Bilingual Advantage Effects in Executive Control and Their Moderators: Evidence from Meta-Analysis

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Abstract

The bilingual advantage in executive control conferred by bilingual experience has long been a focus of attention; however, theoretical explanations and specific manifestations of the bilingual advantage effect remain controversial. To further clarify the underlying mechanisms of the bilingual advantage effect in executive control, the present study distinguished between interference inhibition and response inhibition, and incorporated moderator variables such as age and language family type. Through a meta-analysis of 102 studies, it was found that the overall bilingual advantage in executive control was marginally significant (g = 0.11), but disappeared after controlling for publication bias. Specifically, the bilingual advantage in the interference inhibition component was marginally significant (g = 0.08); the bilingual advantage in the response inhibition component disappeared after controlling for publication bias; and the bilingual advantage in cognitive flexibility was moderated by participant age and publication year. The results suggest that future research could focus more on the differences between interference inhibition and response inhibition in the bilingual advantage effect and their underlying mechanisms, as well as the influence of bilinguals' age and the linguistic distance between the second language and native language on the bilingual advantage in executive control.

Full Text

Preamble

The Bilingual Advantage Effect on Executive Control and Its Moderators: Evidence from Meta-Analysis

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Abstract

The executive control advantage conferred by bilingual experience has long attracted considerable attention, yet theoretical explanations and specific manifestations of the bilingual advantage effect remain controversial. To further clarify the underlying mechanisms of the bilingual advantage effect in executive control, the present study distinguished between interference suppression and response inhibition while incorporating moderating variables such as age and language family type. Through a meta-analysis of 102 studies, we found that the overall bilingual advantage in executive control was marginally significant (g = 0.11), but disappeared after controlling for publication bias. Specifically, the bilingual advantage in the interference suppression component was marginally significant (g = 0.08); after controlling for publication bias, the bilingual advantage in the response inhibition component disappeared; and the bilingual advantage in cognitive flexibility was moderated by participant age and publication year. These findings suggest that future research should pay greater attention to differences between interference suppression and response inhibition in the bilingual advantage effect and their underlying mechanisms, as well as the influence of bilingual age and linguistic distance between the second language and native language on executive control bilingual advantages.

Keywords: executive control, bilingual advantage, interference suppression, response inhibition, meta-analysis

With the advent of globalization, second language learning and use have become increasingly widespread. Research indicates that second language acquisition not only creates more opportunities but, more importantly, promotes individuals' executive control functions, demonstrating advantages in metalinguistic awareness, learning strategies, and attention regulation—collectively known as the executive control bilingual advantage effect (He Wenguang & Chen Baoguo, 2011). Although numerous studies have confirmed that bilingual experience can confer general cognitive advantages, different explanations exist regarding the underlying mechanisms of bilingual cognitive benefits. According to the inhibitory control model, bilinguals must suppress the non-target language to successfully produce the target language, thus bilingual advantages stem from enhanced inhibitory control abilities (Green, 1998). Other research suggests that language switching processes share common components with non-verbal switching tasks, and bilinguals' frequent language switching experience facilitates performance on executive control tasks (Yang Zhichen, 2020). Additionally, because bilinguals must constantly select the target language according to conversational context, executive control advantages arise from bilinguals' sustained monitoring of conflicting environmental information (Hilchey & Klein, 2011).

To further clarify the internal mechanisms of bilingual cognitive advantages, researchers have proposed using quantitative methods to measure the effect size of bilingual advantages and their influencing variables. Related studies have found

that the bilingual advantage effect in executive control may only be reflected in specific cognitive components. Moreover, factors such as socioeconomic status, immigrant background, and language culture also influence the bilingual advantage effect (Bao Shengfei et al., 2019). Previous meta-analyses have examined bilingual advantage effects across various components of executive control in children and adults separately, but after controlling for publication bias, only cognitive flexibility showed a bilingual advantage effect, while the bilingual advantages in inhibitory control and working memory disappeared after correction (Lehtonen et al., 2018; Gunnerud et al., 2020). The present study argues that controversies regarding the bilingual advantage effect in executive control, and the failure of meta-analytic research to find stable advantage results, are closely related to the classification of executive control components, particularly inhibitory control. On one hand, research confirms that the core mechanism shared by executive control and bilingual control is inhibitory control (Wu Junjie et al., 2018), yet different definitions exist regarding the specific connotation of inhibitory control (Diamond, 2013). On the other hand, experimental studies on bilingual inhibitory control often employ different task paradigms, and the types of inhibitory control components reflected by various tasks differ essentially (Lehtonen et al., 2018; Gunnerud et al., 2020). Therefore, this study aims to examine bilingual advantage effects and potential influencing factors for different components by providing a more detailed division of executive control, particularly focusing on similarities and differences between interference suppression and response inhibition, thereby forming a more systematic and comprehensive understanding of the internal mechanisms of bilingual cognitive advantages.

