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Comprehension-based language switching in experienced and newly learned languages: Evidence from induced brain oscillations

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ABSTRACT

When speaking and listening, bilinguals have the ability to seamlessly switch between their two languages using complex control processes. In the present study, we use electroencephalography (EEG) and time-frequency representation (TFR) analyses to investigate comprehension-based switching between experienced and newly learned languages. Bilinguals performed an auditory picture-word matching task in two experienced languages (Chinese and English) and in two newly learned languages (German and Japanese). The behavioral results revealed asymmetrical switch costs when switching between experienced languages, with larger costs in Chinese than in English, but no costs between the two newly learned languages. The results of the TFR analyses found that for the experienced languages, switch trials induced a power decrease in delta and theta bands, while for the two newly learned languages, switch trials led to a power decrease in the theta and alpha bands. The findings underscore the dynamic nature of language control and provide evidence for the Dynamic Restructuring Model.

1. Introduction

A common phenomenon that is often investigated in studies on bilingual language processing is the ability for bilinguals to fluently alternate between their two languages with relative ease (Bosma & Pablos, 2020; Liu, Timmer, Jiao, & Wang, 2020; Timmer, Christoffels, & Costa, 2019). Many of these studies have examined the underlying processes that facilitate this ability, particularly during production-based language switching, and it is widely accepted that inhibitory control plays a key role (Green, 1998; Liu et al., 2016, 2017). However, much less is known about the cognitive control mechanisms involved in comprehension-based language switching (Declerck, Koch, Duñabeitia, Grainger, & Stephan, 2019; Declerck & Philipp, 2018; Struys, Woumans, Nour, Kepinska, & Van den Noort, 2019). Furthermore, the scant number of studies examining comprehension-based language switching have used behavioral or traditional event-related potentials (ERPs) analyses (Liu et al., 2016), making it unclear as to whether these methods are robust enough to make inferences about cognitive control during language switching (Fernandez, Litcofsky, & van Hell, 2019; Pérez & Duñabeitia, 2019; Xie, Li, Zhang, & Liu, 2019). As such, in the present study we investigate comprehension-based language switching by collecting electroencephalography (EEG) data and measuring neural oscillations using time-frequency representation (TFR)

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analysis.

The theoretical motivation of the present study stems from the Dynamic Restructuring Model (DRM, Pliatsikas, 2020). The DRM emphasizes the structural plasticity of the bilingual brain through three stages: An initial exposure stage, a consolidation stage, and a peak efficiency stage. The model proposes that structural adaptations are dynamic and depend on the quantity and quality of language learning and experiences with language switching (Pliatsikas, 2020). For example, initial exposure to a language may cause changes to the cortical areas involved in vocabulary acquisition, semantic/conceptual learning, and executive control. According to the DRM, with increased language experience, the bilingual brain optimizes the mechanisms for controlling and switching between languages, reflecting the variability and dynamicity of bilingual language control. Similarly, DeLuca, Rothman, Bialystok, and Pliatsikas (2019) describe bilingualism as a spectrum of language experiences and offer empirical evidence revealing that the bilingual brain efficiently adapts to be able to control two (or more) languages in a variety of communicative situations. Accordingly, in the present study, our aim is to investigate the dynamicity of comprehension-based language control. Specifically, we conduct both behavioral and TFR analyses to explore language switching at two very different points on the bilingual spectrum: switching between experienced languages and switching between two newly learned languages.

1.1. Comprehension- and production-based language switching

A common paradigm used to investigate language switching requires that participants name or listen to names of pictures in lists. The picture naming/listening trials are considered either repeat trials (i.e., trials whose response language is the same as the previous trial) or switch trials (i.e., those whose response language is different than the previous trial) (Linck, Schwieter, & Sunderman, 2012, 2020; Liu et al., 2019; Schwieter & Sunderman, 2008). A switch cost, calculated by subtracting mean reaction times (RTs) of repeat trials from switch trials, has been used as an index of bilingual language control, with most evidence showing larger switch costs when switching into a more-dominant language (Costa & Santesteban, 2004; Meuter & Allport, 1999).

In the bilingualism literature, research on production-based language switching has received widespread attention and has supported the critical role of inhibitory mechanisms in production-based language switching (see Green's, 1998, Inhibitory Control Model). Some studies have consistently found the presence of production-based switch costs, suggesting that bilinguals inhibit the non-target language to accurately switch into the target language (Kang, Ma, & Guo, 2018; Liu et al., 2016, 2019; Peeters, Runnqvist, Bertrand, & Grainger, 2014). Moreover, empirical evidence has also revealed the close relationship between domain-general cognitive control and language control in production (Jiao, Grundy, Liu, & Chen, 2020; Kang, Ma, Li, Kroll, & Guo, 2020). For instance, Liu et al. (2016) trained bilinguals on an inhibition task and found that the enhancement of nonverbal inhibition improved language switching performance. Linck, Schwieter, and Sunderman (2020) focused on English- French-Spanish group and examined the relationships between different executive control and production-based language switching. Specifically, participants were asked to complete a picturing naming task involving three languages and a series of cognitive control tasks measuring working memory updating, inhibitory control, and task switching. The results revealed that better inhibitory control was related to smaller switch costs, whereas better working memory was related to larger switch costs, suggesting different contributions of domain-general cognitive control to language control processing.

However, the control mechanisms in comprehension-based language switching are less clear, and it may not be appropriate to infer what processes are involved in comprehension-based language control based on findings from production-based switching research. For example, Blanco-Elorrieta and Pylkkänen (2016) compared these two types of language switching and revealed distinct engagement of production- and comprehension-based language control. The production-based language switching recruited dorsolateral prefrontal regions bilaterally reflecting the engagement of inhibition, while comprehension-based language switching mainly recruited anterior cingulate cortex signifying the engagement of monitoring.

