The dynamic influence of language switching contexts on domain-general cognitive control: An EEG study

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Abstract

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The dynamic influence of language switching contexts on domain-general cognitive control: An EEG study

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Abstract

In everyday conversation, bilingual individuals switch between languages not only in reaction to monolinguals with different language profiles but also voluntarily and naturally. However, whether and how various switching contexts dynamically modulate the domain-general cognitive control was still elusive. Using a cross-task paradigm which flanker task was interleaved with language switching task trial-by-trial, the present study manipulated forced, voluntary and natural switching contexts. A group of unbalanced Chinese-English bilinguals performed a flanker task in the three switching contexts. The results showed that the cross-domain interaction on the P3 effect revealed an atypical flanker effect in forced switching contexts only, and P3 amplitude of incongruent trials in forced switching contexts was smaller than both natural and voluntary switching contexts. Furthermore, the robust brain-brain and brain-behavior relationships between language control and domain-general control were significantly emerged in the forced switching context only. Altogether, our findings support the dynamic adaptation of language control to cognitive control and highlight the importance of switching contexts.

Keywords: language switching; cross-task conflict adaptation; language control; domain-general cognitive control.

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Introduction

In day-to-day life, bilinguals manage two languages in one mind and switch language for a variety of reasons. For instance, bilinguals often encounter situations where they must switch into a language in response to situational demands or environmental cues (i.e., forced switching). They may also find themselves conversing with others who share the same languages, and thus, can freely switch between these languages at will (i.e., voluntary switching). According to Adaptive Control Hypothesis (ACH; Green & Abutalebi, 2013), the forced switching has been suggested to trigger (more) top-down control processes (such as monitoring, inhibitory control), whereas voluntary switching is at least partly driven by top-down control processes as a consequence of the decision process regarding whether or not to switch (Blanco-Elorrieta & Pylkkänen, 2016, 2017; Green & Abutalebi, 2013). However, sometimes, bilinguals exhibit a preference for using one language over another to name objects based on familiarity or cultural preference (i.e., natural switching). This latter switching situation is driven by lexical accessibility and has also been referred to as bottom-up switching (Dijkstra & van Heuven, 2002; Gollan et al., 2014; Kleinman & Gollan, 2016; Zhu et al., 2022).

Varying linguistic contexts have a wide influence on domain-general cognitive control. A growing body of research has repeatedly observed the modulation effect of linguistic contexts on domain-general control in both language production and comprehension (Green, 1986; Jiao et al., 2019, 2020; Linck et al., 2012; Liu et al., 2022a; Liu et al., 2022b). However, most of these have examined the relative "static" influence of linguistic contexts on domain-general cognitive control, such as behavioral performance (e.g., the flanker effect) and event-related potentials (ERPs), by comparing different contexts (Jiao et al., 2019, 2020; Linck et al., 2012; Liu et al., 2022b), or manipulating the task orders of language switching task and cognitive tasks (Liu et al., 2022a; Kang et al., 2017; Wu et al., 2018). In the present study, using a cross-task paradigm which flanker task was interleaved with language switching task trial-by-trial, we tried to reveal the dynamic modulation effect of various switching contexts on domain-general control.

There is a trial-to-trial upregulation effect in cross-task paradigm called cross-task conflict adaptation. Studies have found, compared with non-switching contexts (i.e., the single-language context), switching context (i.e., the mixed-language context) facilitated conflict resolution immediately (Jiao et al., 2019; Liu et al., 2022b; Wu & Thierry, 2013). Such conflict adaptation effect is well explained by the conflict monitoring theory (Botvinick et al., 2001), which argues that response conflict involved in incompatible trials causes them to be associated with a subsequent intensification of top-down control. Concerning the cross-task studies, this intensification adjustment is usually achieved by the dynamic adaptation of the increased cognitive demanding induced by language control to the subsequent domain-general control. Switching between language could heighten selective attention on task-relevant information and reduce interference from task-irrelevant information.

That is, the cross-task conflict adaptation is a dynamically adaptive adjustment derived from homogeneous conflict resolution mechanisms (Liu et al., 2022b; Yuan et al., 2021). However, the relevant studies have yielded inconsistent findings.

In a seminal study by Wu and Thierry (2013), the flanker task was interleaved with target words. The authors manipulated the language context by intermittently presenting words in Welsh, English, or both. Results showed that in switching contexts, there was a reduced P3 effect for incongruent trials in the flanker task compared to the non-switching context. P3 amplitude, a positive deflection around 300-500 ms following stimulus onset, serves as a marker of response inhibition and is enhanced by response conflict (Clayson & Larson, 2011; Groom & Cragg, 2015; Kropotov et al., 2011; Smith et al., 2007). This reduced P3 effect emerged from the incidental presentation of words from two languages, enhancing executive functioning to assist in conflict resolution. Consistent with Wu and Thierry (2013), Liu et al. (2022) conducted a cross-task paradigm in an interpersonal situation and repeatedly found a reversed flanker effect (i.e., higher synchronization in incongruent trials relative to congruent trials) in switching context. The authors further argued that the conflict adaptation was merely reflected in the conflict situation induced by incongruent task-relevant stimulus features (Jiang et al., 2015; Liu et al., 2022b).

Nevertheless, findings on this issue have been mixed. In a series of ERP studies conducted by Jiao et al. (2019; 2020a; 2020b; 2022), a modified flanker task was interleaved with a language switching task in language production (i.e., picture-naming task) or comprehension (i.e., picture-word matching task). The results consistently revealed a larger N2 effect but a smaller P3 in switching contexts compared to non-switching contexts for both congruent and incongruent trials. The reduced P3 effects observed in both congruent and incongruent trials reflect the underlying mechanisms for conflict monitoring and conflict resolution (see also Jiao et al., 2019; Neuhaus et al., 2010). They suggested that ongoing monitoring and coordination during language switching should generalize equally to both incongruent trials, which induce conflict resolution, and congruent trials, which do not require interference inhibition (Coderre & van Heuven, 2014; Costa et al., 2009; Hilchey & Klein, 2011; Hannaway et al., 2017).