1.1 Bilingual Advantage Effects in Executive Control Components

As a higher-order cognitive ability, executive control involves multiple cognitive components. With deepening research and technological innovation, the classification and connotation of these components continue to evolve (Miller & Cohen, 2001; Yang Guochun et al., 2019). Early research divided executive control into three sub-components: inhibitory control, cognitive flexibility, and working memory updating (Miyake et al., 2000). Subsequent researchers reached relatively consistent understanding regarding cognitive flexibility and working memory updating, but proposed that inhibitory control can actually be distinguished into two independent executive control components: interference suppression (also called interference control or conflict resolution) and response inhibition (also called behavioral inhibition) (Bialystok, Craik, & Ryan, 2006). Interference suppression primarily involves suppressing irrelevant information and selective attention to target information, as in Simon, Stroop, and Flanker tasks. Such conflict tasks typically include congruent and incongruent conditions, requiring participants to overcome interference from incongruent conditions. In contrast, response inhibition more involves flexible adaptation in changing environments and the ability to suppress dominant prepotent responses, as

in Go/No-Go and stop-signal tasks, where participants must inhibit responses inappropriate for the current context (Costa, Hernández, & Sebastián-Gallés, 2008; Diamond, 2013). The essential difference between the two components is that the former focuses more on conflict monitoring and enhancement of target information—an enhancement process—whereas the latter focuses more on individual response control abilities, belonging to an inhibitory process (Qi Yue et al., 2021).

Neuroscientific evidence has confirmed that interference suppression and response inhibition involve different brain activation patterns (Wang Ting et al., 2012), and bilinguals' performance on these two executive control components also differs (Liu Cong et al., 2016). Some studies have found that bilinguals show advantage effects in interference suppression-related tasks (Wang Ting et al., 2017; Xu Ying, 2020; Li Chuanjiang, 2018; Esposito, Baker-Ward, & Mueller, 2013; Martin-Rhee & Bialystok, 2008; Grote et al., 2021; Tran et al., 2019), while no advantage effects appear in response inhibition (Fan Xiaoyue et al., 2012; Wu Anlian, 2020; Carlson & Meltzoff, 2008; Bialystok & Viswanathan, 2009). However, other studies have found bilingual advantages in both interference suppression and response inhibition components (Jiao et al., 2019), or found no advantage effects in either (de Bruin, Bak & Sala, 2015; Kousaie et al., 2014; Víctor et al., 2016). These inconsistent conclusions suggest that interference suppression and response inhibition are dissociable to some extent. However, because more studies treat them equivalently as inhibitory control and employ different task paradigms, and previous meta-analyses have not clearly distinguished between interference suppression and response inhibition, conclusions about bilingual advantage effects have become confounded. Therefore, the present study separates interference suppression and response inhibition from the traditionally defined inhibitory control, examining the bilingual advantage effects and influencing factors of each component separately.

In addition to inhibitory control, researchers widely recognize that bilingual experience is closely related to cognitive flexibility and working memory in executive control. First, bilinguals' executive control advantages benefit from their language environment requiring more working memory engagement, thus the bilingual advantage effect in working memory has been confirmed across extensive research domains (Antón et al., 2019). Meanwhile, previous meta-analytic work systematically summarized bilingual experience and working memory, finding stable bilingual advantage effects (Grundy & Timmer, 2017). Accordingly, the present study no longer includes working memory as a variable. Second, compared with monolinguals, bilinguals have more experience switching between languages, thus performing better in task switching. However, existing research has not reached consensus on whether bilingual advantage effects exist in the cognitive flexibility component, and different studies employ substantially different cognitive flexibility tasks (Wang Ling, 2018; Xie Zhilong, 2018; Luo Haodong, 2021). Therefore, this study further examines the effect of bilingual experience on cognitive flexibility. In summary, the present study distinguishes tasks related to interference suppression and response inhibition in executive

control, and primarily examines bilingual advantage effects and influencing factors in three sub-components: interference suppression, response inhibition, and cognitive flexibility.

