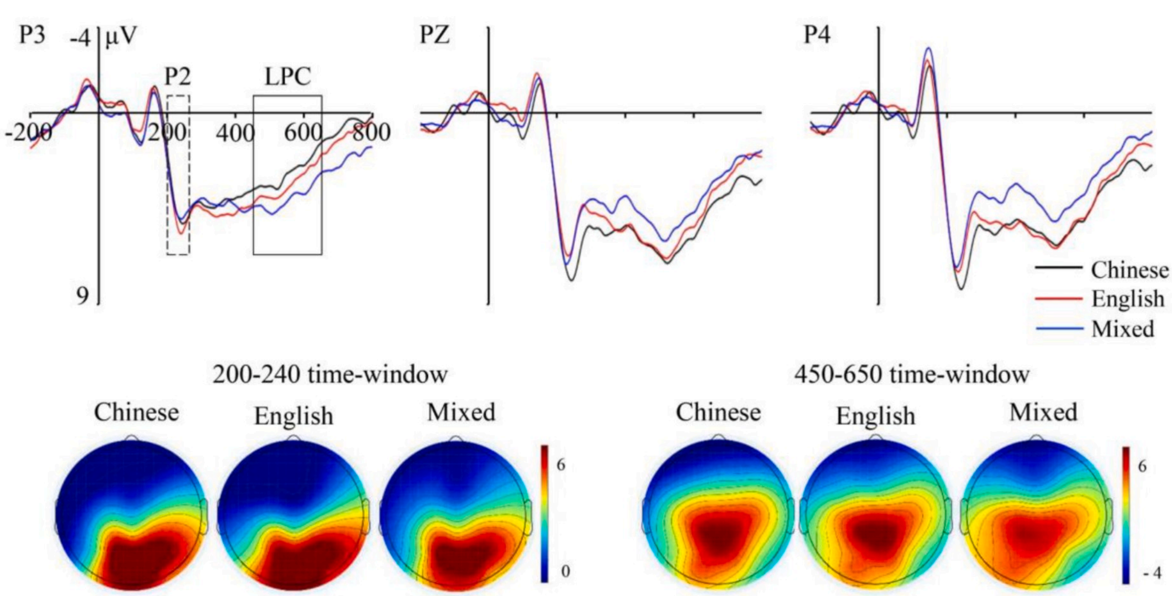

Fig. 5. Grand average waveforms and topographic maps of picture naming task in L1, L2 and mixed-language contexts.

present study. Previous work has shown that language contexts in comprehension can influence performance on a Flanker task within a group of bilinguals (Jiao et al., 2019). The behavioral results from Jiao and colleagues showed that compared to single-language contexts, participants responded faster on the Flanker task in a mixed-language comprehension context, and this facilitative effect appeared on both congruent and incongruent trials. This study suggests that for language comprehension, mixed-language contexts facilitate domain-general cognitive monitoring given the global performance enhancement across trial types. Consistently, Adler et al. (2019) investigated the short-term effect on executive control by manipulating a sentence comprehension task, and revealed that reading code-switched sentences facilitated ensuing conflict resolution of Flanker trials.

Moreover, in an ERP study, Wu and Thierry (2013) showed that language context affected domain-general cognition, but this effect was constrained to incongruent trials on the Flanker task. Lower error rates and reduced P3 amplitudes were observed in the mixed-language context. The reduced P3 amplitude in Wu and Thierry (2013) suggests that language context may influence response suppression of irrelevant information. But in the present study, we found larger N2 amplitudes on the Flanker task across congruent and incongruent trials. Larger N2 amplitudes may reflect the need to rely more on the conflict monitoring mechanisms to identify the critical feature of target stimulus (van Veen and Carter, 2002).

It is interesting to note that the findings of our study are consistent with some studies examining the effect of language comprehension context on executive control (Adler et al., 2019; Jiao et al., 2019), but not consistent with the study of Wu and Thierry (2013). It may be related to the similarity and distinction between comprehension and production. Given the parallel activation of two languages, bilinguals have to rely on some control processes to resolve competition between languages during both comprehension and production contexts (Kroll et al., 2015). As such, both comprehension and production contexts have shown that bilingual language control affects the executive control system (Adler et al., 2019; Jiao et al., 2019; Wu and Thierry, 2013). However, to some extent, the distinct language control demands between comprehension and production results in inconsistent effects on executive control (Blanco-Elorrieta and Pylkkänen, 2016; Declerck and Philipp, 2018; Mosca and de Bot, 2017). Specifically, the present study focuses on language production contexts by presenting a picture-naming task, and examines the local control and global control during language production. During the mixed -language production context of the present study, participants need to rely on the monitoring mechanism to detect the cue of each trial in order to name pictures in the correct language, eliciting a context effect on domain-general monitoring. On the other hand, Wu and Thierry (2013) presented a word stimulus before each flanker trial, with no need for any response, and only found an effect of mixed-language context on incongruent trials. This pattern of results suggest that a mixed-language context might enhance the specific ability to inhibit irrelevant information, but that production requires an additional monitoring mechanism that influences all trial types. In sum, the language context effect on executive control is closely related to the language control processes in different contexts.

