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ARTICLE

An interplay of inhibitory and facilitative mechanisms during language control: evidence from phonetic-level language switching with a letter-naming task

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Abstract
Language control in the bilingual brain has remained in the limelight of research over the past decades. However, the mechanisms underlying bilingual language control may be more intricate than typically assumed due to the hierarchical nature of language. This study aimed to investigate the dynamics of bilingual language control at the phonetic level. Participants, who were speakers of Chinese, English and German, named the letters of the alphabet in English (L2) or German (L3) following an alternating language-switching paradigm. Two sets of letters were selected, differing in the phonological similarity of their pronunciation across the two languages, thereby allowing the exploration of cross-language phonological influences. Each participant completed two sessions of letter-naming tasks. In one session, seven phonologically similar letters were randomly repeated either in single-language blocks or in alternate-language blocks. In the other session, seven phonologically dissimilar letters were similarly manipulated. The results indicated local inhibition, reflected by switch costs and global inhibition, reflected by mixing costs. Reversed language dominance, another indicator of global inhibition, was not observed. However, there was a tendency for larger global inhibition to be applied to the more dominant language. Moreover, there was significantly faster naming for phonologically similar letters compared to dissimilar ones, suggesting a facilitation effect for both English and German, irrespective of whether letter naming occurred in single- or alternate-language blocks. These findings provided evidence for the role of inhibitory and facilitative mechanisms at the phonetic level, suggesting language-specific control in the bilingual brain and underscoring the complexity and dynamics of managing language control across multiple levels of processing.

Keywords: facilitative mechanism; inhibitory mechanism; language control; language switching; phonological similarity

1. Introduction

Bilinguals/multilinguals exhibit remarkable cognitive flexibility and adaptability in handling tasks like language switching, selective attention and inhibition of non-relevant languages (e.g., Abutalebi & Green, 2007; Crinion et al., 2006; Declerck & Koch, 2023; Declerck & Philipp, 2015a; Green, 1998; Rodriguez-Fornells et al., 2002). This constant juggling enhances various cognitive functions, making it an excellent model for studying cognitive control (e.g., Bialystok & Feng, 2009). This unique capability not only highlights the ability of bilinguals/multilinguals to adapt to complex linguistic environments but also offers insights into broader cognitive processes.

There has been ongoing debate about whether the executive functions underlying the ability to manage between languages, also referred to as bilingual language control, are domain-general or language-specific. Currently, the most dominant consensus is that bilingual language control is subsidiary to the domain-general executive control system (e.g., Abutalebi & Green, 2007; Dijkstra & Van Heuven, 2002; Meuter & Allport, 1999; Tao et al., 2021). However, the present study focuses on language-specific control in bilinguals/multilinguals. More specifically, this study aims at language control at the phonetic level.

1.1. Language control in bilinguals/multilinguals

Language switching is one of the most commonly used tasks to investigate bilingual language control, just as task switching is one of the most commonly used tasks to investigate executive control. Inhibition is a critical component of executive control in both task switching and language switching, essential for suppressing cognitive processes related to a previously performed task to facilitate the transition to a new task (Green, 1998; Monsell, 2003). In this vein, an inhibitory control mechanism has been proposed to account for asymmetrical switch costs at the local level as well as mixing costs at the global level (for reviews, see Declerck & Philipp, 2015a; Koch et al., 2010). Consequently, the overlap between task switching and language switching naturally suggests that both processes rely on executive functions, especially inhibitory control.

This domain-general perspective is supported by studies showing that bilinguals often outperform monolinguals on tasks requiring executive control (for reviews, see Antoniou & Wright, 2017; Bialystok, 2017; Bialystok & Feng, 2009; Kroll et al., 2018). The 'bilingual advantage' hypothesis posits that the constant need for bilinguals to manage and switch between two languages generalizes to nonlinguistic cognitive domains, which strengthens their domain-general cognitive control mechanisms. Such an advantage has been demonstrated to extend to infant as well as aging bilinguals. However, some studies have failed to find a bilingual advantage, leading to debates about the consistency and generalizability of these findings (for reviews, see Lehtonen et al., 2018; Paap et al., 2015). Factors such as age, proficiency in both languages, cultural differences and socioeconomic status may influence the presence and extent of the bilingual advantage (e.g., Hartanto et al., 2019; Masullo et al., 2023).

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Some researchers have even suggested that the benefits of bilingualism may be task-specific (e.g., Gollan et al., 2002; Ivanova & Costa, 2008) or due to a publication bias (e.g., de Bruin et al., 2015).

Other researchers contend that bilingual language control is, at least in part, language-specific. From a usage-based perspective, language is conceptualized as a complex adaptive system, composed of interconnected subsystems (e.g., phonology, lexicon, semantics, syntax, etc.), which do not operate in isolation but rather interact dynamically over time (Schmid, 2020). This perspective aligns closely with the concept of 'linguistic multi-competence' in research on bilingualism, which highlights the flexibility and integration of languages within a single system (Cook & Wei, 2016). In this framework, multiple languages coexist and draw upon shared cognitive resources, adapting to context and experience. Such complexity and dynamics pose a significant challenge for bilinguals, who must simultaneously navigate and manage these various subsystems (or loci) across languages during both comprehension and production tasks. Consequently, language control is not localized to a single locus but operates at multiple loci within the language system (Bobb & Wodniecka, 2013; de Bruin et al., 2015; Declerck & Philipp, 2015a; Gollan et al., 2014; Kroll et al., 2006; Zhang et al., 2019). There is some evidence for the involvement of various processing loci during language control, including lemmas (e.g., Tarlowski et al., 2012), phonology (e.g., Declerck & Philipp, 2015b) and orthography (e.g., Orfanidou & Sumner, 2005). Each of these loci plays a role in managing the flow of language production and comprehension. Bilinguals must exercise dynamic control over these loci to avoid cross-language interference and ensure smooth, efficient communication. Apparently, this control is not limited to the coordination of phonological and syntactic structures but also encompasses the management of lexical access, semantic retrieval and pragmatic considerations. Such multifaceted control is essential for effective communication, preventing language interference and underscoring the complexity of bilingual language management.

