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Neural correlates of compound head position in language control: Evidence from simultaneous production and comprehension

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Research Article

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Abstract

Compound words consist of two or more words which combine to form a single word or phrase that acts as one. In English, the head of compound words is usually, but not always, the right-most root (e.g., "paycheck" is a noun because the head, "check," is a noun). The current study explores the effects of head position on language control by examining language switching performance through electroencephalography (EEG). Twenty-one pairs of Chinese (L1)–English (L2) bilinguals performed cued language switching in a simultaneous production and comprehension task. The results showed that bilinguals recognized the head position earlier both in production and comprehension. However, the language control of the head position during production occurred in the middle stage (N2), but in the late stage (LPC) during comprehension. These findings indicate that the head position in compound words exerts differential influences on language control.

1. Introduction

Bilinguals often find themselves switching between their two languages depending on their communicative situations. Studies investigating the cognitive nuances of this ability often have employed the language switching paradigm in which participants use one of two or more languages according to a pre-determined cue (e.g., a colour association) (Abutalebi, 2008; Abutalebi & Green, 2007; Blanco-Elorrieta et al., 2018; Blanco-Elorrieta & Pylkkänen, 2016; Declerck et al., 2012, 2017; Linck et al., 2012; H. Liu et al., 2019; L. Liu et al., 2022; Schwieter & Sunderman, 2008). This body of research demonstrates that language switching is complicated by the need to understand and produce the target language in the context of interference from the non-target language. To overcome such cross-language interference, language control mechanisms are deployed (Green, 1998).

Language control can be indexed by a LANGUAGE SWITCHING COST, which is calculated as the difference between performance (in speed and accuracy) on language switching trials and non-switching (repeat) trials. A higher switching cost indicates a greater difference between switching trials and repeat trials, and that non-target language interference during language switching is not well controlled. In the past two decades, research has focused on how bilinguals produce a language while preventing interference from other languages, as well as the phases of language switching. In addition to cross-language interference, other language features may play a role in language switching. Compound words, and, in particular, their head position, present one variable that merits investigation. Most languages use compound words as a morphological operation to create new lexical items (Pollatsek et al., 2011). In compounds, at least two words are combined to form a single lexical item or phrase. One of these words acts as a functional head and the other word as a modifier (Bisetto & Scalise, 2005). For example, in both English and Chinese, there are head-final compounds consisting of verb + noun (e.g., "playground", "操场"), and head-initial compounds formed by a noun + verb (e.g., "sunrise", "日出"). It is possible that bilingual performance may be influenced by the compound head position in language switching. Below we discuss in more detail this possibility and our motivation to examine it.

1.1 Background

An interesting question arises regarding how the privileged status of the head constituent influences language control during bilingual communication. Some results have indicated that head position has an important effect on processing compound words. Semenza et al. (2011) explored the reading of compound words among Italian speakers with left-sided neglect dyslexia to assess the influence of headedness. The left neglector omits or substitutes the first component more often than the second component, and the second component largely retains its integrity. The participants were asked to read each word aloud. The results revealed fewer neglect errors made on head-initial compounds compared to head-final compounds. In a study by Jarema et al. (2010), English–French aphasics conducted a reading, repetition, and translation task with isolated compound words. The results showed that there were fewer errors on heads than modifiers in French head-initial compounds. However, for English head-final compounds, errors were similarly distributed across the head and the modifier.

A recent behavioral study by Contreras-Saavedra et al. (2021) explored the impact of head position on language switching. In the study, German–English–Spanish trilinguals participated in a cued picture-naming task with compound words. German has only head-final (noun + verb) compounds, Spanish has only head-initial (verb + noun) compounds, and English has both. The data only analyzed two types of English head position trials, with language switching being from German or Spanish to English, and language non-switching being limited to English. The results showed an interaction between head position switching and language switching – that is, when the target was a head-final word, larger switch costs emerged on head position-repetition trials (head-final to head-final) than on head position-switch trials (head-initial to head-final). This finding indicates that language control is influenced by head position. Moreover, their study demonstrated larger switch costs in head-final compound trials than in head-initial compound trials. The Inhibitory Control Model (ICM; Green, 1998) argues that switching between languages requires inhibition to suppress cross-language interference. The dominant language causes more interference for the non-dominant language than vice versa, and thus requires more inhibition. When switching back to the dominant language, overcoming this relatively large inhibition leads to larger switch costs. Contreras-Saavedra et al. (2021) applied the logic of the ICM to study morpheme dominance structures, believing that the presence of larger switch costs in a morphological structure is considered an indicator of dominant morphological structures. The authors found that larger switch costs are observed for head-final compounds than for head-initial compounds, indicating that head-final compounds appear to be more dominant than head-initial compounds. Both Jarema et al. (2010) and Contreras-Saavedra et al. (2021) have explored the role of compound head position in bilingual/trilingual language processing. Jarema et al. (2010) examined one unique head position in each language, while Contreras-Saavedra et al.'s study (2021) analyzed compounds with two head positions. Cross-language interferences could not be ruled out based on their findings. When switching to English, the head-final compound is the dominant structure, but to our knowledge, there has been no research exploring whether there is a head position preference when switching to Chinese.

At the same time, previous studies on head position have mostly focused on behavioural techniques and explicit measures, and thus, cannot reveal the specific phases at which head position affects language control. Furthermore, these effects may also be influenced by the processing method of compound words. There are several studies focusing on whether a compound: is represented holistically (i.e., the compound is represented as one entity within the mental lexicon) (Aitchison, 2012; Miozzo et al., 2015; Osgood & Hoosain, 1974; Silva & Clahsen, 2008; Strijkers et al., 2010, 2017; Zyzik & Azevedo, 2009); is decomposed (i.e., two compositions of compounds are represented separately in the mental lexicon) (Li et al., 2017; Taft & Forster, 1975, 1976; Uygun & Gürel, 2017); or is a hybrid combination of both (Pinker, 2015; Pinker & Ullman, 2002; Sandra, 1990, 2020; Zhou & Marslen-Wilson, 1995). Thus, in the present study, we use EEG technology to examine two languages, Chinese and English, which have head-initial and head-final compounds, respectively, to explore preferences for head position and the role that it plays in bilingual language control.

The Bilingual Interactive Activation Model from a Developmental perspective (BIA-d; Grainger et al., 2010) argues that both bilingual production and comprehension require activation of the target language node and inhibition of non-target language lexical representations. However, the control pathways between production and comprehension are distinct. In production, endogenous control operates via top-down activation to ensure that only lexical representations in the target language are selected for output, while inhibiting non-target word representation. In comprehension, exogenous control arises via automatic bottom-up activation of language nodes through lexical representations, and the subsequent inhibition of non-target lexical representations.