It seems that the empirical evidence fails to converge with respect to the conflict adaptation of language control on domain-general control. Furthermore, there is a lack of direct evidence to compare the impact of different switching contexts on conflict adaptation in cross-task paradigm. Previous cognitive studies primarily focused on the comparison between forced switching context and non-switching context, and failed to reach a consensus. Moreover, as aforementioned, there exist three switching modes in bilingual real-life, and the control processes that underpin these contexts are not fixed. Hence, these discrepancies motivate us to further investigate two main questions: (1) whether different switching contexts, regardless of the control processes involved, contribute differentially to domain-general control; (2) further, how different switching contexts dynamically modulate the cross-task conflict adaptation effect.

To this end, following previous research effort, the present study employed the cross-task paradigm of which flanker task was intermixed with picture-naming task trial-to-trial. Flanker trials were embedded in the forced, voluntary and natural switching contexts. In the forced switching context, participants were instructed to name the picture according to the language cues set by our experiment. While in voluntary context, bilinguals had full freedom to decide which language to use. Natural switching, on the other hand, is realized by the language-biased words acquired before the formal experiment (see Section 2.2 for a full description). The electrophysiological activities of the participants were recorded. Statistical analyses of behavioral response and brain activity, as well as Ridge regression prediction models were conducted to capture the dynamic and predictive effects of the three switching contexts on domain-general control. According to the introduced theoretical and empirical evidence, we hypothesized that if conflict adaptation effect in cross-task paradigm was merely dependent on higher cognitive demanding induced by previous trials, thus: (1) for both cognitive performance and predictive results, the forced switching context would promote the flanker's performance compared to voluntary and natural switching contexts; (2) moreover, better performance in incongruent trials than congruent trials at least in the context of forced and voluntary contexts which involves the top-down control processes.

2. Methods

2.1 Participants

Thirty right-handed Chinese (L1)-English (L2) bilingual university students with normal or corrected-to-normal vision were recruited in the experiment. All participants were born in China and had no immigration or study abroad experience. On average, the participants began learning English in traditional classroom settings at the age of 8.40 years ($SD = 2.18$, range: 6-13). No participant reported neurological, cognitive, or motor impairments. Research ethics approval was obtained from the Committee of Protection of Participants at Beijing Normal University and all participants provided written informed consent before beginning the experiment. One participant was excluded because of excessive EEG artifacts. The final sample consisted of 29 participants (10 males, 19 females, mean age: 22.66, range: 19-27).

To gather information about the participants' language proficiency, we administered the Oxford Quick Placement test (OPT; Geranpayeh, 2003) and asked participants to provide self-ratings of their language abilities on a 6-point scale (1 = no knowledge; 6 = perfect knowledge) (Liu et al., 2021; Liu et al., 2023a; 2023b). The mean score from the OPT was 36.63 ($SD = 5.52$), which falls within the A2 level of the Common European Framework of Reference. The average self-ratings of L1 proficiency were: listening ($M = 5.62$, $SD = .49$), speaking ($M = 5.17$, $SD = .54$), reading ($M = 4.59$, $SD = .78$), and writing ($M = 5.1$, $SD = .77$). For L2 proficiency, the self-ratings were: listening ($M = 3.62$,$SD = 1.05$), speaking ($M = 3.45$, $SD = .74$), reading ($M = 3.03$, $SD = .98$), and writing ($M = 3.31$,$SD = 1.2$). Paired-sample t -tests revealed that the participants' L1 was significantly stronger than L2 in all four domains: listening ($t = 10.41$, $p < .001$), speaking ($t = 11.65$, $p < .001$), reading ($t = 8.81$,$p < .001$), and writing ($t = 7.81$, $p < .001$). These self-ratings and OPT scores are similar to those reported on intermediate Chinese-English bilinguals in prior research (Kang et al., 2017; Liu et al., 2016; Liu et al., 2021; Liu et al., 2023b; Yuan et al., 2021; Wu et al., 2019), suggesting unequal proficiency between their two languages.

2.2 Materials

To investigate the cross-task adaptation effect of bilingual language control on executive control in forced, voluntary, and natural switching contexts, we adopted a cross-task paradigm in which flanker trials were intermixed with picture-naming trials. To ensure that the switching contexts mirrored the bilingual experience in real-life switching situations as accurately as possible, we administered a survey to 35 participants from same population, but who were not involved in the formal experiment. The survey presented pictures and their Chinese and English names at the same time in two parts. In the first part, participants were instructed to choose in which language the pictures were most commonly used in daily life, and to report the frequency of such use. Language-biased items were selected for the experiment if more than 80% of respondents could name them in one language, or if the average rating for its use exceeded 80% (Zhu et al., 2022). In the second part, participants were instructed to rate the familiarity of the target Chinese words and their English translation equivalents. Words that were judged equally familiar in their two languages were chosen for the experiment.

The picture stimuli included 36 black-and-white line drawings (Snodgrass & Vanderwart, 1980; standardized by Zhang & Yang, 2003), of which 24 were used in the formal experiment and 12 were used in a practice block. In the natural switching block, there were eight picture stimuli with strong language-biased names. Specifically, four of them were strongly biased towards English, meaning it was difficult to use a Chinese word to name the stimulus (e.g., *Windows* , an operating system), and four were strongly biased towards Chinese (e.g., *zongzi* , a traditional food in China), meaning it was difficult to use an English word to name of the stimulus. In the forced switching block, 4 words with the same familiarity of L1 names and L2 equivalents were used as target stimuli. In the voluntary switching block, another 4 words with the same familiarity of L1 and L2 names were used as target stimuli.

Flanker stimuli comprised a display of five horizontal arrows, wherein the central arrow either matched or did not match the direction of the flanking arrows. This arrangement provided four distinct types of stimuli: 1) all arrows pointing left, 2) all arrows pointing right, 3) all arrows pointing left except for the center arrow, and 4) all arrows pointing right except for the center arrow.

2.3 Procedure

Participants were individually placed one meter from a computer screen in a quiet room. The picture-naming task with interleaved flanker trials was presented in the center of the screen using E-Prime 2.0. As illustrated in Figure 1, each trial began with a fixation cross, which lasted for 250 ms, and was followed by a picture-naming trial. The picture then disappeared when participants named it aloud or after 1500 ms passed. A blank screen lasted for 1000 ms before another fixation cross appeared for 250 ms followed by a flanker trial. The flanker trial disappeared when participants responded to it or after for 1500 ms passed. Finally, a blank screen appeared for 1500 ms before the next trial started.