4.2. The role of local control during the mixed-language context

Another focus of the present study was to determine the source of facilitation on executive control in the mixed-language context. Based on previous studies, one possible explanation is that switching between languages during the mixed-language context affects the ensuing executive control. For example, Verreyt and colleagues examined the role of language proficiency and language switching on executive control performance (Verreyt et al., 2016). This study compared the behavioral performance on a Flanker and a Simon task among three bilingual groups differing in language background, i.e., unbalanced bilinguals (non-proficient and non-switching), balanced non-switching bilinguals (proficient but non-switching), and balanced switching bilinguals (proficient and switching). The balanced switching bilinguals outperformed the other two groups, with no group differences between unbalanced and balanced non-switching bilinguals, suggesting the crucial role of language switching for executive control performance. Importantly, combined with the ERP results of picture naming task in the present study, the local control reflected by comparing single-language and mixed-language contexts plays an indispensable role. According to the LPC amplitude in the picture-naming task, the distinct language control processes between single-language and mixed-language contexts might occur in the lexical selection phase of language production (Liu et al., 2016; Martin et al., 2013). When two languages are mixed within a block (i.e., mixed-language context), bilinguals have to monitor the critical feature of each linguistic stimulus and then access the target language system. In turn, bilinguals in single-language contexts have been informed of the target language in advance, without any language switching demands, leading to less reliance on cognitive monitoring.

An alternative explanation of the findings in the present study is that all participants are unbalanced bilinguals with a dominant native language. Given that these participants spend most of their time immersed in a single-language context, especially in home, the bilingual language control in the mixed-language context is more difficult and costly than in single-language contexts. This was reflected the different LPC amplitude in picture naming task. Hence, one possibility for the effect of the mixed-language context is that the mixed-language context was a more difficult linguistic task that required executive control, and executive control was then ramped-up for the subsequent Flanker task.

Unlike Wu and Thierry (2013), the present study failed to provide behavioral evidence for an effect of language context on Flanker task performance. Compared with previous studies focusing on task-induced language contexts, this limitation may be related to the prolonged stimulus interval between the linguistic task and the following Flanker task that weakened the context effect. Nonetheless, our ERP data provide preliminary evidence that mixed-language production contexts affect executive control processes. Future studies are encouraged to examine the conditions and parameters that lead to both behavioral and ERP modulations.

4.3. Theoretical implications

The results presented here support an adaptive control view of how language context in production affects executive control. As postulated by the adaptive control hypothesis, bilinguals adaptively trigger control mechanisms in accordance to the current language context (Green and Abutalebi, 2013). In the present study, when faced with different control demands during single-language and mixed-language contexts, bilinguals appear to adaptively enhance executive control on the Flanker task. The adaptive nature of these control processes suggests that studies wishing to examine electrophysiological responses that result from bilingualism need to take into account not only the long-term effects of bilingualism, but also the immediately relevant cues that change the course of control processes. According to the BAPSS model (Grundy et al., 2017a), greater bilingualism generally leads to earlier and more automatic processing over time on executive control tasks like the Flanker task. As such, greater bilingualism usually leads to larger N2 and smaller LPC amplitudes. The present study suggests that these adaptations may not be evident until contextual cueing of the bilingual experience (i.e., mixed-language context in the present study) is in place. Larger N2 and smaller LPC amplitudes were only evident in the mixed-language context. Thus, long-term outcomes predicted by BAPSS and other models might not be evident until cued by the appropriate context.

5. Conclusion

The present study sheds light on the cross-talk between language control and domain-general executive control in bilinguals by showing that executive control is affected by language contexts in production. Compared to single-language contexts, mixed-language contexts enhance efficiency on both congruent and incongruent trials of the Flanker task by triggering reliance on earlier cognitive processing and lessening the need for later more controlled and demanding processing. In other words, control demands cued by language contexts affect subsequent executive control processes.

CRediT authorship contribution statement

Lu Jiao: Methodology, Formal analysis, Writing - original draft. **John G. Grundy:** Writing - original draft. **Cong Liu:** Methodology, Formal analysis. **Baoguo Chen:** Methodology, Writing - original draft.

Acknowledgments

This work was supported by funding of National Natural Science Foundation of China (31970976) for Baoguo Chen.

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