These hypotheses have been supported by evidence from separate production and comprehension electrophysiological studies. First, language switching tasks at the level of both production and comprehension have yielded N2 effects. It has been found that inhibition may help to resolve cross-language schema interference (e.g., target language selection) as reflected by the finding that switch trials trigger more pronounced N2 effects than non-switch trials (Jackson et al., 2001; Zheng et al., 2020). Second, language switching studies examining production and comprehension have revealed Late Positive Component (LPC) effects. The LPC has been posited to reflect inhibition of non-target lexical representations, as shown by the finding that switch trials evoke larger LPC amplitudes than non-switch trials (Jackson et al., 2001; Jiao et al., 2020, 2022; H. Liu et al., 2016). Simultaneous bilingual production and comprehension involves inhibitory control, also indexed by an LPC. For example, the study by H. Liu et al. (2018) asked pairs of bilinguals to collaboratively complete a cued picture-naming task. The cue phase guides selection of the target language task schema, and the picture naming phase involves the selection of the target lexicon. The researchers found that, for both production and comprehension, switching from the L1 to the L2 elicited larger LPC amplitudes than the reverse. These results indicate that inhibition occurred at the lexical selection phase. Moreover, LPC modulation is associated with more strategic/explicit and controlled aspects of semantic retrieval, integration, and revision, with larger LPC amplitudes potentially being triggered by an increase in semantic control (Amsel & Cree, 2013; Fang & Perfetti, 2017; Kounios et al., 2009; Rohaut et al., 2015). Third, the P2 component is also sensitive to the difficulty of lexical access as demonstrated by a strong positive correlation between naming latencies and mean P2 amplitudes (Branzi et al., 2014; Costa et al., 2009; Strijkers et al., 2011).

1.2 Present study

The current study investigates the influence of head position on language control in bilingual communication using EEG hyperscanning technology. Hyperscanning is a technique that permits measurement of the neural activity of interacting dyads. In our study, we recorded EEG activity from pairs of Chinese–English bilinguals as they simultaneously completed a production and comprehension task in which one individual participated in a cued picture-naming task (production) and the other individual completed a cued head judgment task (comprehension). Our hypotheses are that behavioral performance (i.e., reaction times (RTs) and accuracy) are sensitive to different preferences for head position. For example, participants may have a preference for head-final compounds in English, as reflected by faster and more accurate performance on head-final trials than on head-initial trials. The preference for head position in Chinese is currently unknown, so it may be the same or different from English. Future research may be able to reflect head position preference in Chinese by analyzing RTs and accuracy. Moreover, we expect that the ERP components will show that head position has an impact on language control in production and comprehension – for example, there may be switching costs on N2 or LPC in head-final trials. This said, the results may also indicate that head-final compounds are the dominant structure. However, due to the different control methods of the two modalities (i.e., production is top-down; comprehension is bottom-up – see BIA-d Model of Grainger et al., 2010), the role of head position in language control may vary. For instance, production occurs in early (P2) and/or mid stages (N2), while comprehension occurs in later stages (LPC). Finally, we assume that compound words are processed sequentially or in a hybrid way that combines decomposed forms and whole forms. This permits us to measure the impact of head position on language control.

2. Method

2.1 Participants

The calculated sample size was 16 using G.power 3.1.9.7 (Faul et al., 2007) according to the following settings: *F*-tests > ANOVA: Repeated measures, within factors, Effect size $f = .25$ (medium effect size), α error probability = .05, correlation among repeat measures = .5, Power (1-β error probability) = .8, Number of groups = 1, Number of measurements = 8, and non-sphericity correct ∈ = 1. To avoid the reduction of effect size due to invalid subject data, 27 dyads of unbalanced Chinese (L1)–English (L2) bilinguals were recruited to participate in the study and were paired arbitrarily. All participants were right-handed with normal or corrected-to-normal vision and had no history of neurological, psychiatric, or major somatic disorders. Six dyads were excluded from the study because of excessive EEG data artifacts during the preprocessing stage. Thus, the final sample included 21 dyads (18 pairs of females, $M_{age} = 22$ years, $SD_{age} = 2$ years, 3 pairs of males, $M_{age} = 26$ years, $SD_{age} =$ 2 years). The research protocol was approved by the Research Center of Brain and Cognitive Neuroscience at Liaoning Normal University and all participants provided their written informed consent prior to taking part in the study.

Table S1 shows characteristics of the participants' objective and subjective language proficiency. The objective proficiency level of English was tested by the Oxford Quick Placement Test (QPT) (Syndicate, 2001). The average scores among the participants in the present study was 34, indicating a lower intermediate L2 proficiency (see Table S2 for English proficiency criteria of the QPT). The participants also completed a subjective questionnaire in which they provided self-ratings of their L1 and L2 abilities in listening, speaking, reading, and writing. The ratings were based on a seven-point scale in which "7" indicated "perfect knowledge" and "1" indicated "no knowledge". Paired sample *t*-tests showed that the proficiency ratings were significantly higher for the L1 compared to the L2 in listening, speaking, reading, and writing. These ratings and QPT scores both indicate that the participants are Chinese–English unbalanced bilinguals with intermediate L2 proficiency. Both proficiency measures were completed before administering the joint production-comprehension task.

2.2 Materials

The stimuli consisted of 28 white-and-black line drawings representing compound words (see Table S3 and Figure S1). Among them, half were head-initial (i.e., noun-verb) combinations like "sunrise" and the other half was head-final (i.e., verb-noun) combinations like "playground." An additional eight compound words (4 head-initial and 4 head-final) were used in practice trials. A separate group of participants ($N = 23$) who did not take part in the formal experiment, but who were from the same research population, rated their familiarity with the experimental words. Their ratings were based on a 9-point scale on which "1" meant "least familiar" and "9" meant "most familiar." Table S4 shows the means and standard deviations of the familiarity ratings for the experimental words. A two-factor within-subject ANOVA was performed on the familiarity ratings with language (L1, L2) × head position (head-initial, head-final) as factors. There was no main effect of language (L1: $M = 8.03 \pm .40$, L2: $M = 8.01 \pm .47$), $F(1,13) = .24$, $p = .633$, $\eta^2 = .02$, or of head position (head-initial: $M = 7.98 \pm .47$, head-final: $M = 8.06 \pm .39$), $F(1,13) = .19$, $p = .670$, $\eta^2 = .01$. Moreover, the interaction between language and head position was not significant, $F(1,13) = .004$, $p = .953$, $\eta^2 < .001$, suggesting that there were no differences in familiarity of head position across the two languages.