2.3.1 Picture-naming task

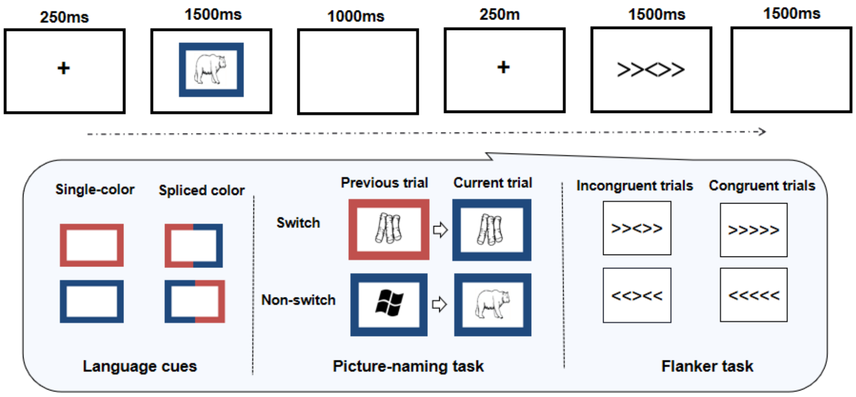
The response language in picture-naming trials was determined by a color cue. In each trial, a picture with a red, blue, or spliced border appeared. In the forced and natural switching blocks, only red and blue cues were used. Participants were instructed to name the pictures based on the color cues provided. It is important to note that monochromatic cues were presented in both forced and natural contexts. This was done to maintain a "forced" constraint in the natural switching block. With this manipulation, if we still observe that the advantages of forced switching context outweigh those of natural switching context, then the benefits of forced switching can be more effectively elucidated. In the voluntary switching block, the language cue was spliced with a red and blue border, indicating that participants were free to decide in which language to name the picture. The color-language associations were counterbalanced across participants. Based on whether the language of the current trial was the same as the immediate preceding trial, two type of trial sequences were classified: switch trials (i.e., the response language was different from the preceding trial; L2-L1, L1-L2) and non-switch trials (i.e., the response language was consistent with the preceding trial; L1-L1, L2-L2). Picture stimuli, trial types, and response languages were pseudo-randomized throughout the task such that there were no more than three consecutive trials of the same response language.

2.3.2 Flanker task

Two types of trials, congruent (i.e., »»> or ««<) and incongruent (i.e., »<» or «>«), were included in the flanker task. As is typical in flanker-type tasks, participants were instructed to decide whether the central arrow pointed to the left or the right by responding with the "F" or "J" button on the keyboard. Since we introduced picture-naming trials before flanker trials, the response language and trial type of picture-naming were intermixed with pseudorandom presentations of flanker trials (except for the voluntary switching block).

There were 6 blocks, each of which included 114 cross-task trials (2 warm-up trials followed by 56 congruent trials and 56 incongruent trials). The six blocks were divided into two natural blocks, two forced blocks, and two voluntary blocks, with the ordering of blocks being counterbalanced across participants. Trial sequences were randomized throughout the task so that participants could not anticipate upcoming trial types.

Figure 1. *Procedure of the present study. Cross-task trial structure (upper panel) and experimental design (lower panel).*



2.4 Data recording and analyses

Electrophysiological data were recorded using 64-channel caps with Ag/AgCI impedance-optimized active electrodes. Standard electrodes were placed according to the extended 10-20 positioning system, and impedances were kept below 5 kΩ. The continuous signal was recorded with a sampling rate of 1000 Hz and referenced online to the electrode placed over the Cz. Using EEGLAB (Brunner et al., 2013; Delorme & Makeig, 2004; Makeig et al., 1995) for data processing, EEG data was down-sampled to 500 Hz offline and filtered online within a high-pass filter for .1 Hz and a low-pass filter for 30 Hz. All electrode sites were rereferenced offline to the average of the left and right mastoids. Reduction of ocular movement artifacts was performed through Independent Component Analysis (ICA) rejection (Makeig et al., 1995; Delorme & Makeig, 2004). The mean number of ICs rejected was 1.66 ± .91 per participant (natural: 1.65 ± .71; forced: 1.79 ± .89; voluntary: 1.56 ± 1.11). The continuous recordings were cut into epochs ranging from -200 to 800 ms relative to the onset of each flanker trial. Baseline correction was performed in reference to pre-stimulus activity (-200 to 0 ms). We subjected all epochs to a rejection procedure in which epochs containing deviations larger than 100 µV were discarded. This procedure rejected 670 epochs (rejection rate: .17%), and the mean rejection rate per participant was 1.73%.

ERP components were defined based on previous literature and visual inspection of wave-forms. Two time-windows were used to explore the components of interest. Firstly, a 120-220 ms time-window classically defined as N1 was selected. Secondly, a 350-450 ms time-window was chosen to analyze the P3 component. In accordance with prior studies (Christoffels et al., 2007; Jackson et al., 2001; Martin et al., 2013; Verhoef et al., 2010), we focused our analyses on two regions of interest (ROIs): central-parietal: CP3, CP1, CPz, CP2, CP4; and parietal: P3, P1, Pz, P2, P4. The N1 effect is assumed to be indicative of persistent covert visual attention control and sensitive to the level of visual attention intensity on the target stimuli (Di Russo). The greater N1 amplitude for incongruent relative to congruent trials implys more attention allocated to a given stimuli (Luck et al., 2000). Traditionally, a parietal P3 component was thought to index context updating operations, demonstrating the late, top-down controlled process associated with the allocation of attentional resources and updating of working memory (Donchin & Coles, 1998; Duncan-Johnson & Donchin, 1977; Polich, 2007; Liu et al., 2023b). In flanker tasks, the P3 effect has often been found to be enhanced and delayed on incongruent trials compared to congruent trials (Folstein et al., 2008).

Response times (RTs) and accuracy on each flanker trial were recorded. We excluded the first two warm-up trials of each block and RTs ±2.5SD (.64% of the total) from the analyses. In addition, since accuracy rates of flanker trials was 97.88% (SD = .14), and there was only a significant main effect for trial type, we did not conduct further analyses on accuracy rates. In total, the remaining 96.07% trials were included in the RT analyses. RTs were log-transformed to better approximate a normal distribution.