Moreover, researchers have questioned whether inhibition alone is the primary mechanism underlying effective language control in bilinguals (e.g., Costa et al., 1999; La Heij, 2005; Philipp et al., 2007). Instead, it has been proposed that bilingual language processing involves multiple mechanisms, as inhibition and facilitation (increased activation) are not mutually exclusive but can operate concurrently (Declerck & Philipp, 2015a). Evidence suggests that both interference and facilitation can occur at different loci within the language processing system, with the coactivation of both languages playing out in different ways depending on the context (Muscalu & Smiley, 2019; Tabori & Pyers, 2024). For example, a recent study demonstrated that the interaction between L1 translation knowledge and L2 proficiency significantly affected tip-of-the-tongue experiences, with L1 translation interference more pronounced at lower levels of L2 proficiency and L1 translation facilitation emerging at higher levels (Tabori & Pyers, 2024). Similarly, in a written translation task, Muscalu and Smiley (2019) found that cognate facilitation impacted onset latencies, while full-word typing durations were affected by cognate interference. They concluded that cognate facilitation operates at the lexical level, whereas cognate interference occurs at the sub-lexical level. These findings highlight the complexity of bilingual language control, suggesting that it likely involves both inhibition and increased activation, which give rise to interference and facilitation effects across different levels of language processing. This study will focus specifically on the complexity and adaptability of language control at the phonetic level.

1.2. Phonetic-level control in the language switching paradigm

Research into the effects of phonological properties on language switching often involves manipulating the 'cognate status' of words (e.g., Broersma & Cutler, 2011; Christoffels et al., 2007; Declerck & Koch, 2023; Filippi et al., 2014; Li & Gollan, 2021; Thomas & Allport, 2000). Cognates are words in two languages that have similar forms and meanings with a shared etymological origin, such as *nation* in English and *nación* in Spanish. By comparing how bilinguals process cognates and noncognates, researchers can gain insights into how phonological properties influence bilingual language processing. Studies have shown that cognates are generally processed more quickly and accurately than noncognates, suggesting a cognate facilitation effect (e.g., Broersma & Cutler, 2011; Christoffels et al., 2007; Declerck & Koch, 2023; Filippi et al., 2014; Li & Gollan, 2018; Thomas & Allport, 2000). This is attributed to the overlapping phonological and semantic features that facilitate lexical access in both languages (e.g., Costa et al., 2000; Hoshino & Kroll, 2008). However, this cross-language phonological effect appears to differ based on language-switching contexts: smaller switch costs with cognates than noncognates are observed when cognates and noncognates are presented in separate blocks (e.g., Broersma & Cutler, 2011; Declerck et al., 2012), whereas larger switch costs with cognates than noncognates are found when they are presented within the same experimental block (e.g., Filippi et al., 2014; Thomas & Allport, 2000). According to Declerck and Philipp (2015a), these differing effects across and within blocks may reflect variations in the level of control required: in the former case, persistent effects such as (increased) activation or inhibition at the phonological level may be at play, while in the latter case, within-trial control processes could be responsible.

Alternatively, the cognate effect observed in bilingual production literature has been interpreted as the late feedback reactivation of the nontarget language (Kroll et al., 2006). Specifically, the cognate word in the nontarget language becomes reactivated due to its orthographic and/or phonological association with the cognate word in the target language during the selection of the target word for production. This reactivation is thought to arise from cross-linguistic effects, where the activation of a cognate in the nontarget language influences the phonological and lexical retrieval processes of the target language. Such late-stage effects are believed to reflect a top-down feedback mechanism, in which earlier stages of lexical processing in the target language can trigger the activation of related items in the nontarget language, thereby contributing to cross-linguistic effects. Similarly, Kroll et al. (2000) explained the cross-language homophone interference observed during a picture naming task as resulting from the feedback reactivation of the nontarget language.

Unlike much research on the cognate status of words with overlapping phonological and semantic features, Declerck and Philipp (2015b) focused on the effect of noncognates with partial phonological overlap. More specifically, words of the picture names (i.e., object names) with the first two phonemes being identical to those of the word in the previous trial (e.g., drill-dress) were compared to words with no overlap in the first two phonemes (e.g., cherry-bone) in a language switching context. The results revealed that switch cost asymmetry was influenced by the manipulation of noncognates with partial phonological overlap. This effect was explained by the persistent influence of (partial) phonological overlap from the current trial, which carried over to affect the subsequent trial (i.e., trial n + 1), consistent with the assumptions of the inhibitory control (IC) model (Green,

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1998). These findings clearly demonstrate that partial phonological manipulations can influence language switching. However, in another study (Experiment 4), Declerck et al. (2013) manipulated words with language-unspecific phonemes that occur in both languages and words with language-specific phonemes (e.g., German-specific phoneme /χ/ and English-specific phoneme /θ/). The results showed no difference in switch costs between words with language-unspecific phonemes and words with language-specific phonemes, suggesting that variations in the phonological properties of stimulus words do not influence language switching.