To ensure that there were no differences in the semantic transparency of the compound word stimuli, participants, the same as $N = 23$ participants in the previous paragraph, were asked to rate the semantic overlap of the heads (e.g., between "sun" and "sunrise"), modifiers (between "rise" and "sunrise"), and whole compounds ("sun + rise" and sunrise) on a 9-point scale ("1" for low semantic overlap and "9" for very high semantic overlap). A two-factor within-subject ANOVA was performed on these ratings with language (L1, L2) and compound word components, separately for (a) the modifier, (b) the head, (c) the whole-word compound in two head position. There was no main effect of language (head: $F(1,13) = .39$, $p = .542$, $\eta^2 = .03$; modifier: $F(1,13) = .89$, $p = .364$, $\eta^2 = .06$; whole-word compound: $F(1,13) = .07$, $p = .790$, $\eta^2 = .01$), or of head position (head: $F(1,13) = 1.11$, $p = .311$, $\eta^2 = .08$; modifier: $F(1,13) = .02$, $p = .897$, $\eta^2 = .001$; whole-word compound: $F(1,13) = .51$, $p = .489$, $\eta^2 = .04$). Moreover, the interaction between language and head position was not significant (head: $F(1,13) = .08$, $p = .777$, $\eta^2 = .01$; modifier: $F(1,13) = 1.05$, $p = .325$, $\eta^2 = .07$; whole-word compound: $F(1,13) = .07$, $p = .792$, $\eta^2 = .01$). These analyses suggest that there was no difference in the transparency of heads, modifiers, or compounds corresponding to the two head conditions across the two languages.

To ensure that the participants were not confused by the classification of English words we used as stimuli, we asked another sample of participants ($N = 20$) from the same research population to evaluate the materials, including the parts of speech of the components and the compounds' heads.

The results showed that all participants believed that the head-initial compounds used in the experiment were NV structures, while the head final compounds were VN structures. The percentage of participants who believed that the compounds met the classification criteria in each condition was: 98.21% L1-head-final, 97.86% L2-head-final, 98.21% L1-head-initial, 98.21% L2-head-initial.

2.3 Design and procedure

The study is a language (L1, L2) × switching (non-switch, switch) × head position (head-initial, head-final) within-subject design and was administered using E-Prime 2.0. To create a simple interactive response for each dyad, we asked participants to perform a joint naming-listening task in which one participant (Participant A) named pictures while another (Participant B) listened and subsequently uttered the head of the compound that was heard. Each dyad wore an EEG cap and sat in the same room to perform the task. An opaque foam board (1.5 m × 1.1 m) separated Participants A and B and divided the computer screen into two equal parts.

Before the experiment, the participants were familiarized with the experimental pictures and their corresponding names in the two languages. After doing so, they participated in a practice task of 32 trials followed by the formal experiment. During the experiment, Participant A named pictures into a microphone in the L1 or L2 based on a color cue (e.g., pictures in red boxes were named in the L1 and pictures in blue boxes were named in the L2). The language-color association was counterbalanced across dyads. After hearing each word, Participant B performed a head judgement by naming the head of the compound in the same language into a microphone, regardless of the head position. The rationale for asking Participant B to provide oral responses was twofold: 1) to prevent the impact of different response modalities (oral response vs. button response) on the results, ensuring that the results of production and comprehension tasks could be compared; and 2) to elicit an interactive response that could be heard by Participant A.

There were 6 experimental blocks with 58 trials per block. Each block included 2 warm-up trials and 7 trials of each: L1-head modifier non-switch/switch, L1-modifier head non-switch/switch, L2-head modifier non-switch/switch, and L2-modifier head non-switch/switch. We formed six blocks that included pseudo-randomized non-switch and switch trials. The trials were shown in the form of pictures and were arranged based on their switching type, such that the same switching type did not appear continuously for more than two trials, and that the same picture did not appear more than once within five consecutive trials. All participants completed the same order of blocks and trials within blocks. To test potential practice effects, we divided the behavioral data into two parts and conducted separate language (L1, L2) × switching (non-switch, switch) × head position (head-initial, head-final) mixed-effects models for both production and comprehension (see Appendix S1: Testing practice effects).

Figure 1a illustrates an example of the procedure for a single trial. Each trial started with a 250 ms presentation of a red or blue square visible to both Participants A and B. After a blank screen of 500 ms, a target picture appeared. Upon seeing the target picture, Participant A uttered the name of the picture into a microphone in the L1 or the L2 according to the predetermined color cue. The picture disappeared when Participant A responded or after 2000 ms. Participant B then heard a beep at which time they named the head of the compound uttered by Participant A. The screen disappeared when Participant B responded or after 2000 ms. A blank screen appeared for a random amount of time (between 1000-1500 ms) before the next trial began.

2.4 Behavioral data analyses

Behavioral data analyses were performed on RTs and accuracy for both naming and listening. In the RT analyses, we excluded incorrect responses (e.g., wrong target word, disfluent responses, no responses, or self-corrected responses); the first two trials of each block; and responses that were < 200 ms or beyond $M \pm 3$ *SD* (within participants). The excluded data totaled 6.04% of the naming data and 7.67% of the listening task. We used R software (version 3.6) (lme4 and lmerTest package, Bates et al., 2014; Kuznetsova et al., 2017) to perform a linear mixed model for RTs and a generalized linear mixed model for accuracy. In order to make the data more in line with linear association, we performed log transformation on the RT data. We used language (L1, L2), switching (non-switch, switch), and head position (head-initial, head-final) as fixed effects. Apart from the fixed effects, the models included participants and items as random effects (random intercepts and slopes). When the models did not converge, we removed the slope that explained the least variance until they converged. We used the Akaike information criteria to determine the optimal model in which smaller values generally reflect more likely models (Symonds & Moussalli, 2011; Tremblay & Newman, 2015). We started with the most complex model and gradually reduced its complexity until it converged to the Akaike values that were smallest. The best-fitting model was: logRT ~ data$ language* data$ switching* data$ head + (1|participant). We conducted follow-up analyses when an interaction reached significance at $p < .05$.