Statistical analyses were conducted in R using the lme4 package (Bates et al., 2015). The RT values and single-trial mean amplitude were submitted separately to 3 × 2 × 2 linear mixed-effects models. The fixed effects included “context” (natural vs. forced vs. voluntary), “trial type” (switch vs. non-switch), and “flanker” (congruent vs. incongruent), and interactions between these factors; and random effects in the RT model included participants and items, whereas only participants were added as a random effect of the model on single-trial mean amplitude. We started with a full model including the structure of maximal random effects (Barr et al., 2013), and added the three factors and their interactions as random slopes. If the model failed to converge, we used a backwards-stepping procedure until the model fit. The decision to include or exclude random slope effects of each model was based on the smallest Akaike Information Criterion (AIC) value, and the model with the smallest AIC was selected as the best-fitting model. Because “context” in the model involved three levels, any significant main effects or interactions were further analyzed by comparing the estimated means using the “emmeans” package. Moreover, we performed pairwise comparisons between flanker trials and each context to identify any differences. The p -values obtained were adjusted for multiple comparisons using false discovery rate (FDR) correction. Given the aims of the study, we only present the effects involving the factors “flanker” and/or “context.”

2.5 Prediction model

We utilized a family of regularized Ridge Regression (RR) models to predict brain activity during the immediate flanker task using the EEG data collected during the preceding picture-naming trials. RR is a widely employed parameter estimation technique for addressing linear regression challenges characterized by multicollinearity, offering robustness against noise (Engemann et al., 2020; Meir-Hasson et al., 2014). Following EEG data preprocessing during language processing to align with flanker task standards, a series of RR models were implemented. Initially, 48 electrodes were retained and averaged after removal of electrodes with high impedance from the outer circle. Subsequently, EEG activity for each participant across language-switching contexts (forced, natural, and voluntary switching) and subsequent flanker tasks (congruent, incongruent) was isolated for each trial, condition (switch-congruent, switch-incongruent, non-switch-congruent, non-switch-incongruent), and time point (within the 0-500 ms window).

Due to the absolute autonomy of language selection in the voluntary switching context, the trial count under each condition was not uniform. Thus, averaging was performed across the trial dimensions for the three contexts, resulting in a three-dimensional matrix of 4 (conditions) × 29 (participants) × 500 (time points). Next, the condition and participant dimensions were merged to yield a matrix of 116 × 500, with the initial 58 × 500 serving as the training set and the subsequent 58 × 500 constituting the test set. Model training involved employing bootstrapping to determine the optimal alpha value for each response. Specifically, 50 of the 58 matrix data were randomly sampled from the training set for model training, and the remaining 8 were used for validation. Fifteen rounds of cross-validation were executed to ascertain the best alpha value for each response. Upon determining the optimal alpha value, model weights were acquired. Utilizing the language task test set 58 × 500 (independent variable X) as input and the weight multiplication of the trained model, the predicted EEG signal of the flanker task (i.e., the predicted value, $\hat{y}$) was obtained. To validate the fit of the model, Pearson’s correlation analyses were conducted between the predicted brain activity (i.e., $\hat{y}$) during the flanker task and the actual amplitude data (i.e., y) of the flanker task at each time point. A higher r -value indicates better prediction performance. In essence, utilizing coding activity from language-switching tasks as the independent variable X , we predicted the corresponding processing of the flanker tasks (i.e., dependent variable y), yielding ridge correlation coefficients. These coefficients, reflecting the correlation between language processing and executive control processing, address the second question of this study: the influence of different switching modes on executive control, particularly which type of executive advantage predominates.

2.6 Specification curve analysis

To further explore whether the predictability between language control and executive control influenced behavioral performance, we conducted the specification curve analysis (SCA, Simonsohn et al., 2020). The SCA is a framework of modeling all possible specifications (consisting of independent, dependent and control variables) to provide an unbiased brain-behavior relationship to test all reasonable specifications. Recent studies demonstrated its benefits lie in reducing the overall false-positive rate and strengthening the robustness of a given finding (Cosme & Lopez 2020; Flournoy et al. 2020; Yuan et al., 2023). In the current study, we aimed to reveal the relationship between brain activity and corresponding behavioral performance in the flanker task. Furthermore, we tentatively examined the probability of the predicted values derived from the RR model would interact with behavioral performance.

This analysis was performed with the specr package (Masur & Scharkow, 2020) in R. First, the mean RTs of congruent and incongruent trials across three switching contexts were separately specified in the flanker task as the outcome variables. Then, the mean EEG amplitudes of each flanker condition in three switching contexts were extracted within a 0-800ms time window (the real values). Additionally, using the RR prediction model, the weights of the prediction model were multiplied with the independent variable X (i.e., amplitudes during the picture-naming trials). This calculation yielded the predicted values (the predicted amplitude of the flanker task by the model) in each switching context. Both the real and predicted values from three contexts (each model for congruent and incongruent conditions contained 6 values.) were then input into the SCA as the neural predictors to examine the corresponding brain-behavior relationships and how brain-to-brain predictions interact with behavioral performance (i.e., significant interactions between the predicted values and RTs). In addition, participants' demographics (i.e., age and gender), language proficiency (L1 self-rating scores, L2 self-rating scores, OPT scores and CET-4 scores), and the L2 age of acquisition were added as control variables. In each specification, a single indicator (i.e., each value) was set as the predict of interest, and its association with the outcome variable was examined with the changes of specifications and covariables included in the model. The standardized regression coefficients for each predictor were subsequently calculated and ordered by the effect size to plot the specification curve. Finally, the median standardized regression coefficient was tested with the proportion of the statistically significant positive and negative coefficients. The regression coefficients were statistically inferred through a bootstrapping process (1000 times), which generated confidence intervals around the median of the curve and assessed the discrepancy between the observed curve parameters and the null distribution which assumed no statistically significant relationship between each predictor-outcome pair.