1.2 Moderating Variables in Executive Control Bilingual Advantage Effects

Previous research analyzing various moderating variables of bilingual advantage effects in executive control has found that sample size, second language proficiency, age of second language acquisition, and socioeconomic status all significantly influence bilingual advantage outcomes. First, sample size affects data analysis results and consequently bilingual advantage conclusions, with small-sample studies more likely to yield bilingual advantage results (Paap et al., 2015). Second, proficient bilinguals use their second language more frequently and have better mastery of it, thus more easily demonstrating bilingual advantages (Rosselli et al., 2016; Choi et al., 2018). Third, early and late bilinguals have different neural bases for language activities due to differences in age of second language acquisition (Hull & Vaid, 2007), with early bilinguals showing more bilingual advantages (Luk et al., 2011). Additionally, socioeconomic status affects family income levels and whether parents have opportunities to learn a second language, which also influences children' s opportunities for second language learning. Bilinguals from middle socioeconomic status backgrounds show more bilingual advantages (Gunnerud et al., 2020). Finally, earlier published studies more strongly supported bilingual advantages, while recent studies have found more mixed or non-supportive results (Noort et al., 2019).

However, because existing meta-analyses have only focused separately on child or adult bilinguals, and primarily summarized bilingual research under Indo-European language systems, the influence of two important variables—learner age and language family type—on bilingual advantage effects in executive control remains unclear. The present study argues that age and language family type are also important factors influencing bilingual advantage effects in executive control. On one hand, age is closely related to brain neurodevelopment as well as the duration and proficiency of second language learning; on the other hand, language family type relates to the entire process of second language learning and the various cultural backgrounds it entails. Therefore, this study includes sample size, second language proficiency, age of second language acquisition, and socioeconomic status as moderating variables, while newly incorporating learner age and language family type to examine how environmental factors and individual differences moderate bilingual advantage effects in executive control.

1.2.1 Age

Age is closely related to both second language learning experience and executive control function performance. Children and adults often have substantially different second language learning experiences, and because children are in a period

of rapid executive control development, the brain functions related to executive control are not yet fully developed. Previous research from a brain plasticity perspective has proposed that second language learning has more significant effects on children's executive control (Gao Yusong, 2020; Wang Ting et al., 2017). However, some studies have found that 56.4% of adult studies support executive control bilingual advantage effects, while only 42.8% of child studies do (Noort et al., 2019). Compared with children and young adults, bilingual advantages are more easily found in middle-aged and elderly populations (Hilchey & Klein, 2011). Research on school-age children has found that the promoting effect of bilingual learning on executive function tends to decrease with age (Li Jun et al., 2023). Meanwhile, meta-analyses focusing on child and adult populations separately have shown that children show bilingual advantages in overall executive control, with advantages only in the cognitive flexibility component (Gunnerud et al., 2020); adult populations show bilingual advantages in inhibitory control, cognitive flexibility, and working memory components (Lehtonen et al., 2018). Therefore, it is necessary to include participant age as a moderating variable in meta-analyses of bilingual advantage in executive control to directly compare whether bilingual advantages differ between child and adult populations.

1.2.2 Language Family Type

Differences between native and second languages directly affect language transfer and second language acquisition outcomes. Compared with bilinguals whose languages belong to the same language family, languages from different families have greater differences in basic word formation and grammar, thus bilinguals expend different cognitive resources and learning experiences when learning a language that differs from their native language. The non-language-specific extraction theory posits that when two languages belong to the same language family, native language experience more easily facilitates second language learning through transfer, and smaller linguistic distance requires shorter second language acquisition time. However, simultaneously, when native and second languages are both activated, greater conflict may occur between them (Butler, 2012). Moreover, language structure and vocabulary embody national or ethnic culture. Language learning is cultural learning, so different cultural backgrounds inevitably influence language learning and use, thereby affecting learners' bilingual advantage effects. Some meta-analytic studies have found that when two languages share substantial structural and lexical overlap, this affects the bilingual advantage effect in the monitoring component of executive control (Lehtonen et al., 2018). However, participants in existing meta-analyses mostly come from the United States, Canada, and Europe, where bilinguals' languages have high similarity and mostly belong to the same language family, not including samples with large linguistic differences or different language family types.

How inter-language differences affect bilingual advantage effects in executive control requires more research evidence (Bialystok, 2017). Meanwhile, as Chinese-English bilingual research—representing bilingual executive control

studies under different language family types—has rapidly increased in recent years, it is necessary to include language family type as an important moderating variable in meta-analytic work examining bilingual advantage effects in executive control.