2.5 Electrophysiological data and analyses

Electrophysiological data were recorded from each dyad using two sets of 64 electrodes placed according to the extended 10-20 positioning system. The signal was recorded from eemagine (ANT Neuro) at a rate of 500 Hz in reference to CPz electrode. The electrodes M1 and M2 were separately placed on the left and right mastoids. Impedances were kept below 5 kΩ. Offline processing was referenced to the average of M1 and M2. Electroencephalographic activity was filtered online within a bandpass between 1 and 100 Hz and refiltered offline with a high-pass filter of .01Hz and a lowpass filter of 30Hz. Finally, 40 electrodes were left after removing the peripheral electrodes with more artifacts (FPz, FP1, FP2, AF3, AF4, AF7, AF8, F7, F8, FT7, FT8, T7, T8, TP7, TP8, P7, P8, PO7, PO8, Oz, O1, O2). Ocular artifact reduction was performed through an independent component analysis using EEGLAB (Makeig et al., 1995). The mean number of independent components rejected was $1.00 \pm .73$ per participant. In the preprocessing stage, the time series of each dyad were aligned, and the number of trials retained between each condition was the same for each dyad (i.e., the data analysis included only successful simultaneous production and comprehension trials – for example, if either party deleted the trial due to artifacts or other issues, the trial of the other participant was also deleted accordingly). In production and comprehension tasks, continuous recordings were analyzed in cue-locked −100 to 700 ms epochs and naming/listening-locked −100 to 800 ms

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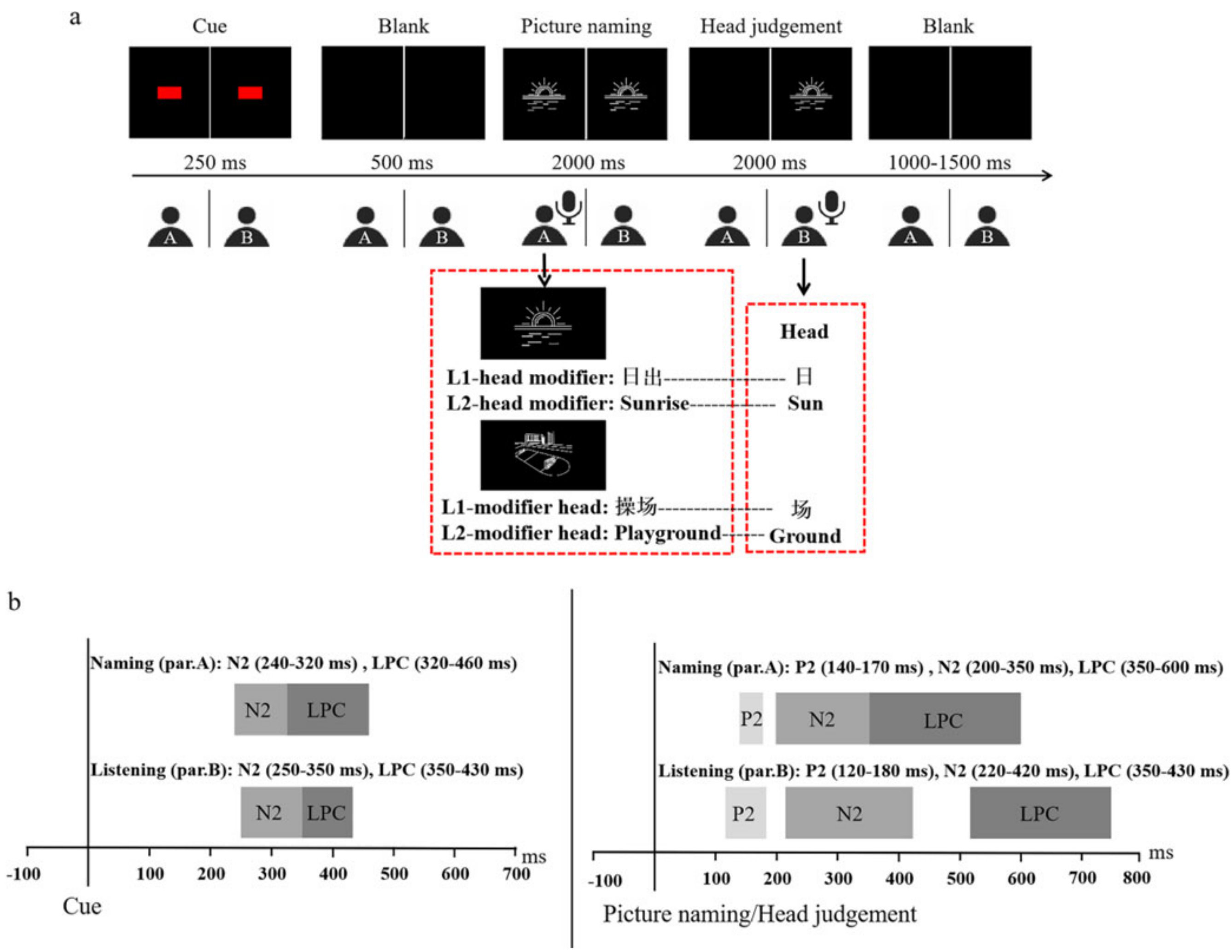

Figure 1. Procedure of an Example Trial from the Picture Naming (Participant A) and Head judgement (Participant B) Task (a); and the EEG analysis stage (b).

epochs. Correspondingly, the epochs were referenced to a 100 ms pre-stimulus baseline. Signals exceeding ±90 mV in any given epoch were discarded. As mentioned previously, six dyads were excluded from the initial sample of participants, given that the data processing resulted in the conservation of less than 20 trials per condition. A three-way ANOVA was performed on number of trials for each condition per participant with language (L1, L2) × switching (non-switch, switch) × head position (head-initial, head-final) as factors. There was no main effect of language, switching, or head position ($p > .05$). Moreover, there was no significant interaction ($p > .05$), suggesting that there were no differences in number of trials for each condition per participant. The mean (and SD) number of accepted epochs per condition across participants are shown in Table S5. All preprocesses were performed by EEGLAB (Brunner et al., 2013; Delorme & Makeig, 2004).

ERP components were defined based on grand means and analyzed in time windows that are typically used for Participant A in cue-locked naming epochs: N2 (240-320 ms), LPC (320-460 ms), in picture-locked naming epochs: P2 (140-170 ms) (Branzi et al., 2014; Misra et al., 2012; Strijkers et al., 2011), N2 (200-350 ms) (Branzi et al., 2014; Jackson et al., 2001; Jiao et al., 2022; H. Liu et al., 2016, 2018; Misra et al., 2012), LPC (350-600 ms) (Jackson et al., 2001; Jiao et al., 2020, 2022; H. Liu et al., 2016, 2018), and for Participant B in cue-locked listening epochs: N2 (250-350 ms), LPC (350-430 ms), in judgement-locked listening epochs: P2 (120-180 ms) (Branzi et al., 2014; H. Liu et al., 2018; Misra et al., 2012; Strijkers et al., 2011), N2 (220-420 ms), LPC (520-750 ms) (Davis & Jerger, 2014; H. Liu et al., 2018). Figure 1b shows a listing of the stages of EEG analyses of Participants A and B. In order to better display the differences between regions, the drawing of topographic maps was based on 40 electrodes. Spatially, we pre-defined frontal-central regions of interest (Jackson et al., 2001; Jiao et al., 2022; H. Liu et al., 2016, 2018) (sensors: F3, F1, Fz, F2, F4, FC3, FC1, FCz, FC2, FC4, C3, C1, Cz, C2, C4). The analysis of mean amplitude is based on pre-defined frontal-central regions of interest. The structure of the linear mixed model for ERP data was specified in the same way as was done for RT data. For each time window, we conducted a generalized linear mixed model using language (L1, L2), switching (non-switch, switch), and head position (head-initial, head-final) as fixed effects and participants as the random effect, as well as the average amplitude of each condition within the pre-defined 15 electrodes as the dependent variable (normal Probability-Probability plot of EEG data under each time window in Figure S2). We conducted follow-up analyses when an interaction reached significance at $p < .05$.