3. Results

3.1 Behavioral results

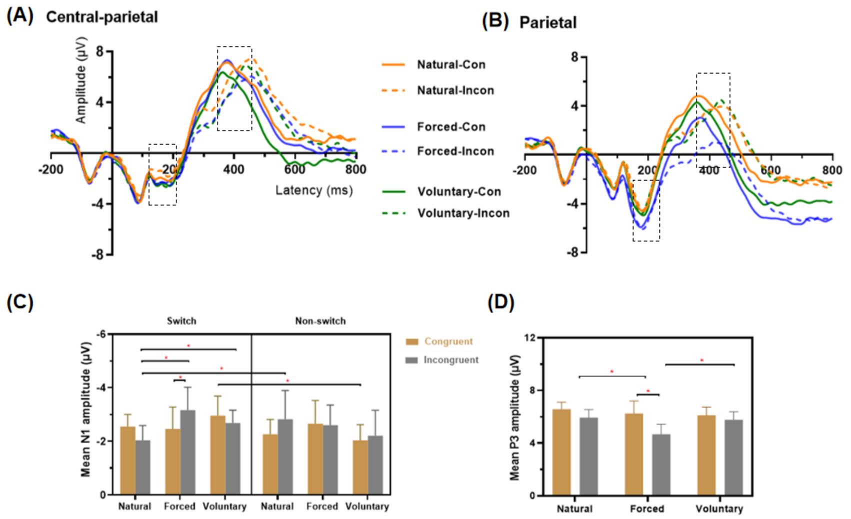
With respect to accuracy rates, participants achieved an average accuracy of 97.88% (SD = .14) on flanker trials. Analyses on accuracy rates and RTs only revealed a significant mixing effect for flanker trials. Participants were more accurate on congruent trials (M = 1.00 ± .07) compared to incongruent trials (M = .96 ± .19), t = 177.86, p < .001. Slower responses were revealed in incongruent trials (M = 465 ± 69 ms) compared to congruent trials (M = 403 ± 65 ms), t = 16.91, p < .001. That is, no significant differences were detected between three switching contexts either in RTs, accuracy rates, or the flanker effect.

3.2 ERP results

3.2.1 N1 (120-220 ms)

The analyses on the N1 component detected a significant three-way interaction for type × flanker × context, F (2, 36778) = 4.31,p = .014 (see Figure 2). Follow-up tests revealed a significant interactive effect for flanker × type in the natural switching context (t = 5.84, p = .016), such that switch-incongruent trials (M = -2.03 ± 15.04 µV) elicited a smaller N1 effect compared to repeat-incongruent trials (M = -2.80 ± 15.92 µV). However, no such interactive effect was found in either the forced or voluntary switching contexts. Additionally, in the forced switching context, switch-incongruent trials (M = -3.11 ± 14.77 µV) elicited a stronger N1 effect compared to switch-congruent trials (M = -2.35 ± 13.29 µV), indicating that the typical flanker effect was only found in forced switching (Estimate = .74, SE =.37, t = 2.00, p = .045). Moreover, switch-incongruent trials in the natural switching context (M = -2.03 ± 15.04 µV) showed a smaller N1 effect compared to both the forced switching context (M = -3.12 ± 14.77 µV; Estimate = 1.13, SE = .32, t = -3.51, p = .001) and voluntary switching context (M = -2.46 ± 11.16 µV; Estimate = .84, SE = .33, t = 2.55, p = .016). No such differences were found between the forced and voluntary switching contexts (Estimate = -.29, SE = .33, t = -.87, p = .383).

Figure 2. *Grand average waveforms time-locked to stimulus onset in the three switching contexts across central-parietal (A) and parietal (B) electrodes.*



Notes. Dash boxes represent early (120-220 ms) and middle (350-450 ms) time windows during the flanker task. Panel (C) presents the mean N1 amplitude for the three-way interaction for type × flanker × context. Panel (D) displays the mean P3 amplitude for the significant interaction for flanker × context. Con = Congruent trials; Incon = Incongruent trials.

* $p < .05$.

3.2.2 P3 (350-450 ms)

The analyses on the P3 component detected a significant main effect of context, F (2, 38361) = 8.03, $p < .001$, and a significant interaction for flanker × context, F (2, 38363) = 6.05, $p = .002$. Follow-up tests showed that the forced switching context ($M = 5.54 \pm 17.53$ µV) elicited a smaller P3 effect compared to both natural switching ($M = 6.28 \pm 14.47$ µV; Estimate = -.76, SE = .19, t = -3.99, $p < .001$) and voluntary switching ($M = 5.99 \pm 14.51$ µV; Estimate = -.44, SE = .19, t = -2.28, $p = .034$). Differences between the natural and voluntary switching contexts did not reach significance (Estimate = .33, SE = .19, t = 1.71, $p = .088$).

Planned pairwise comparisons within each context revealed a reversed flanker effect in the forced switching context (Estimate = 1.61, SE = .42, t = 3.81, $p < .001$), such that there was a stronger P3 effect on congruent trials ($M = 6.37 \pm 17.60$ µV) compared to incongruent trials ($M = 4.71 \pm 17.42$ µV). However, this effect was not significant in the natural and voluntary switching contexts (t s < 1.48, p s $> .14$). Moreover, in incongruent trials, the forced switching context ($M = 4.71 \pm 17.42$ µV) elicited smaller P3 amplitude compared to both natural switching ($M = 5.96 \pm 14.61$ µV; Estimate = -1.26, SE = .27, t = -4.66, $p < .001$) and voluntary switching ($M = 5.79 \pm 14.45$ µV; Estimate = -1.07, SE = .27,t = -3.95, $p < .001$). Differences between the natural and voluntary switching contexts were not significant (Estimate = .19, SE = .27, t = .70, $p = .483$).

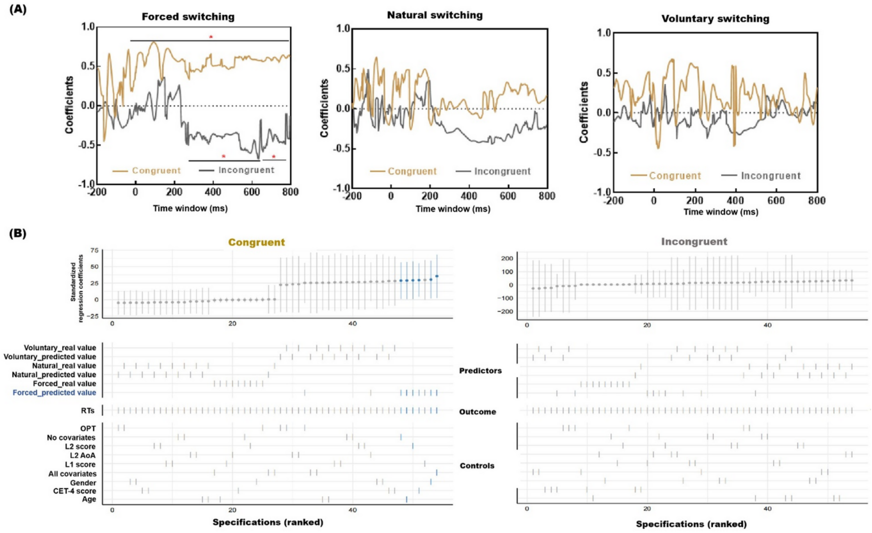
To recap, we observed a smaller N1 effect in the switch-incongruent condition of the natural switching context compared to the other two switching contexts. Differences between voluntary and forced switching contexts were not significant. Importantly, the P3 amplitude of incongruent trials in the forced switching context was smaller than both natural and voluntary switching contexts. In addition, an atypical flanker effect was detected on the P3 effect in the forced switching context, whereas such effect was not found in the other two switching contexts. These findings indicate that context-dependent language control modulates executive control.