Based on the above summary and analysis, the present study primarily addresses two aspects: First, separating interference suppression and response inhibition from traditional inhibitory control to examine whether bilingual advantage effects in interference suppression and response inhibition components of executive control differ. Second, incorporating age and language family type—two previously unanalyzed important factors—as moderating variables to fully examine how moderating variables including sample size, participant age, language family type, age of second language acquisition, second language proficiency, socioeconomic status, and publication year specifically influence bilingual advantage effects in executive control and its components.

2 Methods

To ensure high-quality systematic evaluation, increase research transparency and replicability, and avoid bias, this meta-analysis was pre-registered on the PROSPERO platform during its initial stage.

2.1 Literature Search

Chinese and English literature was searched on CNKI and Web of Science Core Collection. Keywords were: bilingual + bilingual advantage (exact) AND (executive function + executive control + cognitive control + inhibitory control + cognitive transformation + working memory (exact)); bilingualism or bilingual advantage (author keywords) and executive function or executive control or cognitive control or working memory or inhibitory control or cognitive transformation (author keywords). The search deadline was February 10, 2022. Additionally, valuable references provided in the literature were examined using the snowball method.

2.2.1 Conceptual Definitions

Based on the preceding summary and analysis, this study divides executive control into interference control, response inhibition, cognitive flexibility, and working memory updating. Definitions of bilinguals also differ across studies. Some researchers believe bilinguals should have equal proficiency in native and second languages (Declerck & Philipp, 2015), others consider anyone who has been exposed to a second language as bilingual (Macnamara, 1967), and another perspective defines bilinguals as individuals who have opportunities and abilities to use both native and second languages in daily learning and life (Grosjean, 1984). Accordingly, bilinguals in this study include all above types: balanced and unbalanced bilinguals, proficient and non-proficient bilinguals, early and

late bilinguals, etc., but exclude bilinguals who acquired their second language through short-term training or immersive learning.

2.2.2 Inclusion and Exclusion Criteria

Because behavioral and physiological indicators are two independent outcome measures with different coding methods and explanatory differences in psychological mechanisms, and there is no methodological basis for merging the two types of indicators, this study only included behavioral indicators. Searched literature was screened by reading titles, abstracts, and full texts according to the following criteria: Inclusion: (1) studies with monolingual-bilingual control groups or containing monolingual-bilingual comparisons; (2) studies measuring participants' interference control, response inhibition, or cognitive flexibility through experimental tasks, analyzing only behavioral indicators when both behavioral and physiological indicators were available; (3) studies providing sample size, mean, standard deviation, or other information calculable for effect sizes. Exclusion: (1) studies providing only neuroimaging or electrophysiological indicators, or using non-healthy or special populations such as interpreters as participants; (2) studies on short-term second language training; (3) duplicate publications (only recorded once), review articles, theoretical articles, unpublished conference papers, and non-English foreign language articles. A total of 102 articles were included in the meta-analysis, including 7 Chinese articles and 95 English articles, comprising 315 effect sizes. The literature search and screening process is shown in Figure 1 [Figure 1: see original paper].

2.3 Literature Coding

Literature included in the meta-analysis was coded as follows: (1) three executive control components; (2) task types in the literature corresponding to the three executive control components and the data types entered; (3) the number of each task type. The correspondence between the three executive control components and task types is shown in Table 1 . Following previous research (Lehtonen et al., 2018; Gunnerud et al., 2020), literature coding was completed independently by two graduate students in psychology. For coding disagreements, the two coders discussed and verified together, and determined the final coding after consulting with the corresponding author. All data analyses were completed using R.

2.4.1 Coding of Moderating Variables

Moderating variables included in the study were sample size, participant age, age of second language acquisition, language family type, second language proficiency, socioeconomic status, and publication year. Sample size was coded as a dichotomous variable (< 50 and ≥ 50); participant age as a dichotomous variable (< 18 years and ≥ 18 years); age of second language acquisition as a dichotomous variable (acquired before age 3 and after age 3); language family type coded as same or different types according to the ten major language

families; second language proficiency coded as proficient/highly proficient or other based on original literature descriptions; socioeconomic status coded as low, middle, and upper-middle based on descriptions of education years and academic qualifications in the original literature (education years were matched to local education systems: high school or below as low socioeconomic status, above high school to graduate degree as middle socioeconomic status, and above graduate degree as upper-middle socioeconomic status; these could refer to either participants' parents or participants themselves); publication year was a continuous variable.