Moreover, the limited amount of research on comprehension-based language switching has been inconsistent with respect to language control mechanisms in comprehension-based language switching. Some studies propose that there is no engagement of language control as interpreted by the absence of comprehension-based switch costs (Declerck et al., 2019; Declerck & Philipp, 2018). However, other studies have reported the presence of switch costs during comprehension through asymmetrical patterns between the L1 and L2. For example, Alvarez, Holcomb, and Grainger (2003) asked unbalanced English-Spanish bilinguals to perform a semantic categorization task in their two languages. This task consisted of three experimental trials: L1-L1/L2-L2 repetition trials where the items were the same word in the same language; L1-L2/L2-L1 repetition trials in which the items were the same concept but in different languages; and first representation trials where the item in preceding trial was a different word. The results showed that an asymmetrical pattern was observed in ERP measures with larger costs when switching into the L2. This reversed symmetry in comprehension-based switching can be explained by the Bilingual Interactive Activation model (BIA, Grainger & Dijkstra, 1992), which emphasizes that language control in comprehension exhibits exogenous control driven by stimuli. Compared to the dominant language (L1), more time is needed to reach the "recognition threshold" of the less-dominant language (L2), resulting in larger L2 switch costs.

Furthermore, based on the Dynamic Restructuring Model (Pliatsikas, 2020) and previous empirical evidence (Olson, 2017; Timmer et al., 2019), these inconsistent findings for comprehension-based language switching may be due to adaptive changes in language control processes (see Green & Abutalebi, 2013 to read more on the adaptive control hypothesis). For instance, Declerck et al. (2019) conducted a series of switching tasks that examined several variables (e.g., stimuli, bilingual group) and found that the language control mechanism (inhibition or monitoring mechanism) did not always occur during comprehension-based language switching, which may be related to the activation of the two languages, individual differences among the bilinguals, and other factors. The dynamicity of bilingual language control implies that bilingualism can be treated and measured as a continuum of experiences, and incorporating switching between new and experienced languages is an important step towards doing so.

1.2. Language switching and EEG evidence

Several studies have explored the neurocognitive mechanisms of language switching by using EEG and ERP techniques because of their high temporal resolution. ERP studies have revealed that the N2 component (around 200–300 ms after stimulus onset) and the late positive component (LPC, around 400–600 ms after stimulus onset) are associated with language switching in bilinguals (Christoffels, Firk, & Schiller, 2007; Dong & Zhong, 2017; Grundy, Anderson, & Bialystok, 2017; Jackson, Swainson, Cunnington, & Jackson, 2001; Liu et al., 2016; Timmer et al., 2019). The N2 effect represents the language task schema competition phase, while the LPC effect is linked to the lexical selection response phase of bilingual language control (Liu et al., 2016; Timmer et al., 2019). Evidence from ERPs during production-based language switching tasks has revealed differences between switch and repeat trials for both the N2 and the LPC. To our knowledge, only a few studies have examined the neurocognitive mechanisms of comprehension-based language switching using EEG. For example, one study looked at the role of language context in picture-word matching tasks by comparing electrophysiological activity during monolingual and bilingual contexts (Jiao, Liu, de Bruin, & Chen, 2020). The ERPs results showed that the bilingual switching context elicited an earlier N2 effect and a larger LPC effect compared to the monolingual context, suggesting the engagement of language control mechanisms during comprehension. Similarly, Shi, Xiao, Yan, and Guo (2023) examined language switching when bilinguals comprehended L1/L2 emotional words. The ERPs results revealed a larger LPC effect for L2 switch trials compared to L2 repeat trials.

Recently, a few EEG studies on language switching have begun to employ TFR analyses to decompose EEG signals into different frequencies. Traditional analyses of ERPs measure time-related responses to stimuli and extract the time- and phase-locking components from EEG signals. However, the brain's electrical activity in the frequency domain (e.g., the oscillatory responses to stimuli) can validly reflect different cognitive processes (Kamarajan et al., 2004). The core advantage of TFR analyses is that the energy content of signals is assigned to the time-frequency two-dimensional space (Liu et al., 2017). Therefore, compared to analyses of static average responses of ERPs (Keil et al., 2022), TFR analyses can better examine how oscillatory responses at various frequencies of EEG signals evolve over time, providing a precise delineation of the temporal dynamics involved in cognitive processing (Jiang, Cai, & Zhang, 2022).

In the language switching literature, there are three frequency bands that have received wide attention, namely the delta, theta, and alpha bands (Fernandez et al., 2019; Liu et al., 2017). Low-frequency oscillations (delta, 1–3 Hz and theta, 4–7 Hz) are active when processing speech rhythm phase entrainment (Rossi & Prystauka, 2020). Increased delta oscillation is associated with segmentation or identification of intonation phrases (Giraud & Poeppel, 2012; Meyer, 2018) and in the generation of syntactic phrases (Meyer, Henry, Gaston, Schmuck, & Friederici, 2017). Neural oscillations in the theta-band are closely related to language-specific effects. For instance, increased theta oscillation is linked to the retrieval of semantic-related information (Bastiaansen, Oostenveld, Jensen, & Hagoort, 2008). Liu et al. (2017) investigated production-based language switching in a picture naming task performed by two groups of bilinguals, one with higher and one with lower inhibitory control abilities. TFR analyses on delta and theta bands revealed that bilinguals with higher inhibitory control abilities exhibited decreased power in the theta band for L1 switch trials. This pattern did not emerge for bilinguals with lower inhibitory control, indicating an association between theta oscillations and word-level control during language switching. Alpha-band oscillations (8–13 Hz) have been implicated in cognitive processes such as verbal working memory (Meyer, 2018) and the intelligibility of spoken words (Obleser & Weisz, 2012). In particular, increases in alpha oscillation are closely related to increased listening effort and difficulties in semantic processing (Fernandez et al., 2019), along with enhanced cognitive load in inhibiting irrelevant information (Foxe & Snyder, 2011; Jensen & Mazaheri, 2010).

Taken together, TFR analyses are an important tool in uncovering the cognitive mechanisms of language processing, and have been widely used in psycholinguistic literature (Bastiaansen et al., 2008; Jiang et al., 2020; Liu et al., 2017). However, to our knowledge, only a handful of EEG studies have focused on time-frequency distributions of comprehension-based language switching. Even though analyses on static ERPs have examined language switching mechanisms during comprehension in the time domain, TFR analyses can explore oscillatory dynamics of brain signals and can capture cognitive processing operations that originate from neuronal activity at different frequencies, times, and locations.