3.3 Results from the prediction models

Adhering to the same EEG pre-processing standards, the brain activity from the preceding prcture-naming trials were put into a family of regularized RR models as independent variable to reveal its predictability on the brain activity during the current flanker trials. The predictive results regarding the impact of language control on executive control across three switching contexts are displayed in Figure 3A.

Results showed that robust brain-brain relationships were observed in the forced switching context for the modeling of congruent trials and incongruent trials. More precisely, language processing notably anticipated brain activity in subsequent congruent trials (-10 – 800ms:r = .57, $p < .001$). Additionally, for the modeling of incongruent trials, a negative relationship was significantly detected in the two time windows (272 - 640ms: r = -.43, p = .007; 648 - 772ms: r = -.44, p = .007). Furthermore, planned paired-sample t -tests showed that the prediction value of language processing in the forced switching context for congruent trials in flanker task was significantly stronger than natural or voluntary switching contexts (t s > 30.96,p s < .001).

Figure 3 . *Prediction results of ridge regression models between the three language switching contexts and flanker trials (A) and specification curve for congruent and incongruent trials separately (B).*



Note: (A) * $p < .05$, after Benjamini-Hochberg correction. (B) The blue dot indicates a significant positive regression coefficient ($p < .05$) with the vertical line in upper panels depicting the 95% confidence interval. The lower panels showed each specification model with selection of predictors and control variables. Forced_pv = predicted value in forced switching context, Forced_rv = the actual values in forced context; Natural_pv = predicted value in natural switching context, Natural_rv = the actual values in natural context; Voluntary_pv = predicted value in voluntary switching context, Voluntary_rv = the actual values in voluntary context.

To further explore whether this predictability generalized to the behavioral performance, we conducted SCA to reveal the effect of predicted value calculated by RR models for each context on RTs. The specification curve was shown in Figure 3B, and the bootstrapped results were shown in Table 1. The results showed significant positive relationship between the predicted values in the forced switching context and RTs of congruent trials. However, no significant relationships were detected for other specifications.

Table 1. Bootstrapped results of the specification curve analysis for congruent trials.

Predictors	The median standardized regression coefficients	Number of significant positive associations	Number of s
	β	p	N
Forced_pv	29.32	$< .001$	6
Forced_rv	-0.39	0.236	0
Natural_pv	-4.02	0.303	0
Natural_rv	-4.02	0.295	0
Voluntary_pv	26.2	$< .001$	0
Voluntary_rv	26.2	$< .001$	0

Note: N = the number of specification models in each specification curve analysis that the positive/negative regression coefficient is statistically significant at $p < .05$. The total number of specifications for each predictor is 9. The boostrapping was performed 1000 times. Forced_pv = predicted value in forced switching context, Forced_rv = the actual values in forced context; Natural_pv = predicted value in natural switching context, Natural_rv = the actual values in natural context; Voluntary_pv = predicted value in voluntary switching context, Voluntary _rv = the actual values in voluntary context.

4. Discussion

Language control exhibits its adaptability in two primary ways: firstly, it can flexibly implement a set of cognitive control processes to meet the demands of varying interactive contexts; secondly, it can dynamically adjust to subsequent cognitive control processes, a phenomenon commonly referred to as the cross-task conflict adaptation effect. However, the available evidence is mostly incomplete and far from conclusive. Manipulating switching contexts that approximates switching situations in bilinguals' daily lives, the present study aims to investigate how the varying switching contexts modulate cross-task conflict adaptation effect. Our findings yielded the following insights: 1) natural switching contexts caused a smaller N1 effect in switch-incongruent trials compared to forced and voluntary switching contexts; 2) the cross-domain interaction on the P3 effect, however, revealed an atypical flanker effect in forced switching contexts only, and P3 amplitude of incongruent trials in forced switching contexts was smaller than both natural and voluntary switching contexts; 3) further, the prediction models revealed robust brain-brain relationships between language control and cognitive control in the forced switching context only for both congruent and incongruent trials; 4) specification curve analysis confirmed this predictability generalized to the behavioral performance (i.e., RTs of congruent trials). Collectively, our findings indicate the modulation effect of switching contexts on cross-task adaptation effects. Especially, the forced switching context profoundly exhibited a predictive effect on the domain-general control processing in both conflict and non-conflict situations.

Our first research question concerned whether cross-task conflict adaptation effect varied among distinct switching contexts. Although no behavioral differences between the three contexts were found, the results of the N1 and P3 components confirmed the differential effects of the three switching contexts on domain-general cognitive control, especially the forced and natural switching contexts. More specifically, for N1 effect, switch-incongruent trials in the natural switching context showed a smaller N1 compared to both the forced switching context and voluntary switching context. However, there was no significant difference between voluntary and forced switching context. Instead of the N2 effect observed in previous studies (Bartholow et al., 2005; Folstein & Van Petten, 2008; Jiao et al., 2019; Kopp & Mattler, 1996; Van Veen & Carter, 2002), a negative ongoing waveform in the early time window of 120-220 ms was elicited in our study, which we preferred to define as N1 effect. The N1 effect is assumed to be indicative of persistent covert visual attention control and sensitive to the level of visual attention intensity on the target stimuli (Di Russo). The greater N1 amplitude for incongruent trials in forced and voluntary switching contexts relative to corresponding condition in natural switching context implied more attention allocated to the conflict situation in the contexts of forced and voluntary switching (Luck et al., 2000). This concentrated attention on conflict situation may be indicated as an efficient harbinger of conflict adaptation (Liu et al., 2022b; Yuan et al., 2021). The reduced N1 effect in switch-incongruent trials in natural switching contexts compared to forced and voluntary switching contexts suggests that brain activity in the former indeed stays at a lower functional level.