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3. Results

3.1 Behavioral results

3.1.1 Reaction times in naming

The results of the language (L1, L2) × switching (non-switch, switch) × head position (head-initial, head-final) mixed-effects model showed significant main fixed effects of language and switching (see Table S6 for full statistics). There were faster RTs in the L1 (M = 874 ms ± 229) compared to the L2 (M = 959 ms ± 240), and faster RTs in non-switch trials (M = 901 ms ± 228) than in switch trials (M = 932 ms ± 248). There was also a significant interaction between language and head position (see Figure 2a). Further analyses showed faster RTs in head-final trials compared to head-initial in the L2 (head-initial: M = 971 ± 246 ms > head-final: M = 947 ± 234 ms), b = .02, SE = .008, z = 2.98, p = .003, but not in the L1 (head-final: M = 876 ± 233 ms; head-initial: M = 872 ± 226 ms), b = -.004, SE = .008, z = -.51, p = .609.

3.1.2 Reaction times in listening

The results of the language (L1, L2) × switching (non-switch, switch) × head position (head-initial, head-final) mixed-effects model on listening RTs showed significant main fixed effects of the three variables (see Table S6 for full statistics). There were faster RTs in the L1 (M = 812 ms ± 257) compared to the L2 (M = 961 ms ± 265), faster RTs for non-switch trials (M = 881 ms ± 270) compared to the switch trials (M = 891 ms ± 273), and faster RTs for head-final trials (M = 879 ms ± 264) compared to head-initial trials (M = 893 ms ± 279). There was also a significant interaction between language and head position (see Figure 2b). Further analyses showed faster RTs in head-final trials (M = 944 ± 264 ms) compared to head-initial trials (M = 978 ± 265 ms) in the L2, b = .04, SE = .008, z = 4.63, p < .001, but not in the L1 (head-final: M = 814 ± 248 ms; head-initial: M = 809 ± 267 ms), b = −.01, SE = .008, z = −1.58, p = .114.

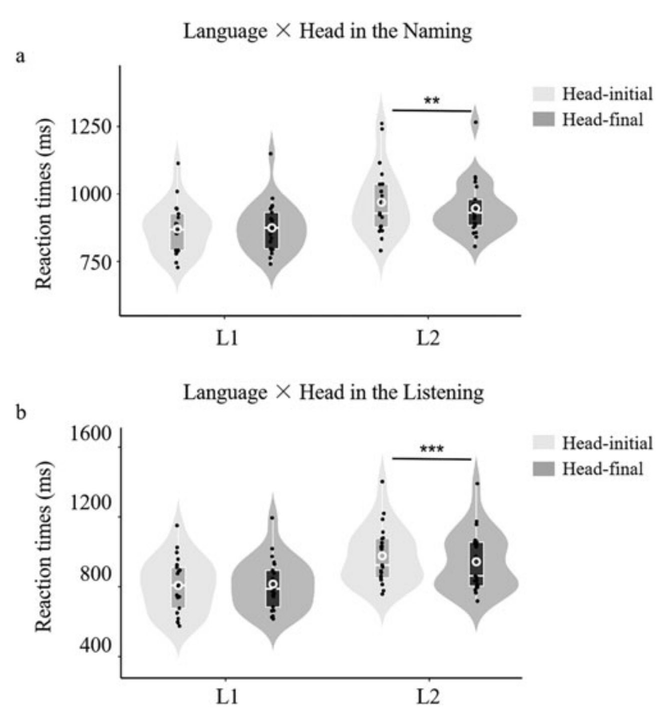

Figure 2. RTs of Naming for (a) Language × Head Position and (b) of Listening for Language × Head Position.
Notes. White circles indicate mean values, white lines indicate medians, and black dots represent data distribution. Box plots indicate 75% and 25% quartiles.
*** p < .001.

3.1.3 Accuracy in naming

A similar mixed-effects model was conducted on the accuracy rates of the naming data. The results revealed a main fixed effect of head position, such that head-final trials (M = .985 ± .12) were more accurate than head-initial trials (M = .977 ± .15), b = .44, SE = .179, z = 2.46, p = .014. There was no other significant effect or interaction identified by the analyses.

3.1.4 Accuracy in listening

A similar mixed-effects model was conducted on the accuracy rates of the listening data. The results showed a main fixed effect of head position, such that head-final trials (M = .985 ± .12) were more accurate than head-initial trials (M = .974 ± .16), b = .58, SE = .174, z = 3.36, p < .001. There was no other significant effect or interaction found in the analyses.

3.2 Electrophysiological results

3.2.1 Cued-locked naming phase

A language (L1, L2) × switching (non-switch, switch) × head position (head-initial, head-final) mixed-effects model on cued-locked naming phase showed a significant main fixed effect of switching in the N2 and LPC time-windows. Switch trials generated larger N2 effects (larger negative amplitudes) than non-switch trials (switch: M = −6.28 ± 10.85 μV, non-switch: M = −5.62 ± 10.70 μV), b = −.66, SE = .248, t = −2.67, p = .008, and non-switch trials triggered larger LPC amplitudes than switch trials (non-switch: M = −3.44 ± 10.83 μV > switch: M = −4.34 ± 10.81 μV), b = −.91, SE = .248, t = −3.67, p < .001. There was a significant interaction between language and switching in the N2 time-window (see Figure 3a), showing that in the L1, switch trials generated larger N2 effects than non-switch trials (switch: M = −6.60 ± 10.91 μV, non-switch: M = −5.22 ± 10.68 μV), b = 1.36, SE = .351, z = 3.87, p < .001. This effect did not emerge in the L2 (switch: M = −5.97 ± 10.79 μV, non-switch: M = −6.03 ± 10.71 μV), b = −.3, SE = .351, z = −.09, p = .927. There was also a significant interaction between language and switching in the LPC time-window as reflected by a reversed switch cost effect in the L1. Non-switch trials in the L1 generated larger LPC effects than switch trials (non-switch: M = −2.97 ± 10.60 μV > switch: M = −4.70 ± 10.79 μV), b = 1.73, SE = .350, z = 4.93, p < .001. These effects did not emerge in the L2 (non-switch: M = −3.91 ± 11.03 μV, switch: M = −3.98 ± 10.83 μV), b = .09, SE = .350, z = .260, p = .795.