A recent study (Zuo et al., 2022) examined language switching with a letter-naming task, offering a unique opportunity to explore the interaction between the two phonetic networks of bilingual individuals. In their research, Chinese-English bilinguals named pinyin in Chinese or alphabet letters in English with a cued language switching paradigm. They observed asymmetrical switch costs and mixing costs, which they attributed to the inhibitory control mechanism. Notably, some letters have more similar pronunciations (e.g., 's', 'k'), while others have more distinct pronunciations (e.g., 'w', 'r') in Chinese pinyin compared to the English alphabets. Therefore, the potential impact of phonological overlap between equivalents of letters was not explicitly examined in their study. Examining this impact is intriguing, as it would shed light on the dynamics of language control at the phonetic level and advance our understanding of language control mechanisms in general.

In summary, research on the effects of phonological properties with language switching has produced mixed results regarding whether phonological overlap facilitates or interferes with language processing. These variations seem to be influenced by the type and extent of overlap and the broader experimental context. Further research is needed to explore these effects further by incorporating phonological stimuli that vary in their degree of overlap. Examining these dynamics at the phonetic level could reveal new insights into the fine-grained mechanisms of language control.

1.3. The present study

The present study sought to examine the influence of cross-language phonological similarity on letter naming using an alternating language-switching paradigm. In this context, cross-language phonological similarity refers to the degree to which the pronunciation of a letter in one language resembles its pronunciation in another language. For instance, the letter 'n' is pronounced similarly in both English and German ([ɛn]), whereas the pronunciation of the letter 'j' differs considerably between the two languages (English: [dʒeɪ], German: [jɔt]). The rationale of this study is simple: Despite these phonological similarity or dissimilarity, the visual representation of the letters remains consistent, with the same orthographic symbols being used across both languages. This allows for a meaningful comparison of phonetic processing between two phonetic networks. Presumably, this cross-language phonological similarity can potentially influence the cognitive processes involved in language switching. Therefore, this study used phonetic switching to examine phonetic-level control. More specifically, the letter names of the alphabets (26 letters) in English (L2) and German (L3) were used as the experimental stimuli, because the letter names can basically be seen as words in their own right out of context. Moreover, the letters in this study, unlike words with cognate status,

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contained no lexical or semantic information, which minimized potential confounding factors.

Participants in this study were trilingual speakers, with Chinese being their first language (L1), English as their second language (L2) and German as their third language (L3). Unlike alphabetic languages, which require phonological mediation, Chinese is a logographic language with minimal phonological mediation (Zhou & Marslen-Wilson, 1999). Therefore, we selected letters of English (L2) and German (L3) for the naming tasks. For this purpose, we chose two sets of letters from English and German. These sets vary in the level of phonological similarity between the pronunciations in both languages (phonologically similar versus dissimilar). All participants conducted two sessions of letter-naming tasks (i.e., one session with phonetically similar letters and the other with phonetically dissimilar letters), allowing us to examine cross-language phonological influences (see Methods for details).

This study addresses three research questions: (1) Is local inhibition, indicated by switch costs and particularly switch cost asymmetry, present? (2) Is global inhibition, as evidenced by mixing costs and reversed language dominance, observable? (3) Does cross-language phonological similarity in letter naming interfere with or facilitate language switching? Drawing on findings from studies on language switching involving picture-, digit-, or letter-naming tasks (e.g., Bobb & Wodniecka, 2013; Declerck, 2020; Declerck & Koch, 2023; Declerck & Philipp, 2015b; Zhang et al., 2024; Zuo et al., 2022), we hypothesize that language switching during the letter-naming task in this study will result in (asymmetrical) switch costs, which are indicative of local-level inhibition. Additionally, we expect the presence of mixing costs and reversed language dominance, reflecting global-level inhibition. However, it remains unclear whether cross-language phonological similarity in letter naming exerts an interference effect or facilitates language switching.

2. Method

2.1. Participants

Forty-four right-handed Chinese-English-German trilingual participants were recruited (mean age 20 ± 1.3, range 18–22, 37 female). None of them reported language, hearing, or neurological impairments. Additionally, participants were not color blind and had normal or corrected-to-normal vision. Each participant provided written informed consent. The experiment was approved by the Ethics Review Board of Southwest University of Political Science and Law, China.

The language proficiency, use and exposure for each language were assessed using the Chinese version of the Language Experience and Proficiency Questionnaire (LEAP-Q) (Marian et al., 2007). As shown in Table 1, Mandarin, their first language (L1), served as their dominant language. They began learning English as a foreign language around the age of ten. Later, they started learning German as another foreign language, with approximately one year of learning experience (ranging from 0.5 to 1.5 years), indicating a beginner level of proficiency in German. Moreover, paired t-test showed significant differences between English (L2) and German (L3) in age of acquisition (AoA), self-rated proficiency of listening, speaking, reading and writing, language exposure and use, with all P-values being less than .001, suggesting an unbalanced status with English being the more dominant language and German the less dominant language.

Table 1. Language background of participants: age of acquisition (AoA), scores of self-rated proficiency, language exposure and language use

Language background	Chinese (L1)	English (L2)	German (L3)
Age of acquisition (AoA, years)	0.3 (0.3)	10.1(1.4)	18.9 (0.4)
Self-rated proficiency (0–10)			
Listening	9.4 (0.8)	6.0 (0.9)	3.5 (0.4)
Speaking	9.2 (1.0)	6.1 (1.4)	4.0 (0.5)
Reading	9.3 (0.7)	7.1 (0.9)	4.9 (0.5)
Writing	8.7 (0.9)	6.3 (0.8)	3.6 (0.3)
Language exposure (percentage)	65 (9)	13 (5)	22 (4)
Language use (percentage)	74 (11)	9 (2)	17 (3)

Note: Values within parentheses are standard deviations (SD).