1.3. Present study

The present study utilizes EEG technology and TFR analyses to investigate the neurocognitive mechanisms of comprehension-based language switching. Given the dynamic changes of control mechanisms associated with bilingualism (DeLuca et al., 2019; Pliatsikas, 2020), we examined language control processes for both experienced languages (Chinese and English) and for newly learned languages (German and Japanese). In addition to collecting behavioral data, we recorded electrophysiological activity and analyzed oscillatory dynamics of EEG signals using TFR. Based on previous studies in bilingual language switching and the traditional times windows of the N2 and the LPC, we measured three oscillations as power modulations in different frequency bands (delta, 1–3Hz; theta, 4–7Hz; alpha, 8–13Hz). We expect that delta and theta oscillations will increase in the Chinese-English switching task due to the less difficulty in retrieving lexical-semantic information in proficient languages (Jensen & Mazaheri, 2010; Obleser & Weisz, 2012). Furthermore, we expect that during switching between newly-learned languages (German and Japanese), the interference effect of the two experienced languages will be reflected by changes in alpha-band oscillations.

2. Method

2.1. Participants

Twenty-two Chinese-English bilinguals (aged 18–25 years old, M = 21.4, SD = 1.9) were recruited from Beijing Normal University. Data from four participants were excluded: three because of excessive EEG artifacts and one who failed to complete the study. The final number of participants included 18 bilinguals, none of whom had any prior experience with or knowledge of Japanese or German words. We administered a language questionnaire in which participants assessed their Chinese and English language skills. These self-ratings were given on a 6-point scale with "1" being least proficient and "6" being most proficient. *T*-tests revealed significant differences between Chinese and English ratings for listening, speaking, reading, and writing (see Table 1). Although these differences imply that Chinese was significantly more proficient than English, the participants reported starting to learn English at the mean age of 8.83 years old and that they used it daily, albeit less frequently than Chinese.

Research ethics was approved by the Committee of Protection of Subjects at Beijing Normal University. All participants provided written informed consent and confirmed that they had normal or correct-to-normal vision and hearing. None of them had neurological or psychological impairments.

2.2. Procedure, materials, and tasks

The present study consisted of three phases. During the first phase, participants provided their written informed consent and completed a language proficiency questionnaire. They were also administered a comprehension-based switching task in Chinese and English in which they were required to identify whether pictures shown on a computer screen matched word auditorily presented through headphones. We chose to conduct the Chinese-English switching task in the first phase to exclude the potential confounding effect of learning new languages on control processes. In the second stage, which took place over six consecutive days, participants learned Japanese and German words via pictures and sounds. Finally, during the third phase, participants completed a comprehension-based German-Japanese switching task. EEG data were collected during the switching tasks in the first and third phases. Below we provide more details about the procedure and materials of these three phases.

Phase 1: Comprehension-Based Chinese-English Switching Task. An auditory picture-word matching task (Jiao, Liu, Schwieter, & Chen, 2021; Jiao, Liu, et al., 2020) was used to measure comprehension-based language switching processes. The task consisted of three blocks, with 1 filler trial and 60 experimental trials in each block. In the trials, participants heard a word through headphones and saw a picture on a computer screen at the same time. They were asked to identify whether the word they heard matched the picture by pressing a response key. Participants were asked to press the "Z" button for matching trials, and the "M" button for mismatching trials. The response keys were counterbalanced across participants. The picture stimuli consisted of 60 black-and-white line drawings, which were selected from Snodgrass and Vanderwart's (1980) standardized picture set (normalized by Zhang & Yang, 2003). Most of Chinese names of picture stimuli were two-character words with their English equivalents ranging from 3 to 8 letters in length (4.7 ± 1.4). The auditory stimuli (i.e., spoken words either matching or not with the pictures) were recorded by a male speaker in a soundproof room.

For each trial, the procedure was the following: A fixation point was presented on the computer screen for 500 ms; a word was heard through the headphone at the same time as a picture appeared and remained on the screen until the participant responded with a key press or a maximum duration of 2000 ms; and a blank screen appeared for 1000 ms. The next trial then began and followed the same procedure until the end of the block. A brief break was given between each of the three blocks. There were four conditions of interest in the switching task: Language (Chinese vs. English) and Trial Type (Repeat vs. Switch). In repeat trials, the target language was the same as the previous trial and in switch trials, the target language was different than the previous trial (e.g., switching from English to Chinese and vice versa). The number of trials of each condition was equal in the three experimental blocks. Before the formal experiment, participants were allowed to familiarize themselves with the Chinese and English names of pictures in order to reduce error rates. Moreover, there were eight practice trials before the experiment to familiarize participants with the experimental procedures.

Phase 2: Six Days of Learning New Words in German and Japanese. Starting the day after Phase 1 and during the next six days, all participants learned 30 German words and 30 Japanese words. These 60 words corresponded to the names of the same pictures that formed part of the Chinese-English switching task in Phase 1. Participants learned German and Japanese words in a non-lab environment (e.g., school dormitory, classroom) via a learning video in which the pictures and sounds were present, but not their written form. The learning sessions lasted approximately 15 min per day. Immediately prior to administering the German-Japanese switching

Table 1
Mean self-ratings (and SDs) of L1 Chinese and L2 English proficiency.

	Chinese L1	English L2	*t*
Reading	4.78 (.73)	2.72 (.96)	9.99[a]
Writing	4.67 (.84)	2.83 (1.38)	8.42[a]
Speaking	5.33 (.48)	3.17 (1.10)	9.33[a]
Listening	5.78 (.43)	3.44 (1.15)	8.33[a]

[a] $p < .001$.

task, we asked participants to perform a language comprehension task in German and in Japanese to assess the learning outcomes of new words without the demands of switching. In the task, participants were asked to identify whether the word they heard in the headphones matched the picture presented on computer screen. The results showed that accuracy in both languages was very high (German: 94.7%, SD = 4.0; Japanese: 92.3%, SD = 4.8).

Phase 3: Comprehension-Based German-Japanese Switching Task. The picture stimuli and procedure of the German-Japanese switching task was the same as the Chinese-English switching task, except that the words were auditorily presented in Japanese or German. The auditory stimuli (i.e., spoken words in German and Japanese) were recorded by the same speaker who recorded Chinese and English spoken words. We only report oscillation results from the TFR analyses in the present study; the ERP results of the German-Japanese switching task have been reported elsewhere (Jiao, Duan, Liu, & Chen, 2022).