3.2.2 Picture-locked naming phase

As shown in Table 1, a language (L1, L2) × switching (non-switch, switch) × head position (head-initial, head-final) mixed-effects model on picture-locked naming phase showed a significant main fixed effect of head position in the three time windows examined. The effects on P2 showed that larger amplitudes were generated by head-initial trials (M = 5.90 ± 9.79 μV) compared to head-final trials (M = 5.11 ± 9.72 μV). This pattern was also found for LPC: head-initial trials (M = 4.44 ± 12.34 μV) produced larger amplitudes than head-final trials (M = 3.17 ± 12.17 μV). However, there was a reversed effect on N2 in which head-final trials (M = −.99 ± 10.44 μV) generated larger N2 amplitudes than head-initial trials (M = .88 ± 10.44 μV).

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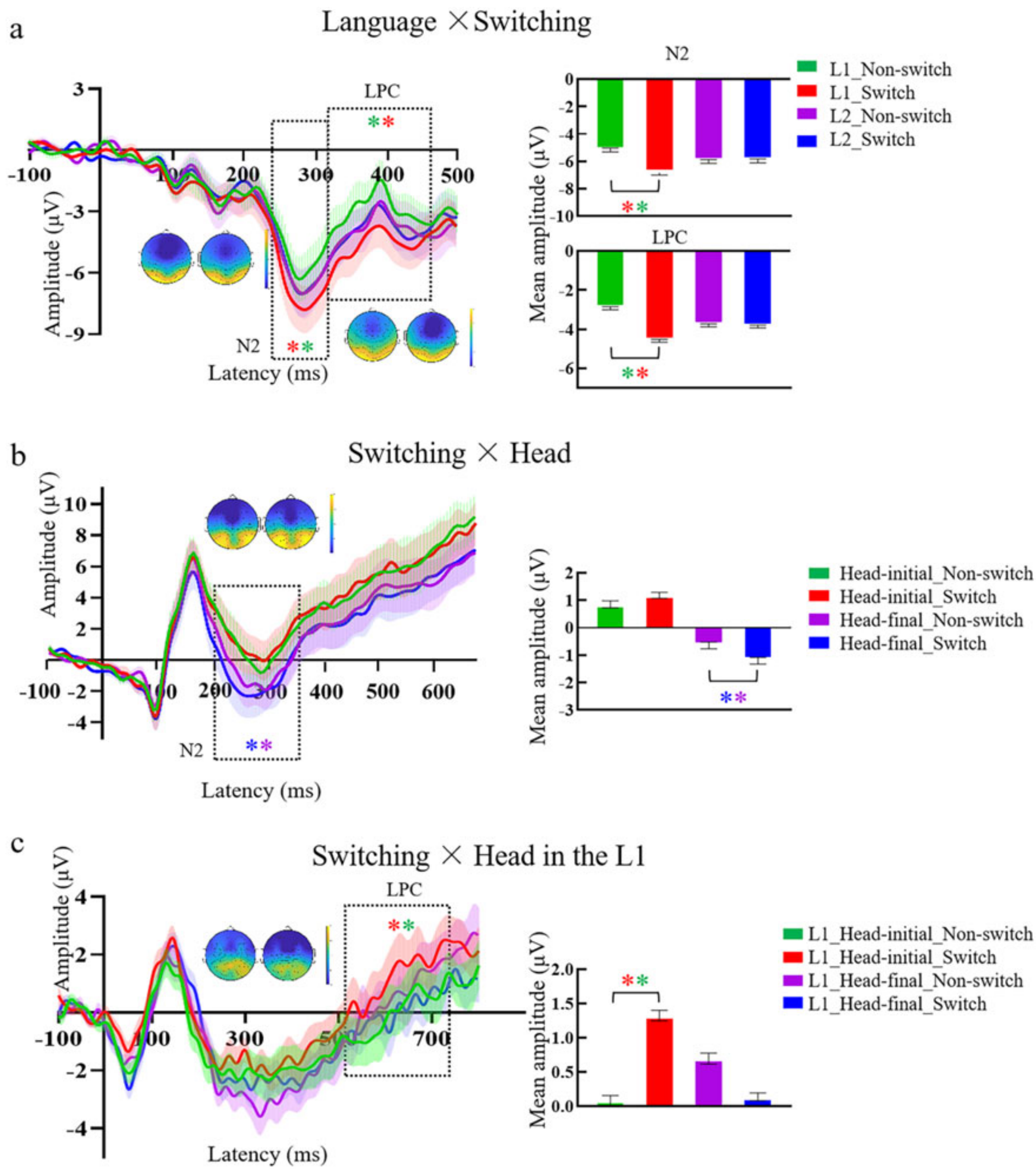

Figure 3. Mean Waveforms Time-Locked to the Onset of Cue-Naming (a), Picture Naming (b), and Judgement Listening (c) and Topographic Distributions of Mean Amplitude for Significant Interactions.

Notes. Panel (a) represents naming-cue data, panel (b) shows picture naming data, and panel (c) show judgement listening data. (a) Language × Switching during the 240-320 ms time (N2) and Language × Switching during the 320-460 ms time (LPC); (b) Switching × Head during the 250-350 ms time (N2); (c) Switching × Head in the L1 during the 520-750 ms time (LPC). The light shaded part indicates the range of standard error for the condition. Double asterisks that appear in the dotted boxes indicate a significant difference between the colored variables listed in the legend (e.g., the two asterisks ** in panel (a) indicate a significant difference between L1 switch trials and L1 non-switch trials). The bar graphs display mean voltages for P2, N2, and LPC in the corresponding conditions averaged across sites. Error bars show the standard error of means. Topographic distributions of mean amplitude for two significantly different conditions in each time window over 40 electrodes.