2.2. Materials

For 26 letters that are orthographically identical in both English and German, an independent cohort of 29 Chinese-English-German trilingual speakers assessed the phonological (or pronunciation) similarity between English and German on a 5-point scale, ranging from very different (1) to very similar (5). Seven phonologically similar letters (n, s, m, f, l, x, o; mean score 4.15 ± 0.55) and seven phonologically dissimilar letters (j, y, r, w, v, z, h; mean score 1.15 ± 0.14) were selected as experimental stimuli. Paired *t*-test showed a significant difference in phonological similarity between these two sets of letters ($P < .001$). The remaining 12 letters were used as practice stimuli during the practice session and as warm-up trials in each block of the formal experiment.

2.3. Procedure

Participants familiarized themselves with the letter names of the alphabet (26 letters), randomly sequenced, in English and German, respectively, on the screen. Then, the participants conducted a practice session with a single English (L2) block, a single German (L3) block and two alternate-language blocks. The instructions and procedures in the practice session were identical to those in the experimental sessions (see below).

The experiment consisted of two sessions: the phonologically similar session (seven letters: n, s, m, f, l, x, o) and the phonologically dissimilar session (seven letters: j, y, r, w, v, z, h). These two sessions were counterbalanced across participants and there was about a 10-minute break between sessions. Each session comprised eight blocks in the following order: block 1 (single English), block 2 (single German), blocks 3–6 (alternate language), block 7 (single German) and block 8 (single English). The order of English and German blocks was counterbalanced across participants to offset the potential block order effect. In the single-language blocks, participants named each letter in either English or German for the entire block, depending on the designated (single) language. In the alternate-language blocks, two languages were mixed in a way that the naming languages switched after every second trial (e.g., L2-L2-L3-L3, etc.). Each single-language block contained 28 trials, while each alternate-language block contained 56 trials. Consequently, each session included 336 trials, with each letter repeated 48 times. This design ensured that each letter was named equally often in each language and appeared equally frequently in both switch

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and nonswitch trials within each block. Additionally, each block began with two warm-up trials which were excluded from analysis. Despite the predictable language sequence in the alternate-language blocks using an alternating language paradigm, each letter was colored with a redundant visual language cue (i.e., red, yellow, blue and green) to remind participants of the response language for each trial. Each language (English or German) is associated with two colors, and the color of the cue changed after every two consecutive trials, regardless of language switches. This was done to minimize confounds between the cue switch and language switch (Heikoop et al., 2016). The color-to-language association was counterbalanced across participants. In the single-language blocks, the letter color also changed on every trial.

Each trial began with a 200-ms cross fixation, followed by a 300-ms blank screen. Then, a colored letter was displayed until a response was made or until 2000 ms elapsed if no response was recorded. Participants were asked to name the letter with speed and accuracy 1) in English in single English blocks, 2) in German in single German blocks and 3) switched languages between English and German after every second trial in alternate-language blocks. Afterwards, a blank screen was displayed for 1000 ms. Letters were presented in lowercase, one at a time, in the center of the screen. The visual angle of each target letter measured 2.5° to 3° vertically and 0.8° to 2.5° horizontally, depending on the specific letter. The main experiment was conducted in a dimly-lit soundproof booth. The experiment was programmed and run using E-Prime 3.0 on a DELL PC. The viewing distance was approximately 60 cm from the screen, which had a refresh rate of 60 Hz and a resolution of 1024 × 768 pixels. Response times (RTs) were measured relative to stimulus onset by means of a Chronos microphone device (Psychology Software Tools, Pittsburgh, PA), and vocal responses were also recorded for offline check for erroneous responses. Meanwhile, outside the soundproof booth, the experimenter coded errors on the spot via a wireless omnidirectional microphone system. Participants were debriefed after the experiment.

2.4. Data analysis

Switch costs and mixing costs were analyzed separately. Switch costs were quantified by examining the differences in RTs or error rates between switch trials and nonswitch trials within alternate-language blocks. A three-way repeated-measures ANOVA was performed on both RTs and error rates, with switching (switch versus nonswitch), language (English/L2 versus German/L3) and phonological similarity (similar versus dissimilar) as within-subject factors. Then, mixing costs were calculated by comparing nonswitch trials in alternate-language blocks to single-language trials in single-language blocks. A three-way repeated-measures ANOVA was also conducted on RTs and error rates, with mixing (single versus nonswitch), language (English/L2 versus German/L3) and phonological similarity (similar versus dissimilar) as within-subject factors.

3. Results

RTs were analyzed on valid trials only. Trials were rated as invalid (2.9%) if the participant made (1) no response, (2) a response in a wrong language, (3) errors (false naming) and hesitations (an oral hesitation such as ‘en’, ‘a’). Trials were also excluded

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from analyses if participants failed to respond within 2,000 ms or a response latency exceeded three standard deviations above or below the average.