2.3. Data recording and analyses

Electrophysiological Recording and Preprocessing. EEG data were recorded at a sampling rate of 1000 Hz from 64 electrodes placed according to the extended 10–20 positioning system. EEG data preprocessing was performed offline using EEGLAB (Delorme & Makeig, 2004) and impedances were kept below 5 kΩ. Data was filtered online with a bandpass between .05 and 100 Hz and filtered offline with a bandpass between 1 and 30 Hz. Data was referenced online to the tip of the nose and re-referenced offline to the average of the bilateral mastoid. Ocular artifact reduction was performed through independent component analysis. The continuous data were segmented into −500 ms–1500 ms epochs. Epochs with voltages exceeding ±80 μV were excluded from the final analyses.

Behavioral Data Analyses. For RTs, data from filler trials and incorrect responses were not included in the behavioral analyses. These responses totaled 5.99% of the data. Furthermore, RTs ±2.5SD from the overall mean were excluded, totaling 2.44% of the data. A linear mixed-effects model was conducted on RTs with three within-subject factors: task (switching between experienced vs. newly learned languages), language (Chinese vs. English; Japanese vs. German), and trial type (repeat vs. switch). All variables were sum coded: task (experienced = −.5; newly learned = .5); language (Chinese and German = −.5; English and Japanese = .5); and trial type (repeat = −.5, switch = .5). Following this, in order to examine language control patterns in comprehending Chinese/English words and in comprehending German/Japanese words, post-hoc tests were conducted on the language and trial type effects from each of the two switching tasks.

Time-Frequency Representation Analyses. TFR analyses were used for frequencies between 1 and 30Hz by applying a Hanning taper with a 200 ms window, followed by a Fourier transform in steps of 1 ms and 1 Hz (Fernandez et al., 2019; Litcofsky & van Hell, 2017; Liu et al., 2017). Neural oscillations were calculated for each trial and averaged across trials for each condition and participant separately. Power changes were computed relative to a 200 ms baseline (−300 ms to −100 ms). In line with previous relevant studies, we chose FCZ as our electrode of interest (Cavanagh, Cohen, & Allen, 2009; Liu et al., 2017). Separate analyses were performed on the three frequency bands of interest, namely delta (1–3Hz), theta (4–7Hz), and alpha (8–13Hz). Based on prior ERP studies on language switching (Jackson et al., 2001; Jiao, Liu, et al., 2020; Liu et al., 2017), we conducted TFR analyses on the 200–270 ms and 400–600 ms time-windows corresponding to the N2 and LPC. Thus, a three-way repeated-measure ANOVA (task, language, and type variables) on the mean power was conducted for each frequency band of interest.

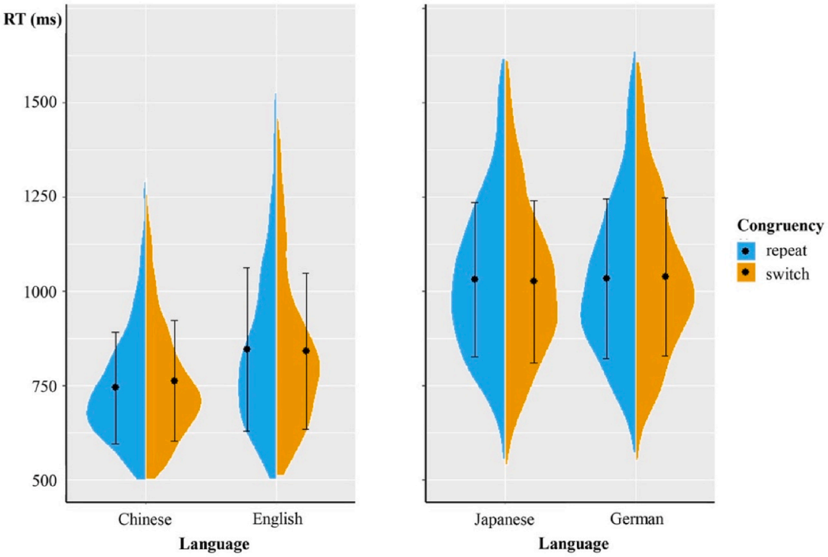

Fig. 1. Split Violin Plots for RTs in the Chinese-English Switching Task (left) and German-Japanese Switching Task (right). Black dots represent mean values and thin vertical black lines represent the standard deviation.

3. Results

3.1. Behavioral results

Fig. 1 presents the RTs of the two switching tasks. The best-fitting model included task, language, type, and their interactions as fixed effects, with a by-subject random slope for task and a by-item random slope for language as random effects.

Table 2 shows the fixed effects structure of the RTs model. The results demonstrated a significant main effect of task, indicating that the response speed when switching between newly learned languages (i.e., German-Japanese) (M = 1032 ms) was slower than when switching between experienced languages (i.e., Chinese-English) (M = 798 ms), $t = 8.25$, $p < .001$. There was also a significant three-way interaction between task, language, and type ($t = 2.10$, $p = .03$), suggesting distinct language control patterns for the two switching tasks. Specifically, in the experienced Chinese-English switching task, the main effect of type was marginally significant ($t = -1.95$, $p = .05$), with slower responses in switch trials (M = 802 ms) than in repeat trials (M = 795 ms). The main effect of language was also significant ($t = 5.61$, $p < .001$), with slower responses in English (M = 844 ms) than in Chinese (M = 754 ms). Moreover, the interaction between language and type ($t = -2.81$, $p = .005$) revealed larger switch costs in Chinese ($M_{cost} = 18$ ms) than in English ($M_{cost} = -5$ ms). However, in the German-Japanese switching task, the main effect of language ($t = -.25$, $p = .80$), the main effect of type ($t = .12$, $p = .90$), and their interaction ($t = -.05$, $p = .96$) did not reach significance.

3.2. Time-frequency results

Figs. 2 and 3 represent participants' oscillatory activity during the Chinese-English and the German-Japanese switching tasks, respectively. Fig. 4 presents the switching costs per language that were calculated by subtracting the oscillation powers of repeat trials from switch trials.