Furthermore, the P3 amplitude of incongruent trials in the forced switching context was smaller than both natural and voluntary switching contexts. Importantly, an atypical flanker effect was detected on the P3 effect in the forced switching context, whereas such effect was not found in the other two switching contexts. This pattern is consistent with previous studies (Hsieh & Lin, 2014; Jiao et al., 2020a; Wu & Thierry, 2013). In the pure flanker task, incongruent trials induced a larger P3 effect compared to congruent trials, which has been interpreted as a 'leakage' of response inhibition ability on the trials involving conflict (Groom & Cragg, 2015). Nevertheless, our findings indicated that constant monitoring of the appropriate language and the local inhibition of the non-target language in forced switching context resulted in a functional generalization of heightened inhibition and monitoring capacities engaged in subsequent flanker trials. Unlike the typical flanker effect, which indicates response competition in response selection, the reversed flanker effect mirrors the enhancement of perceptual processes (Hsieh & Lin, 2014; Rouder & King, 2003). These findings suggest that forced switching may alleviate some cognitive demands introduced by incongruent trials by strengthening the perceptual differentiation to incongruent trials relative to congruent trials. Bilingual participants were able to adaptatively generalize their conflict monitoring and language control to domain-general cognitive control, facilitated by more recruitment of inhibition and conflict monitoring in the switching context. Similarly, in a dual-EEG study by Liu et al. (2022), a reversed flanker effect was revealed in mixed-language contexts, but not in single-L1 contexts. The authors thus argued that the adaptation of language control was limited to a situation involving similar control mechanisms.

Our second research question examined how the adaptive patterns manifested in flanker trials. Concerning our predictive model results, however, it is plausible to demonstrate that the cross-task conflict adaptation effect is not limited to conflict situations. A set of RR models using coding activities of language switching tasks across the three contexts to predict processing in the flanker task revealed that language control processing engaged in forced switching contexts displayed the earliest and most stable (of all predictive models) positive relationships in congruent trials. The positive correlation emerged at -10ms before the congruent stimuli were presented, lasting until 500ms. This suggests that forced switching offers cognitive assistance for subsequent flanker tasks during early processing stages. In the models for incongruent trials, negative brain-brain predictions were detected starting at 272ms in forced switching context, suggesting the effective enhancement of forced switching on conflict resolution. The prediction outcomes indicate varying effects and strengths of forced switching contexts on congruent and incongruent trials. Although in this context, which relies on top-down control mechanisms such as conflict monitoring, resolution, and inhibitory control, the contextual influence differs notably between congruent and incongruent trials. The early emergence of predictive relationships when processing congruent trials suggests that the continuous monitoring of two activated languages in forced switching contexts is swiftly generalized to executive control processing, while inhibition exhibited a later effect. The specification curve results corroboratively showed significant positive relationship between the predicted values in the forced switching context and RTs of congruent trials. However, no significant relationships were detected for other specifications. It seems that the cross-task adaptation of language control to domain-general cognitive control is reasonably general and not limited to conflict situations.

As afore-introduced, previous studies have not reached a consensus. Some studies suggest that this adaptation shifting was limited to conflict situations (Liu et al., 2022b; Wu & Thierry, 2013), i.e., incongruent-specific facilitation, whereas other work has reported a wider advantage for both incongruent and congruent trials (Jiao et al., 2019; Liu et al., 2016). For example, in a behavioral study by Liu et al. (2016), the performance of a group of bilinguals in a nonlinguistic "faces" task was measured before and after completing a language-switching task. Results showed that participants' response inhibition and interference suppression were both improved after language switching. Similar results have been shown in research on code-switching. For instance, Alder and Valdés Kroff (2020) used a cross-task conflict-adaptation paradigm to examine whether reading code-switched sentences would influence performance on subsequent incongruent trials, and confirmed a behavioral enhancement introduced by reading code-switched vs. non-code-switched sentences. The present study, on the basis of previous research efforts, causally provides predictive evidence for the cross-task adaptation of language control to domain-general cognitive control. However, considering the predictive effect in congruent trials were stronger and earlier than incongruent trials, our findings, further substantiated through SCA analysis (a significant brain-behavior relationship between predict value of congruent trials and RTs in forced switching context only), suggest that the promoting effect of forced switching on domain-general control varies between congruent and incongruent conditions. The cross-task adaptation from language control to domain-general control dynamically adjusts the engagement of executive functions to adapt to current task demands.

This finding is consistent with recent neuroimaging studies revealing the overlap between language control and executive control, such as conflict detection and monitoring, along with shifting and inhibitory control (Abutalebi et al., 2012; D'Souza, & D'Souza, 2016; Hwang et al., 2017; Wu et al., 2019; Yeo et al., 2016; Yuan et al., 2021). In a study comparing the performance of English monolinguals, unimodal bilinguals, and bimodal bilinguals (who acquired both English and American Sign Language) in a flanker task, Emmorey and colleagues (2008) found that unimodal bilinguals performed faster than monolinguals and bimodal bilinguals, and that performance of bimodal bilinguals did not differ from monolinguals. These findings traced the bilingual advantage in executive control to bilinguals' experience in switching languages more frequently. Subsequent research has shown that a bilingual advantage only emerged when the two languages were intermittently used in mixed-language contexts compared to single-language contexts (Alder and Valdés Kroff, 2020; Jiao et al., 2019; Jiao et al., 2020a; 2020b; Liu et al., 2016; Liu et al., 2022b; Wu and Thierry, 2013; Yuan et al., 2021). The constructs of language control and cognitive control share multiple subsets, such as conflict monitoring and inhibition of prepotent interference (Abutalebi et al., 2012; Blanco-Elorrieta & Pylkkänen, 2016, 2017; Emmorey et al., 2008; Liu et al., 2022b). Bilinguals need to trigger a stricter top-down control process depending on the needs of forced switching contexts. Building upon these findings, our study further indicates that different switching contexts distinctly modulates the components engaged in a subsequent executive control task.