3.1. Switch costs

Response times. The analysis (see Figure 1, Table 2 and Table 3) revealed a significant main effect of switching [F (1,43) = 167.18, P < .001], with an observed switch cost of 45 ms for switch trials (789 ms) as compared to nonswitch trials (744 ms). No significant main effect of language was observed [F < 1], with RTs for German (768 ms) and English (764 ms) being comparable. A significant main effect of phonological similarity was observed [F (1,43) = 77.67, P < .001], indicating a facilitation effect of 145 ms for phonologically similar trials (694 ms) as compared to phonologically dissimilar trials (839 ms). Additionally, there was an interaction between switching and language [F (1,43) = 5.29, P = .026]. Simple effects analysis indicated a greater switch cost for English (51 ms) compared to German (39 ms), with both languages showing significant switch costs [Ps < .001]. A significant interaction between language and phonological similarity was also significant [F (1,43) = 15.43, P < .001]. Simple effects analysis revealed a larger facilitation effect for German (148 ms) than for English (142 ms), with the facilitation effect significant for both languages [Ps < .001]. No significant interaction was found between switching and phonological similarity [F < 1], nor was there a significant three-way interaction among switching, language and phonological similarity [F < 1].

Errors. The analysis (see Figure 1, Table 2 and Table 3) identified a significant main effect of switching [F (1,43) = 24.58, P < .001], with a switch cost of 1.3%, where switch trials had an error rate of 4.1% compared to 2.8% for nonswitch trials. A marginally significant main effect of language was found [F (1,43) = 3.56, P = .066], with error rates of 3.8% for German and 3.2% for English. A significant main effect of phonological similarity was observed [F (1,43) = 29.60, P < .001], demonstrating a facilitation effect of 2.9%, where phonologically similar trials had an error rate of 2.0% compared to 4.9% for phonologically dissimilar trials. An interaction between switching and phonological similarity was significant [F (1,43) = 7.39, P = .009]. Simple effects analysis revealed a greater switch cost for phonologically dissimilar trials (1.9%) [P < .001] compared to phonologically similar trials (0.6%) [P = .013]. No other interactions were significant [Fs < 1].

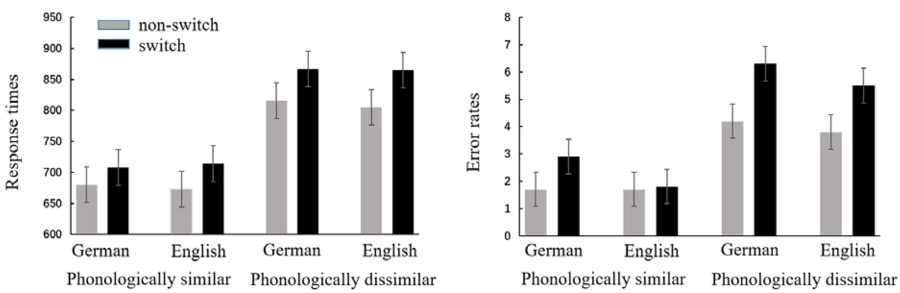

Figure 1. Effects of language switching. Mean response times (RTs) in milliseconds (ms) and error rates in percent (%) of letter naming as a function of switching (nonswitch versus switch), language (German versus English) and phonological similarity (similar versus dissimilar). Error bars represent the standard errors of the mean.

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Table 2. Effects of language mixing and switching

Phonological	Single-language blocks		Alternate-language blocks							
Similarity	Single language		Nonswitch		Switch		Mixing cost		Switch cost	
Language	RTs	Error	RTs	Error	RTs	Error	RTs	Error	RTs	Error
Phonologically similar										
German	633 (103)	1.7 (2.2)	680 (122)	1.7 (1.8)	708 (138)	2.9 (2.8)	−47	0	−28	−1.2
English	596 (100)	0.7 (1.8)	673 (120)	1.7 (2.4)	714 (137)	1.8 (2.9)	−77	−1	−41	−0.1
	37	1	7	0	−6	1.1				
Phonologically dissimilar										
German	778 (119)	3.4 (5.0)	816 (127)	4.2 (4.1)	867 (138)	6.3 (4.5)	−38	−0.8	−51	−2.1
English	694 (117)	1.2 (1.8)	805 (132)	3.8 (3.7)	865 (132)	5.5 (4.8)	−111	−2.6	−60	−1.7
	82	2.2	11	0.4	2	0.8				

Note: Mean response times (RTs) in milliseconds (ms) and error rates in percentage (%) dependent on trial type (single language; nonswitch; switch), response language (L2/English; L3/German) and phonological similarity (similar; dissimilar). Standard deviations (SD) are in parentheses.

Table 3. Analysis of variance performed on response times (left) and error percentages (right), separate for ‘switch cost’ and ‘mixing cost’, with the variables switching (Swi) or mixing (Mix), response language (Lan) and phonological similarity (Ph.S)

		Response times				Errors			
	df_1, df_2	*MSE*	*F*	η_p^2	*P*	*MSE*	*F*	η_p^2	*P*
Switch cost									
Swi	1, 43	1063	167.18	.79	**<.001*****	.001	24.58	.36	**<.001*****
Lan	1, 43	1898	.62	.01	.434	.001	3.56	.08	.066
Ph.S	1, 43	23675	77.67	.66	**<.001*****	.003	29.60	.41	**<.001*****
Swi*Lan	1, 43	532	5.29	.11	**.026***	<.001	2.69	.06	.108
Swi* Ph.S	1, 43	630	15.43	.26	**<.001*****	<.001	7.39	.15	**.009****
Lan* Ph.S	1, 43	1039	.787	.02	.380	.001	.005	.00	.942
Swi*Lan* Ph.S	1, 43	326	.363	.01	.550	.001	.415	.01	.523
Mixing cost									
Mix	1, 43	2753	147.71	.77	**<.001*****	.001	13.65	.24	**.001****
Lan	1, 43	4519	23.47	.35	**<.001*****	.001	7.93	.15	**.007****
Ph.S	1, 43	14091	101.62	.70	**<.001*****	.001	22.42	.34	**<.001*****
Mix*Lan	1, 43	1079	52.58	.55	**<.001*****	<.001	8.87	.17	**.005****
Mix* Ph.S	1, 43	2456	1.50	.03	.227	.003	3.44	.07	.071
Lan* Ph.S	1, 43	1671	8.52	.16	**.006****	.001	1.86	.04	.180
Mix*Lan* Ph.S	1, 43	948	10.88	.20	**.002****	.001	.780	.02	.382

Note: Significant effects are in bold.