Delta Power (200–270 ms). As in the behavioral analyses, the ANOVA on delta power included the within-subject variables of task, language, and type (see Table 3). The results showed a significant effect of task, $F(1, 17) = 10.09$, $p = .006$, $\eta_p^2 = .37$, with the Chinese-English switching task inducing larger delta power than the German-Japanese switching task. A significant main effect of language, $F(1, 17) = 8.23$, $p = .01$, $\eta_p^2 = .33$, was accompanied by an interaction between task and language, $F(1, 17) = 8.19$, $p = .01$, $\eta_p^2 = .32$. There was also a significant main effect of type, $F(1, 17) = 11.98$, $p = .003$, $\eta_p^2 = .41$. Moreover, the three-way interaction between task, type, and language showed trends towards significant differences [$F(1, 17) = 3.92$, $p = .06$, $\eta_p^2 = .19$], suggesting that the two switching tasks may recruit different control processes.

Moreover, we conducted separate ANOVAs on the two switching tasks to further examine the control mechanisms of comprehension-based language switching. The analysis on the Chinese-English switching task showed a significant main effect of language, indicating larger delta power in Chinese than in English, $F(1, 17) = 9.75$, $p = .006$, $\eta_p^2 = .36$. A significant main effect of type revealed that switch trials reduced delta power compared to repeat trials, $F(1, 17) = 8.99$, $p = .008$, $\eta_p^2 = .35$. There was no interaction between language and type during the Chinese-English switching task, $F(1, 17) = .25$, $p = .62$, $\eta_p^2 = .02$. For the German-Japanese switching task, there were no significant main effects or interactions ($ps > .05$).

Theta Power (200–270 ms). Analogous to the above analysis, a three-way ANOVA showed a significant main effect of task such that Chinese-English switching induced larger theta power than German-Japanese switching, $F(1, 17) = 4.96$, $p = .04$, $\eta_p^2 = .23$. There were also significant main effects of type, $F(1, 17) = 12.58$, $p = .002$, $\eta_p^2 = .42$, suggesting that switch trials induced smaller theta power than repeat trials, and a main effect of language, $F(1, 17) = 8.58$, $p = .009$, $\eta_p^2 = .34$. Moreover, the three-way interaction was marginally significant [$F(1, 17) = 3.74$, $p = .07$, $\eta_p^2 = .18$]. Further analyses revealed that the effects of type were significant for both the Chinese-English, $F(1, 17) = 6.63$, $p = .02$, $\eta_p^2 = .28$, and German-Japanese switching tasks, $F(1, 17) = 6.90$, $p = .02$, $\eta_p^2 = .29$, revealing a switch cost between repeat and switch trials. The effect of language was significant in the Chinese-English switching task [$F(1, 17) = 5.20$, $p = .04$, $\eta_p^2 = .23$], but not in the German-Japanese switching task, $F(1, 17) = 2.34$, $p = .14$, $\eta_p^2 = .12$. There was no other significant effect on theta power.

Alpha Power (200–270 ms). The three-way ANOVA on alpha power revealed a main effect of type, $F(1, 17) = 5.26$, $p = .04$, $\eta_p^2 = .24$, showing that switch trials induced smaller alpha power than repeat trials. Separate analyses were conducted to further explore

Table 2
Estimates of fixed effects for RTs mixed-effects model.

	Estimated	SE	*t*	*p*
(Intercept)	921.41	19.93	46.22	<.001
Task	232.63	28.18	8.25	<.001
Language	43.05	12.16	3.54	<.001
Type	−5.56	5.07	−1.09	.27
Task × Language	−94.87	24.31	−3.90	<.001
Task × Type	15.96	10.14	1.57	.11
Language × Type	−19.63	10.14	−1.93	.05
Task × Language × Type	42.64	20.29	2.10	.03

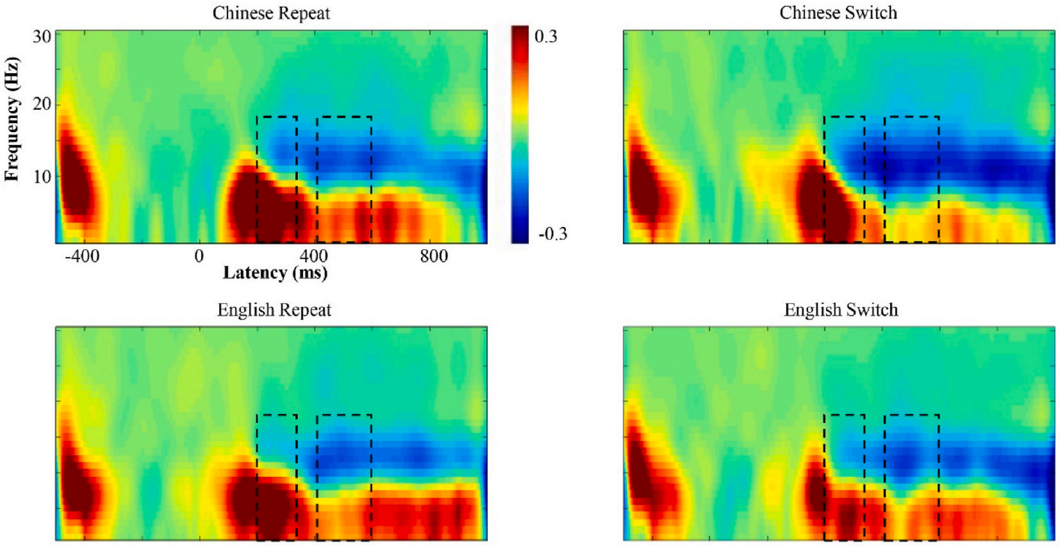

Fig. 2. Time-frequency distribution plots for oscillatory activity in repeat and switch trials in the Chinese-English switching task.