5. Limitations

While our study is the initial endeavor to directly investigate diverse cross-task adaptation patterns across three switching contexts, acknowledging certain limitations is crucial for future research. Firstly, participants in the present study were all late-proficient Chinese-English bilinguals whose reported L2 acquisition occurred after the age of 6. Previous studies have found that the early bilingual experiences yield stronger functional connectivity of brain regions between language and cognitive context, and that this pattern was associated with higher brain activation efficiency (Berken et al., 2016; Stein et al., 2014), suggesting that L2 age of acquisition may affect the efficiency of cross-task adaptation. Secondly, our experiment was conducted on single-person situations without simulating virtual companions. However, a recent study by Rafeekh and Mishr (2021) reported that if a session, in which bilinguals are introduced to a partner with a differing L2 proficiency level, is added before beginning the experiment, bilinguals show a lower conflict effect in the flanker task than in the presence of a balanced bilingual partner, even the partner only appears on screen and is not required to complete the task with the participant. These results suggest that the dynamic regulation of the context mechanism in bilinguals may be influenced by interactions with interlocutors. Future studies should explore the effect of interpersonal interactions on cross-task adaptation in interactive contexts.

6. Conclusion

The present study combined EEG and machine learning models to examine whether and how three language switching situations which bilinguals encounter in their daily lives modulate the cross-task conflict adaptation effect. The results confirmed that cross-task adaptation from forced switching surpassed the adaptative shift of natural switching with minimal cognitive demands. This automatic adaptation is strategically dependent on the switching contexts, and the shared construct between language control and domain-general control. Furthermore, the predictive outcomes confirm that this adaptive advantage is broadly applicable and not confined to specific conditions. In sum, our findings shed new light on the fundamental characterization of how language switching contributes to domain-general cognitive control.

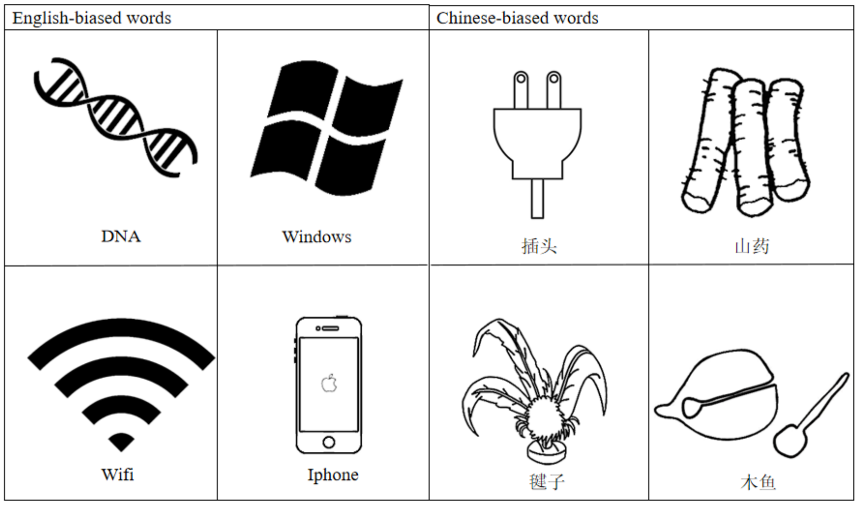
Data availability

Liu, D. (2024, July 26). The dynamic influence of language switching contexts on domain-general cognitive control. Retrieved from osf.io/24ak3

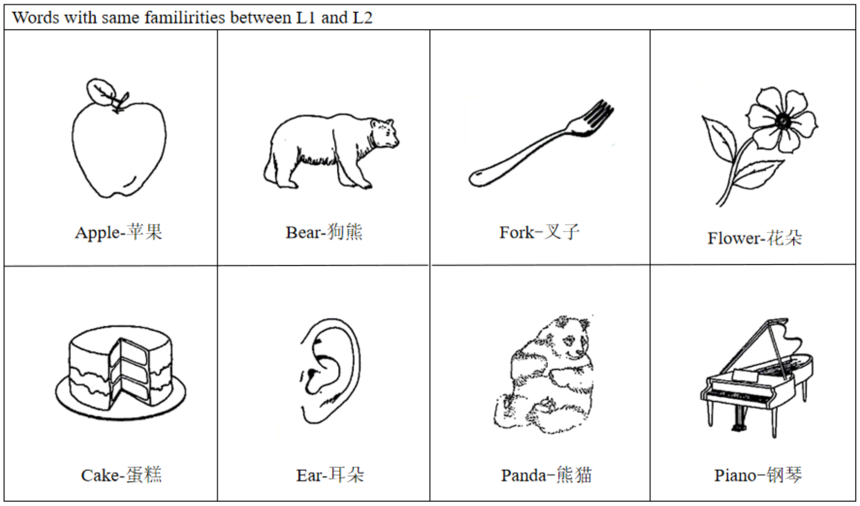
Appendix

Picture stimuli and words used in the picture-naming task

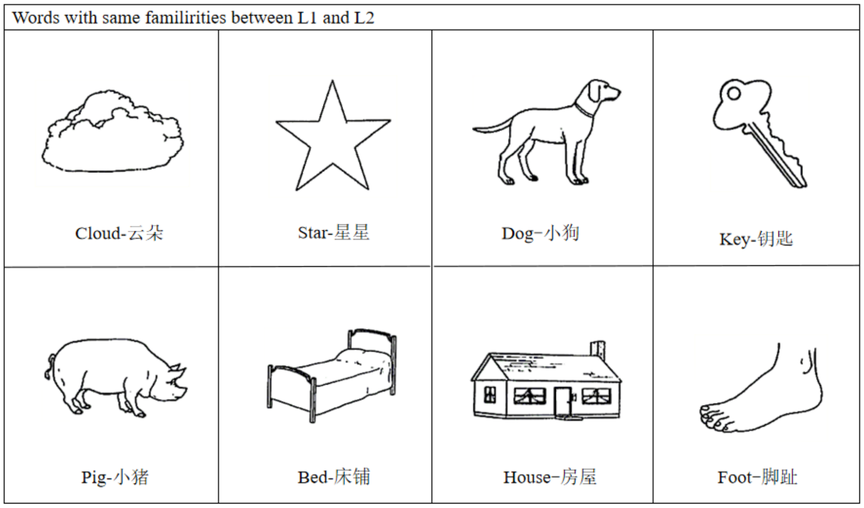
(A) Picture stimuli of the natural context



(B) Picture stimuli of the forced context



(C) Picture stimuli of the voluntary context



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