3.2. Mixing costs

Response times. The analysis (see Figure 2, Table 2 and Table 3) demonstrated a significant main effect of mixing [F (1,43) = 147.72, P < .001], with a mixing cost of 68 milliseconds (ms) for nonswitch trials in alternate-language blocks (744 ms) compared to single-language blocks (676 ms). A significant main effect of language was observed [F (1,43) = 23.47, P < .001], with German (727 ms) being 35 ms slower than English (692 ms). There was also a significant main effect of phonological similarity [F (1,43) = 101.62, P < .001], showing a facilitation effect of 128 ms, with

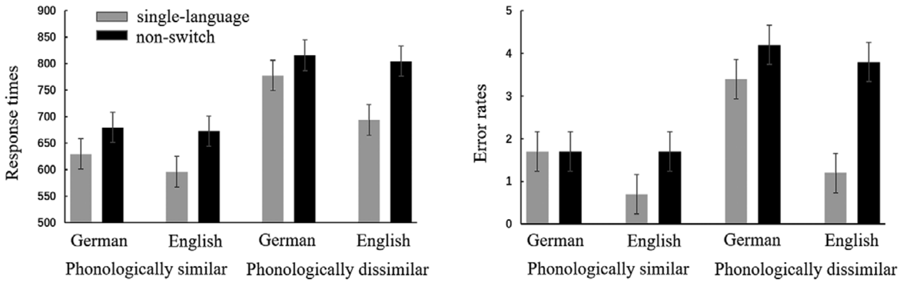

Figure 2. Effects of language mixing. Mean response times (RTs) in milliseconds (ms) and error rates in percent (%) of letter naming as a function of mixing (single-language versus nonswitch), language (German versus English) and phonological similiarity (similar versus dissimilar).

phonologically similar trials averaging 646 ms compared to 774 ms for phonologically dissimilar trials. An interaction between mixing and language was significant [F (1,43) = 52.58, P < .001]. Simple effects analysis indicated a larger mixing cost for English (93 ms) compared to German (43 ms), with both languages showing significant mixing costs [Ps < .001]. Additionally, an interaction between language and phonological similarity was found [F (1,43) = 8.52, P = .006]. Simple effects analysis revealed a larger facilitation effect for German (140 ms) than for English (115 ms), with the facilitation effect being significant for both languages [Ps < .001]. Furthermore, a three-way interaction among mixing, language and phonological similarity was significant [F (1,43) = 10.88, P = .002]. Simple effects analysis showed that German was significantly slower than English in single-language blocks for both phonologically similar and dissimilar trials [Ps < .001], while no significant difference was found between German and English in alternate-language blocks for either type of trial [Ps > .05]. No significant interaction was observed between mixing and phonological similarity [F < 1].

Errors. The analysis (see Figure 2, Table 2 and Table 3) showed a significant main effect of mixing [F (1,43) = 13.65, P = .001], with a mixing cost of 1.0% for nonswitch trials in alternate-language blocks (2.8%) compared to single-language blocks (1.8%). A significant main effect of language was also observed [F (1,43) = 7.93, P = .007], with error rates for German (2.8%) being 0.9% higher than for English (1.9%). Additionally, a significant main effect of phonological similarity was found [F (1,43) = 22.42, P < .001], showing a facilitation effect of 1.7%, with phonologically similar trials having an error rate of 1.5% compared to 3.2% for phonologically dissimilar trials. There was a significant interaction between mixing and language [F (1,43) = 8.87, P = .005]. Simple effects analysis revealed a mixing cost for English (1.7%) [P < .001], but not for German (0.3%) [P > .05]. There were no significant interactions between language and phonological similarity [F (1,43) = 1.86, P > .05] or between mixing and phonological similarity [F (1,43) = 3.44, P > .05]. Additionally, no significant three-way interaction was found among mixing, language and phonological similarity [F < 1].

4. Discussion

This study examined how phonological similarities between languages affected language control using an alternating language-switching paradigm with a letter

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naming task. The results can be summarized as follows: 1) Robust switch costs were observed when switch trials were compared with nonswitch trials in alternate-language blocks. Moreover, there was switch cost asymmetry, with larger costs for the more dominant (English/L2) than the less dominant (German/L3). 2) Mixing costs were present when nonswitch trials in alternate-language blocks were compared with single-language trials in single-language blocks. Also, there was mixing cost asymmetry, with larger costs for English than German. However, we did not observe reversed language dominance. 3) Cross-language phonological similarity showed a facilitation effect on letter naming.