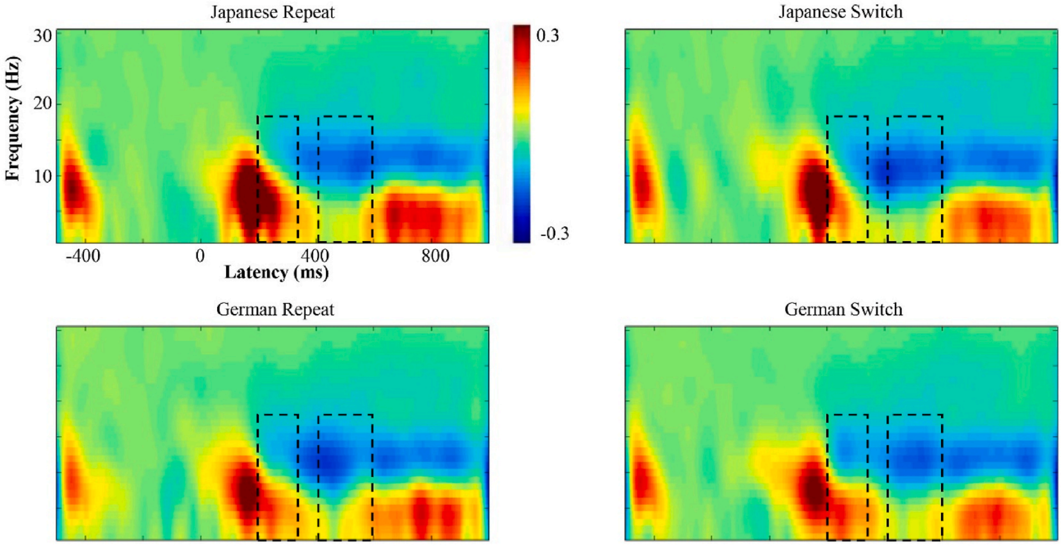

Fig. 3. Time-frequency distribution plots for oscillatory activity in repeat and switch trials in the German-Japanese switching task.

differences in language control between the Chinese-English and German-Japanese switching tasks. A two-way ANOVA on the Chinese-English switching task showed that neither the significant main effects [language: $F(1, 17) = .59$, $p = .45$, $\eta_p^2 = .03$; type: $F(1, 17) = 1.87$, $p = .19$, $\eta_p^2 = .10$], nor the interaction [$F(1, 17) = .03$, $p = .86$, $\eta_p^2 = .002$] were significant. However, the analyses on the German-Japanese switching task revealed significant effects of language [$F(1, 17) = 7.52$, $p = .01$, $\eta_p^2 = .31$] and type [$F(1, 17) = 5.28$, $p = .03$, $\eta_p^2 = .24$], but the interaction was not significant [$F(1, 17) = .52$, $p = .48$, $\eta_p^2 = .03$].

Taking together, the analyses on the early time window (200–270 ms) showed that Chinese-English language switching mainly induced changes in delta and theta power, whereas German-Japanese switching primarily induced changes in theta and alpha power.

Delta Power (400–600 ms). As in the above analyses on the 200–270 ms time window, we conducted a three-way ANOVA on delta, theta, and alpha power during the 400–600 ms window (see Table 4). The results showed a significant main effect of task, with larger delta power in Chinese-English switching than German-Japanese switching, $F(1, 17) = 10.63$, $p = .005$, $\eta_p^2 = .38$. A significant effect of type showed smaller delta power in switch trials than repeat trials, $F(1, 17) = 9.86$, $p = .006$, $\eta_p^2 = .37$. Moreover, the interaction between language and type was significant, $F(1, 17) = 5.47$, $p = .03$, $\eta_p^2 = .24$, and a three-way interaction between type, language, and task was marginally significant, $F(1, 17) = 3.38$, $p = .08$, $\eta_p^2 = .16$. Further analyses showed that in the German-Japanese

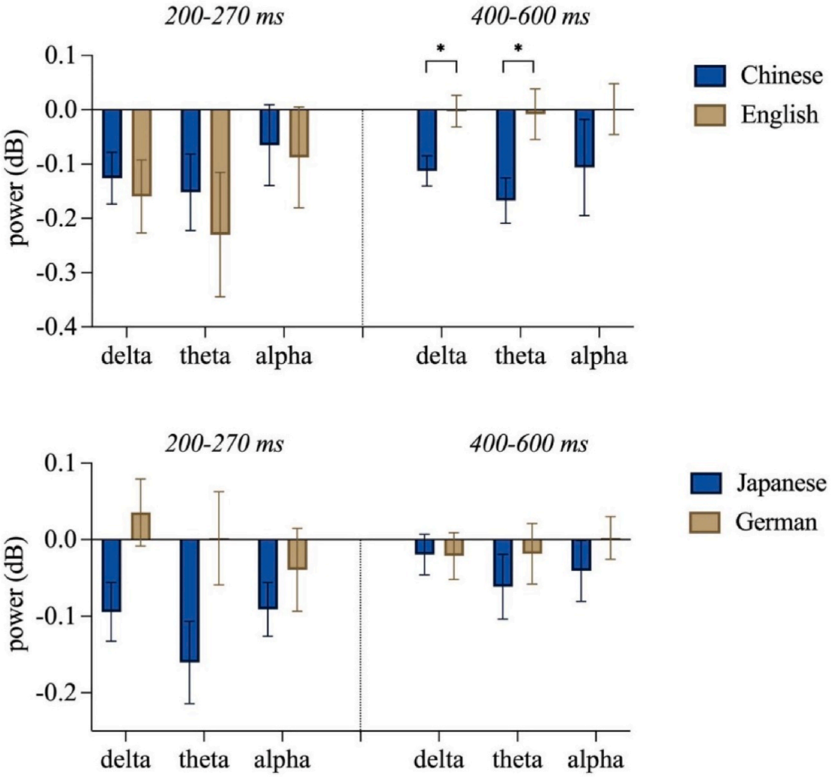

Fig. 4. Plots for language switching costs in the Chinese-English (top) and German-Japanese (bottom) switching tasks.

Table 3
Results of time-frequency representation in the 200–270 ms time-window.