The main fixed effect of switching only occurred in the P2 time-window, showing that non-switch trials ($M = 5.75 \pm 9.68$ μV) triggered larger amplitudes than switch trials ($M = 5.27 \pm 9.85$ μV). The main fixed effect of language only occurred in the LPC time-window, as reflected by a reversed language effect such that the L2 ($M = 4.46 \pm 12.48$ μV) provoked larger amplitudes than the L1 ($M = 3.13 \pm 11.91$ μV). Additionally, there was a significant interaction between switching and head position on N2 (see Figure 3b), showing that in head-final trials, switch trials generated larger N2 amplitudes than non-switch trials (switch: $M = -1.34 \pm 10.67$ μV, non-switch: $M = -.64 \pm 10.19$ μV), $b = .70$, $SE = .334$, $z = 2.09$, $p = .036$, but not in head-initial trials (switch: $M = 1.05 \pm 10.56$ μV, non-switch: $M = .71 \pm 10.33$ μV), $b = -.29$, $SE = .334$, $z = -.88$, $p = .381$.

3.2.3 Cued-locked listening phase

A language (L1, L2) × switching (non-switch, switch) × head position (head-initial, head-final) mixed-effects model on the

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Table 1. Linear mixed model results of the Naming Task (picture-locked phase, Participant A). The three time-windows (P2, N2, LPC) are reported separately.

	Picture Naming Task											
	P2				N2				LPC			
			Contrast				Contrast				Contrast	
	b	*SE*	*t*	*p*	*b*	*SE*	*t*	*p*	*b*	*SE*	*t*	*p*
Fixed effects												
Intercept	**5.63**	**1.055**	**5.34**	**< .001*** **	–.11	1.251	–.09	.927	**3.78**	**1.391**	**2.55**	**.019***
Language	.11	.230	.49	.625	.46	.236	1.95	.052	**1.27**	**.231**	**4.65**	**< .001*** **
Switching	**–.48**	**.230**	**–2.09**	**.037***	–.20	.236	–.86	.389	–.14	.231	–.52	.601
Head	**–.71**	**.230**	**–3.11**	**.002** **	**–2.02**	**.236**	**–8.57**	**< .001*** **	**–1.35**	**.231**	**–4.96**	**< .001*** **
Language × Switching	.28	.459	.60	.548	–.38	.472	–.81	.416	–.52	.461	–.95	.341
Language × Head	–.82	.459	–1.78	.076	–.37	.472	–.79	.432	–.64	.461	–1.18	.239
Switching × Head	–.618	.459	–1.35	.178	**–.99**	**.472**	**–2.10**	**.036***	–.44	.461	–.81	.416
Language × Switching × Head	–1.18	.917	–1.29	.196	.30	.944	.32	.752	–.37	.922	–.34	.734
Random effects												
Participants	23.06	4.803			32.55	5.706			45.61	6.754		

Notes. model = lmer(Amplitude~data$language*data$switching*data$Head+(1|participant)). Bold words mean significant results.
* $p < .05$, ** $p < .01$, *** $p < .001$.

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cued-locked listening phase showed a significant main fixed effect of switching in the LPC time-window such that non-switch trials (M = .63 ± 9.58 μV) triggered larger amplitudes than switch trials (M = .08 ± 9.55 μV), b = -.55, SE = .233, t = −2.35, p = .019.

3.2.4 Judgement-locked listening phase

As shown in Table 2, a similar mixed-effects model was used to analyze the listening data from the judgement-locked listening phase. We found a main fixed effect of language in the P2 time-window such that the L2 (M = 2.16 ± 8.67 μV) elicited greater amplitude than the L1 (M = 1.60 ± 8.72 μV). But on the LPC, the L1 (M = .44 ± 10.12 μV) elicited greater amplitude than the L2 on LPC (M = −.42 ± 9.53 μV). For the N2 time window, a main fixed effect of switching revealed greater amplitude in non-switch trials (M = −2.26 ± 8.60 μV) compared to switch trials (M = −1.77 ± 8.47 μV), and a main fixed effect of head position revealed greater amplitude in head-final trials (M = −2.36 ± 8.48 μV) compared to head-initial trials (M = −1.66 ± 8.58 μV). A three-way interaction of language, switching, and head position reached significance in the LPC time-window. Follow-up analyses for this three-way interaction were split by language. In the L1, we found a significant interaction between switching and head position on LPC (see Figure 3c), showing switch costs in head-initial trials (switch: M = 1.15 ± 10.18 μV > non-switch: M = .04 ± 9.91 μV), b = −1.14, SE = .480, z = −2.38, p = .017, but not in head-final trials (switch: M = .01 ± 9.90 μV, non-switch: M = .55 ± 10.44 μV), b = .55, SE = .475, z = 1.16, p = .248. There was no significant main effect or interaction in the L2.

4. Discussion

Using a simultaneous production and comprehension task, this study explored the role of compound words' head position in bilingual language control. Our results show that Chinese–English bilinguals have faster processing and higher accuracy for head-final compounds than head-initial compounds when switching into the L2, but are more sensitive to the head-initial position when switching into the L1. Moreover, in production, head-initial compounds elicit greater amplitude than head-final compounds on P2 and LPC and cause opposite contrasts (head-final > head-initial) for the N2 effect. In comprehension, head-final compounds elicit greater amplitudes than head-initial compounds on N2, and switch costs emerge in the L1 for head-final position on LPC. These results indicate that head position exerts an influence on language control during bilingual communication; and, specifically, due to the influence of different modalities, processing head position in production and comprehension is distinct and exerts differential influences on language control.

4.1 Head position preference in an L1 and L2

The findings showed that L2 English head-final compounds are processed faster than head-initial compounds, both in production and in comprehension. This is consistent with previous findings that in English, in which a compound's head is usually the right-most element, there is a preference for head-final structures (Lieber & Baayen, 1993; Williams, 1981). For L1 Chinese, there was no head position preference found in the behavioral results of production and comprehension. Overall, for bilinguals who are native speakers of Chinese, head-final compounds compared to head-initial compounds elicit faster responses in production, and more accurate responses in both production and comprehension. These results show that there appears to be no preference for head-final compounds in L1 and L2, so the responses of head-final compounds are consequentially faster and more accurate. However, on the LPC effect in comprehension, switch costs were found for L1 head-initial compounds. This indicates that the head position may have a potential impact on the L1. Following the logic of the ICM (Green, 1998), conditions that cause greater switch costs are taken as indicators of larger inhibition towards a dominant condition. In the present study, larger switch costs for L1 head-initial compounds on the LPC effect in comprehension suggest that head-initial compounds are more dominant than head-final compounds and require more inhibition when switching to the L1.