4.1. Bilingual language control at the local and global levels

Switch costs were observed in the alternate-language blocks, with switch trials showing slower reaction times and higher error rates compared to nonswitch trials, regardless of phonological similarity. These findings align with previous studies on language switching (e.g., Christoffels et al., 2007; Costa & Santesteban, 2004; de Bruin et al., 2018; Declerck & Philipp, 2015a; Meuter & Allport, 1999; Philipp et al., 2007; Timmer et al., 2018; Verhoef et al., 2009; Zhang et al., 2019; Zhang et al., 2024; Zuo et al., 2022). Additionally, the switch costs were asymmetrical, with larger costs for the more dominant language (English/L2) compared to the less dominant (German/L3) in both sessions. This is consistent with prior research indicating greater switch costs when switching to a more dominant language (e.g., Gade et al., 2021; Macizo et al., 2012; Meuter & Allport, 1999; Peeters et al., 2014; Philipp et al., 2007; Verhoef et al., 2009; Zuo et al., 2022).

Mixing costs were also evident in this study, with nonswitch trials in alternate-language blocks showing slower reaction times and higher error rates compared to single-language trials. The mixing costs were again asymmetrical, with larger costs for the more dominant language (English) than the less dominant language (German). These results are consistent with previous findings that report higher mixing costs for dominant languages (e.g., Christoffels et al., 2007; Jylkkä et al., 2017; Mosca & Clahsen, 2016; Peeters & Dijkstra, 2018; Prior & Gollan, 2011). Reversed language dominance effects, typically seen in mixed-language tasks, were not observed in this study. Such effects generally result in poorer performance in the dominant language (L1) during mixed-language blocks, attributed to greater global inhibition of L1 (e.g., Christoffels et al., 2007; Costa & Santesteban, 2004; Gollan & Ferreira, 2009; Heikoop et al., 2016; Verhoef et al., 2009; Wong & Maurer, 2021). However, participants named English (L2) faster than German (L3) in single-language blocks, suggesting higher proficiency in English, with no significant performance difference observed in alternate-language blocks. While reversed dominance effects were not found, the shift from superior performance in single-language blocks to comparable performance in alternate-language blocks suggests increased global inhibition of L1.

According to the IC model (Green, 1998), the inertia of reactive, persisting inhibition can account for (asymmetrical) switch costs. These (asymmetrical) switch costs are frequently considered an indicator of transient, trial-by-trial language control, reflecting the impact of local inhibition in managing cross-language interference during language switching (Declerck & Philipp, 2015a; Guo et al., 2011; Ma et al., 2016). In contrast, mixing costs are associated with sustained, proactive control processes at the global level, which involve cross-language interference management (Kiesel et al., 2010).

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4.2. A facilitation effect of phonological similarity on language switching

In addition to the interference effect caused by inhibition during switching, the results of this study point to effects of increased activation, leading to a facilitation effect for both English and German regardless of whether letter naming occurred in single- or alternate-language blocks. This facilitation effect of phonological similarity was reflected by overall improved performance (i.e., faster RTs and fewer errors) during the phonologically similar session compared to the phonologically dissimilar session. Such a facilitation effect suggests that the interaction between equivalent English and German letters involves increased activation rather than inhibition. Specifically, the coactivation of these letter representations appears to enhance the efficiency of letter naming in both languages, pointing to a shared cognitive mechanism that enables parallel processing. This mechanism likely reflects the bilinguals' ability to integrate and coordinate linguistic information across languages, particularly when dealing with shared or similar orthographic features. The results may be further explained by differences in the accessibility, execution and representation of similar versus dissimilar letters. For equivalent or highly similar letters, the shared visual and phonological features may lead to faster and more automatic retrieval from memory, as both representations are activated simultaneously. This enhanced accessibility facilitates naming tasks, as the overlap reduces cognitive load and increases processing efficiency. In contrast, dissimilar letters might involve distinct or less interconnected representations, requiring separate retrieval and processing pathways. These differences could result in slower execution and less efficient performance.

Interestingly, some research has found a cognate facilitation effect while examining how phonological overlap influences language switching (e.g., Broersma & Cutler, 2011; Christoffels et al., 2007; Declerck & Koch, 2023; Filippi et al., 2014; Li & Gollan, 2018; Thomas & Allport, 2000). This cognate facilitation effect has been explained by cross-language phonological coactivation. However, this cognate facilitation effect seems present only when cognates and noncognates are arranged in separate blocks (e.g., Broersma & Cutler, 2011; Declerck et al., 2012). On the contrary, a cognate interference effect was reported to emerge when cognates and noncognates are mixed within blocks (e.g., Broersma & Cutler, 2011; Declerck et al., 2012). Declerck and Philipp (2015a) elucidated this apparently contradictory pattern by discussing the roles of local-level and global-level control mechanisms, which are applied, respectively, in within-block and between-block manipulations of cognate status. Additionally, phonological similarity was manipulated in separate sessions in this study, demonstrating a phonological similarity facilitation effect. Consequently, future research needs to confirm whether this apparent contradictory pattern for cognate manipulation also applies to letter naming.

In this study, phonological similarity was observed to interact with language. The simple effects from both switch and mixing analyses on RTs indicated a more substantial facilitation effect for the less dominant language (German/L3) compared to the more dominant language (English/L2). Similarly, Costa et al. (2000) in a previous study on the impact of cognates on language switching, found an interaction between cognate status and language, with a more pronounced cognate facilitation effect in the less dominant language than in the more dominant language. Thus, it appears that language is modulated by phonological similarity or overlap, depending on language proficiency.