	Delta		Theta		Alpha	
	F	η_p^2	F	η_p^2	F	η_p^2
Task	10.09[c]*	.37	4.96[b]	.23	.56	.03
Language	8.23[b]	.33	8.58[c]	.34	4.39[a]	.20
Type	11.98[c]	.41	12.58[c]	.42	5.26[b]	.24
Task × Language	8.19[b]	.32	2.00	.10	.29	.02
Task × Type	4.08[a]	.19	1.77	.09	.03	.002
Language × Type	.81	.04	.22	.01	.02	.001
Task × Language × Type	3.92[a]	.19	3.74[+]	.18	.70	.04

[a] $p < .1$.
[b] $p < .05$.
[c] $p < .01$.

switching task, there were no significant main effects or interactions ($ps > .05$). However, for the Chinese-English switching task, the main effect of type, $F(1, 17) = 7.07, p = .02, \eta_p^2 = .29$, and the interaction between language and type, $F(1, 17) = 8.77, p = .01, \eta_p^2 = .34$, were both significant. These results suggest that switch costs are larger in Chinese compared to English. There was no other significant effect on delta power.

Theta Power (400–600 ms). The analyses on theta power during the 400–600 ms time window showed a main effect of type, $F(1, 17) = 8.31$, $p = .01$, $\eta_p^2 = .33$, and an interaction between language and type, $F(1, 17) = 4.87$, $p = .04$, $\eta_p^2 = .22$. We once again conducted separate ANOVAs on the two switching tasks and found that in the Chinese-English switching task, there was a significant main effect of type, $F(1, 17) = 9.21, p = .007, \eta_p^2 = .35$, and a significant interaction between language and type, $F(1, 17) = 5.71, p = .03, \eta_p^2 = .25$, suggesting larger switch costs in Chinese than in English. However, there was no significant effect or interaction in the German-Japanese switching task ($ps > .05$).

Alpha Power (400–600 ms). With respect to alpha power changes in the 400–600 ms time window, the ANOVAs revealed no main effects for task, $F(1, 17) = .02, p = .89, \eta_p^2 = .001$, language, $F(1, 17) = 1.84, p = .19, \eta_p^2 = .10$, or type, $F(1, 17) = 1.31, p = .27, \eta_p^2 = .07$. Furthermore, there was no significant effect observed in the separate ANOVAs on the two switching tasks ($ps > .05$).

Table 4
Results of time-frequency representation in the 400–600 ms time-window.

	Delta		Theta		Alpha	
	F	η_p^2	*F*	η_p^2	*F*	η_p^2
Task	10.63[c]	.38	3.82[a]	.18	.02	.001
Language	.91	.05	1.62	.09	1.84	.10
Type	9.86[c]	.37	8.31[c]	.33	1.31	.07
Task × Language	.003	.001	.02	.010	.48	.03
Task × Type	1.16	.06	1.76	.09	.52	.03
Language × Type	5.47[b]	.24	4.87[b]	.22	1.12	.06
Task × Language × Type	3.38[a]	.16	1.80	.10	.78	.04

[a] $p < .1$.
[b] $p < .05$.
[c] $p < .01$.

4. Discussion

To better understand the neurocognitive mechanisms involved in comprehension-based language switching, the present study employed a picture-word matching task among bilinguals in their experienced languages (Chinese and English) and in two newly learned languages (German and Japanese). We then analyzed their behavioral data (i.e., RTs) and electrophysiological data (i.e., neural oscillations) at two different time windows. The behavioral performance revealed switch costs in the Chinese-English switching task, but not in the German-Japanese switching task, suggesting that there are different language control patterns when switching between experienced versus newly learned languages. The results from the TFR analyses revealed that switching between the experienced languages induced changes in delta and theta power, while switching between newly learned languages led to changes in theta and alpha power.

An important finding from the present study is that switching between experienced languages and switching between newly learned languages differentially modulated language control patterns during bilingual comprehension. Globally speaking about the behavioral performance of two tasks, there were significantly slower RTs in the German-Japanese task compared to the Chinese-English task. This finding was expected given that these participants had been learning Chinese and English for many years whereas they had only been exposed to German and Japanese words for six days. Notably, the behavioral performance revealed asymmetrical switch costs in Chinese-English but not in German-Japanese. This asymmetry in the Chinese-English task showed that switching to Chinese was more costly than switching into English, suggesting that comprehension-based switch costs were modulated by switching direction. This finding is in line with previous research from the bilingual production literature demonstrating that switching into a more dominant language is slower than into a less-dominant language (Costa & Santesteban, 2004; Meuter & Allport, 1999; Schwieter & Sunderman, 2008). The important role of switching direction has also been implicated in bilingual comprehension studies of code-switched sentences (Bosma & Pablos, 2020), underscoring the engagement of language control mechanisms particularly when switching between Chinese and English (Liu et al., 2016; Timmer et al., 2019).

Additional support for the behavioral findings came from TFR analyses which revealed that neural oscillations in the Chinese-English switching task differed from those observed in German-Japanese switching. When switching between two experienced languages (Chinese-English), switch trials induced a significant power decrease in delta and theta frequency bands. Importantly, in the LPC time window, the oscillatory changes in delta and theta power were also modulated by the language into which participants switched, with more power decrease in Chinese than in English. Previous studies have interpreted low-frequency oscillations (delta- and theta-bands) as neural markers of lexical-semantic retrieval processes (Bastiaansen et al., 2008; Obleser & Weisz, 2012), as well as speech error monitoring (Piai & Zheng, 2019). Given the LPC effect in ERPs studies reflecting the lexical selection response phase (Green, 1998; Liu et al., 2016), the presence of switch costs in RTs and modulizations of oscillatory activity in the present study indicate that comprehension-based language control may occur in a specific lexical selection phase and may work together with error monitoring mechanisms in order to access accurate word meaning in the two languages (Jiao, Liu, et al., 2020; Struys et al., 2019). In addition to the theta oscillation changes that are related to language-specific processing, the TFR results in the German-Japanese switching task revealed a significant decrease in alpha power in switch trials, suggesting that switching between new languages may engage inhibitory mechanisms during the early time window. Taken together, the behavioral and EEG findings both suggest that the cognitive mechanisms of comprehension-based language switching may be different for newly learned versus experienced languages.