4.2 The effect of head position on language control is influenced by switching modality

At the cue-locked naming phase in the L1, switch costs emerged in the N2 time window. According to the ICM (Green, 1998), this reflects the fact that during production of a weaker language (e.g., L2), there is more effort needed to suppress interference from a stronger language (e.g., L1). Subsequently, when switching to the L1, more resources are required to resolve residual L1 suppression. Thus, our finding indicates that interference resolution mainly occurrs at the language cue phase, where language schema selection occurs. At the picture-locked naming phase, head-initial compounds elicit greater amplitude than head-final compounds on P2 and LPC and cause opposite contrasts (head-final > head-initial) in the N2 effect. These results show that bilinguals can distinguish the head position at 140 ms after the stimulus onset and that head position processing finishes around 600 ms after onset. More importantly, we observed switch costs for head-final compounds on N2. Greater N2 amplitude has been associated with greater language control (Jackson et al., 2001; Jiao et al., 2022; Verhoef et al., 2010; Zheng et al., 2020). Our results show that in the head-final compounds, interference suppression of switch trials is greater than that of non-switch trials. In brief, due to top-down control in production, language schema selection appears to be completed at the cue phase. At the naming phase, the processing of the head position is always continuous, and inhibitory control of head position occurs in mid-stages (N2).

However, at the cue-locked listening phase, we found no interaction between language and switching, although at the judgement-locked listening phase, the L2 elicited greater P2 amplitudes than the L1, and head-final compounds elicited greater N2 amplitudes than head-initial compounds. These findings indicate that language is first processed, followed by head position based on the temporal course of the components. The LPC effect showed stronger amplitudes in the L1 compared to the L2, with L1 switch costs for head-initial compounds. Bottom-up control enables us to observe the interference from the non-target language that occurs on head-initial trials in the LPC. Overall, inhibitory control of head position emerges in the middle stage (N2) during production, and in a later stage (LPC) in comprehension. These results show that head position in compound words exerts differential influences on language control under different modalities.

4.3 Storage and processing of compound words

Compound word processing has been of great interest in the exploration of word composition and decomposition (Günther

Table 2. Linear mixed model results of the Listening Task (judgement-locked phase, Participant B). The three time-windows (P2, N2, LPC) are reported separately.

	Judgement Listening Task											
	P2				N2				LPC			
			Contrast				Contrast				Contrast	
	b	*SE*	*t*	*p*	*b*	*SE*	*t*	*p*	*b*	*SE*	*t*	*p*
Fixed effects												
Intercept	**1.86**	**.322**	**5.76**	**< .001*** **	**−2.03**	**.369**	**−5.49**	**< .001*** **	.02	.644	.04	.971
Language	**.57**	**.214**	**2.64**	**.001***	.36	.209	1.73	.084	**.88**	**.234**	**−3.77**	**< .001*** **
Switching	.36	.214	1.67	.095	**.47**	**.209**	**2.24**	**.024***	.27	.234	1.14	.256
Head	−.03	.214	−.16	.873	**−.69**	**.209**	**−3.29**	**< .001*** **	−.41	.234	−1.76	.079
Language × Switching	−.10	.428	−.24	.808	.10	.417	−.24	.810	−.03	.468	−.07	.943
Language × Head	−.44	.428	−1.04	.299	−.03	.417	−.08	.933	−.22	.468	−.48	.632
Switching× Head	−.12	.428	−.29	.773	.22	.417	−.52	.604	−.67	.468	−1.44	.150
Language × Switching × Head	−.55	.856	.64	.524	−.23	.835	.27	.787	**2.03**	**.937**	**2.16**	**.031***
Random effects												
Participants	1.94	1.392			32.55	5.706			45.61	6.754		

Notes. model = lmer(Amplitude~data$language*data$switching*data$Head+(1|participant)). Bold words mean significant results.
* $p < .05$, ** $p < .01$, *** $p < .001$.

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& Marelli, 2021; Juhasz, 2018; Leminen et al., 2019). Previous studies on compound word processing have focused on storage and retrieval processes. In general, there are three points of view. Sequential models argue that morphemes are independently stored in the mental lexicon and processed in sequence (Li et al., 2017; Taft & Forster, 1975, 1976; Uygun & Gürel, 2017). Distributed models assume that morphemes are stored in the form of whole words and are processed in parallel (Aitchison, 2012; Miozzo et al., 2015; Osgood & Hoosain, 1974; Silva & Clahsen, 2008; Strijkers et al., 2010, 2017; Zyzik & Azevedo, 2009). Hybrid models hold that decomposed (morpheme-based) forms and whole forms of compounds are equally stored and retrieved in the mental lexicon (Pinker, 2015; Pinker & Ullman, 2002; Sandra, 1990, 2020; Zhou & Marslen-Wilson, 1995). Moreover, Libben et al. (2020) argue that compound words are both greater than the sum of their parts and greater than their overall division.

The present study used a simultaneous production and comprehension task consisting of cued picture naming and head judgments. Although the combination of the two tasks allows participants to pay attention to the composition of a compound, it has a disadvantage in that participants are more likely to notice the composition of compound, leading to sequential processing rather than parallel processing. However, our findings do not support parallel processing of form and meaning of compounds. The behavioral and EEG analyses showed that head position plays differential roles in each language – that is, L2 (English) prefers head-final structures, while L1 (Chinese) prefers head-initial structures. The language-specific head position preference should not emerge if the participants process whole words simultaneously. Thus, the present findings suggest that compound words are processed in accordance with distributed models or hybrid models.

5. Conclusion

This study examined the influence of compound head position on bilingual language control during simultaneous production and comprehension. Behavioural and electrophysiological results showed that language switching is sensitive to head position preferences: the head-final structure is more dominant when switching to English (L2), while the head-initial structure tends to be more dominant when switching to Chinese (L1). In addition, the effect of head position on language control is influenced by switching modality such that bilinguals process head position earlier in production than in comprehension.

Supplementary Material. For supplementary material accompanying this paper, visit https://doi.org/10.1017/S1366728923000883

Supplementary Materials

Table S1. *Mean (± SD) Characteristics of Participants' Language Background*

Table S2. *English Proficiency Classification Criteria of QPT Scores*

Table S3. *Head Position Conditions of the Stimuli*

Figure S1. *Stimulus Pictures in the Joint Production-Comprehension Task.*

Table S4. *Characteristics of the Stimuli (Mean ± SD).*

Figure S2. *Normal Probability-Probability Plot of EEG Data under Each Time Window.*

Table S5. *Mean Number of Trials for Each Condition per Participant after Independent Component Analyses.*

Table S6. *Model Parameters for the Best-Fitting Generalized Linear Mixed Model of RTs for Naming and Listening.*

Appendix S1. Testing Practice Effects

Acknowledgments. We have no known conflict of interest to disclose.

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Availability of data and materials. The datasets generated and analyzed in this study are available in the OSF repository: Liu, H. (2022, December 14). "Head position and language control." Retrieved from https://accounts.osf.io/login (osf.io/pxb8f/).

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