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4.3. An interplay of inhibition and facilitation in bilingual language control

This study reveals that language switching at the phonetic level involves both cross-language interference and facilitation effects. Specifically, the inhibitory control mechanism plays a role in language switching during letter naming by managing cross-language interference and ensuring accurate production in the target language. This is evidenced by asymmetrical switch costs at the local level and mixing costs at the global level. Simultaneously, a facilitative control mechanism enhances cross-language activation, as demonstrated by facilitation effects arising from phonological similarities between English and German letter equivalents. These findings indicate that inhibition and facilitation operate in tandem during language switching, coexisting rather than excluding one another, with their effects observable at both local and global levels.

Interestingly, the effects of inhibition and facilitation in language switching are influenced by the relative dominance of the languages involved. Inhibition tends to exert a stronger interference effect on the dominant language, whereas facilitation more effectively supports the less dominant language. It is important to distinguish that the interference and facilitation effects identified in this study originate from distinct loci. The interference effect is typically explained by the theory of persisting inhibition (Green, 1998). When a particular language is produced in the previous trial (trial n-1), the nontarget language is inhibited to prevent interference. If the previously inhibited language is required in the current trial (trial n, a switch trial), this persisting carryover inhibition from the previous trial must be overcome for the successful production of the previously nontarget language. In contrast, the facilitation effect observed in this study stems from the coactivation of letter equivalents between English and German on the current trial, rather than from residual (increased) activation from the previous trial. Specifically, the phonological similarity between languages facilitates coactivation in the current trial, easing the process of switching.

The interplay of inhibition and facilitation in language switching at the phonetic level, as observed in this study, has significant implications for models of bilingual language control. Traditionally, the influential Inhibitory Control model proposed by Green (1998) has been central to understanding bilingual language regulation. This model prioritizes inhibitory control as the primary mechanism for resolving cross-language interference, making it a cornerstone of bilingual language control theories. In contrast, several activation-based models, such as those developed by Costa et al. (1999), Finkbeiner et al. (2006), La Heij (2005) and Roelofs (1998), take a different approach. These models emphasize the role of enhancing the activation of the intended language to improve bilingual performance and reduce interference from the nontarget language. More recently, Higby et al. (2020) demonstrated that translation equivalents facilitate, rather than interfere with, word retrieval. They attributed this finding to an activation-boosting model of bilingual lexical access, which posits that the parallel coactivation of translation equivalents elevates the resting activation level of both the target word and its corresponding translation. This increase in activation is thought to benefit not only the target word but also its translation equivalent.

However, our findings suggest a subtle but critical distinction. The facilitative mechanism observed in this study aligns with the notion of cooperation rather than competition, an idea proposed by some researchers (Chen & Mirman, 2012; Tabori &

Pyers, 2024). This perspective suggests that bilingual language processing can benefit from the collaborative interplay of linguistic resources across languages, rather than being solely governed by the competitive dynamics traditionally emphasized in existing models.

Moreover, language switching has its own unique characteristics although language switching and task switching share many cognitive mechanisms. Unlike general task switching, language switching involves the complexity of a system that encompasses multiple loci (Bobb & Wodniecka, 2013; Declerck & Philipp, 2015a; Gollan et al., 2014; Kroll et al., 2006; Zhang et al., 2019). Each locus of language processing, from phonetics to orthography, semantics and syntax, demands specific cognitive mechanisms. The present study demonstrated evidence for an interplay of inhibition and facilitation at the phonetic level during bilingual language control. Therefore, the multilocus nature of language adds specificity to language switching, requiring distinct cognitive processes to manage the interference and facilitation between different linguistic loci. This complex structure of language necessitates more specialized cognitive control strategies to effectively switch between languages, making language switching a more intricate and multifaceted process compared to other types of task switching. Future research should focus on investigating inhibition and/or facilitation mechanisms at the semantic and syntactic levels, extending beyond the phonetic level. This would provide a more comprehensive understanding of how these processes operate across different linguistic domains and contribute to bilingual language production.

This study has several limitations. First, the results may not fully reflect the phonological mechanisms involved in natural language processing, as letter names are not typically part of everyday speech or communication. Letter names represent a form of meta-metalinguistic knowledge rather than ordinary linguistic units. They are symbols (letters) used to represent phonological units (sounds) visually and thus exist at a more abstract level. Unlike words or phonemes used in natural language tasks, letter names are not directly engaged in the normal flow of spoken language. As such, their role in phonological processing may not be as straightforward or representative of natural language processing as the study suggests. Second, the familiarity of language users with letter names may not align with their overall proficiency in the language being studied. Letter names are typically acquired in formal educational settings and may not correspond directly to an individual's general language skills in speaking or understanding the language. Consequently, while the study may reveal certain phonological effects associated with letter names, caution is needed when interpreting these findings and applying them to the phonological processes involved in real-world language use.

5. Conclusion

The present study revealed both interference and facilitation effects on bilingual language control. The findings on the role of inhibition and facilitation at the phonetic level are particularly significant. In a narrow sense, this implies that control at the phonetic level involves intricate and dynamic mechanisms. More broadly, it indicates that different from general cognitive control, language-specific control in the bilinguals/multilinguals is multifaceted, given the complex structure of language. This complex structure means that language control mechanisms must operate at

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multiple loci simultaneously, ensuring smooth bilingual processing and minimizing cross-language interference. Overall, this study highlights the complexity and dynamics of bilingual language control, demonstrating that both inhibitory and facilitative mechanisms are crucial for managing language control at multiple loci of processing.

Data availability statement. All data and scripts are available at https://osf.io/vb5zj/?view_only=d0c3d1da02d6419cb9050bb040acd462.

Competing interest. The authors declare none.

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