The presence of language switch costs in comprehension-based tasks is in line with previous work (Jiao, Liu, et al., 2020; Struys et al., 2019). Struys et al. reported a correlation between forward switching costs (i.e., costs associated with L1-to-L2 switching) and domain-general monitoring abilities, which is consistent with the patterns of switching between experienced languages in the present study. Given the co-activation of two languages during comprehension, bilinguals may employ a control mechanism to fluently access the target language system (Marian & Spivey, 2003). Furthermore, during speech comprehension, to some extent, the activation level of target words might exert control on other word representations that are not part of the target language (see BIA model, Grainger & Dijkstra, 1992; Dijkstra & Van Heuven, 2002). Considering the unbalanced proficiency between Chinese and English of our participants, the asymmetrical switch costs observed in Chinese-English switching may originate from dynamic interference with target language lexical-semantic access.

However, a few behavioral studies have reported an absence of language switch costs in comprehension-based tasks (Declerck et al., 2019; Declerck & Philipp, 2018). Declerck et al. (2019) put forward a processing speed account which argues that switch costs do not arise due to fast processing speeds during language comprehension tasks. Faster processing speeds implies that less time is required to adjust activation level of languages, resulting in very small, if any switch costs. However, this explanation cannot account for our findings. If faster language processing minimizes the costs associated with switching in a comprehension-based task, the Chinese-English switching task should have revealed smaller switch costs compared to the German-Japanese switching task. Instead, our results showed the reverse.

Our findings can be explained through the adaptive perspective of bilingual language control. As the DRM proposes (Pliatsikas, 2020), language control is not static, but rather, it is a dynamic process that is shaped by language learning and experiences with various bilingual phenomena such as language switching. The variability and dynamicity of language control mechanisms in comprehension are clearly observable when considering two very different stages of the bilingualism continuum. The unbalanced proficiency of two languages triggers control mechanisms to different degrees, resulting in the modulation of switch costs (Bosma & Pablos, 2020). Thus, in the present study, when comparing switching between two experienced languages and switching between two newly learned languages, it is not surprising that we found distinct language control patterns. It is likely that when switching between two newly learned languages, there was stronger irrelevant information competing (e.g., concepts and words from the two experienced languages) which in turn required more inhibitory control as was reflected by higher oscillatory activity in the alpha-band.

Alpha power changes have been linked to the intelligibility of spoken words (Obleser & Weisz, 2012; Shahin, Picton, & Miller, 2009) as well as to difficulty of semantic retrieval (Fernandez et al., 2019). For instance, Obleser and Weisz (2012) manipulated the intelligibility of auditorily presented words and asked participants to then assess how comprehensible they were. The results revealed a correlation between alpha power changes and comprehension ratings. In the present study, the significant language effect found in the German-Japanese switching task (i.e., RTs were faster in German compared to Japanese), may come from differences in word intelligibility in the two languages, particularly because learning accuracy in Japanese (92.3%) was lower than in German (94.7%), $t(17) = 2.77$, $p = .01$. Given that the alpha effect is also involved in memory-related processes, another possible explanation for our findings is that the alpha power changes may reflect certain difficulties in accessing newly learned German and Japanese words.

5. Limitations

It is worth noting that comparing language switching patterns of experienced and newly-learned languages may involve inherent issues of bilingualism versus multilingualism in which only one (bilingualism) or more than one language (multilingualism) can potentially interfere with learning a new language. For example, Tomoschuk, Duyck, Hartsuiker, Ferreira, and Gollan (2021) asked Dutch-English-French trilinguals to perform a phoneme monitoring task. The results showed that L3 phoneme monitoring suffered more language interference from the L2 than from the more proficient L1. Moreover, the newly-learned L3 showed similar language interference when bilinguals learned the L3 when the language of instruction was their L1, but not when it was their L2. Based on these results, one possible explanation for our findings is that language switching between the newly-learned languages (German and Japanese) might be differentially affected by the participants' L1 and L2. However, unlike the study by Tomoschuk et al. (2021), bilinguals in the present study learned new languages through target pictures and sounds, without the presentation of Chinese or English translations. Therefore, to some extent, German-Japanese switching under these conditions may be independent of the L1 and L2 due to their different proficiency levels. Nonetheless, we must acknowledge that the six days of learning sessions do not represent an extensive amount of acquisition of and exposure to German and Japanese, and thus, the proficiency in these two languages cannot be compared to their Chinese and English proficiencies. Future studies should consider longitudinal research which would allow for tracking changes in language switching patterns from the earliest to most proficiency stages.

Another limitation in the present study is that our sample only included unbalanced bilinguals and thus, we cannot make a prediction about whether similar patterns will emerge for balanced bilinguals. Indeed, it may be the case that different degrees of language dominance may also affect language control pattern. Future work may wish to include a wide spectrum of proficiency levels to examine deeper the variable nature of language control across developmental stages of bilingualism. Moreover, we acknowledge that the sample size was relatively small in the present study. Although our analyses are accompanied by effect sizes, future studies should endeavor to include larger samples.

6. Conclusion

Language switching is a common phenomenon in bilingual communication. However, previous studies have mainly examined the control mechanisms that underpin language switching through production-based tasks. In the context of the dynamic continuum of language experiences that characterize bilingualism, in the present study we examined behavioral and neurocognitive responses in comprehension-based language switching tasks. The behavioral analyses identified differential patterns of language control for switching between experienced versus newly learned languages. TFR analyses further showed that switching between *experienced languages* mainly induced changes in oscillatory power in the delta and theta bands, reflecting the retrieval of lexical-semantic information. Switching between *newly learned languages* elicited changes in the alpha band, signifying the engagement of functional inhibitory control. Future research should consider using TFR analyses to further investigate the neurocognitive mechanisms of bilingual language control.

Finally, an important contribution of the present study is firstly, despite accumulating studies on the neurocognitive mechanisms involved in production-based language switching, work being done on comprehension-based language switching remains scant. Our study contributes toward filling this gap and provides a potential explanation based on recent discussions (DeLuca et al., 2019). Given that our findings showed distinct oscillatory activity when controlling experienced languages compared to newly learned languages, the present study has highlighted the adaptive nature of bilingual language control, offering support for the Dynamic Restructuring Model (Pliatsikas, 2020) in the domain of bilingual comprehension.

CRediT authorship contribution statement

Lu Jiao: Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **John W. Schwieter:** Writing – review & editing. **Cong Liu:** Writing – review & editing, Writing – original draft, Visualization, Funding acquisition, Formal analysis, Conceptualization.

Data availability statement

The data and code used in this study are available from the corresponding author upon reasonable request.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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