2.4.2 Effect Size Calculation

This study used Hedge' s g, a corrected version of Cohen' s d, as the effect size for bilingual advantage in each executive control component. Hedge' s g provides more accurate effect size estimates than Cohen' s d, and although their calculation methods differ slightly, their magnitude divisions are consistent (Goulden, 2006). First, Cohen's d was calculated from raw data including sample size, mean, and standard deviation of monolingual and bilingual groups: $d = (M_1 - M_2)/SD$ d, where SD d $= \sqrt{[(n_1\text{-}1)SD_1{}^2 + (n_2\text{-}1)SD_2{}^2)/(n_1+n_2\text{-}2)]}$. If the original literature provided SE values, they were converted to SD values using the formula: $SD = SE \times \sqrt{n}$. Cohen' s d was then converted to Hedge' s g: $g = d[1 - (3/(4df\text{-}1))]$, where $df = n_1 + n_2 - 2$.

2.4.3 Model Selection

Heterogeneity tests were used to determine whether to use fixed-effect or random-effects models for comprehensive effect estimation. Heterogeneity tests included Q test and I^2 test. In the Q test, if $p < 0.050$, results were considered heterogeneous; the I^2 test further divided heterogeneity degree, with high, medium, and low heterogeneity boundaries at 75%, 50%, and 25% respectively (Higgins et al., 2003). If heterogeneity test results showed low heterogeneity, the fixed-effect model was used; otherwise, the random-effects model was used.

2.4.4 Publication Bias

Publication bias can lead to significantly higher rates of positive results than negative results in published literature, thereby affecting meta-analysis results. Preventing publication bias requires searching for unpublished articles as much as possible during literature collection, while during data analysis, funnel plots, Egger' s linear regression test, and the trim-and-fill method were used to test for publication bias and assess its impact on result stability.

2.4.5 Data Processing and Analysis Procedures

R language meta and metafor packages were used for heterogeneity tests, publication bias tests, main effect tests, and moderator effect tests (Schwarzer, 2007;

Viechtbauer, 2010). Moderator effect tests included subgroup analysis and meta-regression analysis. Subgroup analysis was used to test the moderating effects of categorical variables (sample size, participant age, age of second language acquisition, language family type, second language proficiency, and socioeconomic status); meta-regression analysis was used to test the moderating effects of continuous variables (publication year).

3.1 Heterogeneity Test

Heterogeneity testing for bilingual advantage in executive control yielded Q = 1775.42 ($p < 0.001$), indicating heterogeneity. The I^2 test yielded $I^2 = 83\% > 75\%$, indicating high heterogeneity, thus the random-effects model was selected. The test showed high heterogeneity across studies, with 83% of observed variance coming from real differences between effect sizes across studies, suggesting possible influencing factors causing between-study differences and necessitating moderator effect tests.

3.2 Publication Bias Test

Publication bias testing revealed an asymmetrical funnel plot, suggesting possible publication bias. Further Egger' s linear regression test showed Intercept = -0.14, $p = 0.013 < 0.05$, confirming publication bias. The trim-and-fill method was used to assess whether publication bias affected the comprehensive effect size. Trim-and-fill analysis showed significant changes in the comprehensive effect size, indicating that publication bias affects the comprehensive effect size (Kang Deying et al., 2003). Therefore, publication bias tests were conducted separately for interference suppression, response inhibition, and cognitive flexibility. Although funnel plots for cognitive flexibility and interference suppression were asymmetrical, further Egger' s linear regression tests showed no publication bias for cognitive flexibility (Intercept = -0.29, $p = 0.307 > 0.050$) or interference suppression (Intercept = 0.12, $p = 0.607 > 0.050$). Funnel plot and Egger' s linear regression tests for response inhibition revealed publication bias (Intercept = -0.36, $p = 0.010 < 0.050$), thus the trim-and-fill method was used to correct for publication bias in response inhibition.

3.3 Main Effect Test

Using the random-effects model to test bilingual advantage in executive control, results showed a significant main effect of bilingual advantage in executive control, $z = 3.23$, $p = 0.001$, with a comprehensive effect size $g = 0.11$ and 95% confidence interval [0.04, 0.18]. Sensitivity analysis was conducted by sequentially removing each included study; the significance of the comprehensive effect size did not change substantially, indicating no extreme studies among those included. Publication bias testing revealed that the comprehensive effect size was affected by publication bias, so correction was applied, yielding a corrected comprehensive effect size g = -0.09, 95% CI [-0.17, -0.02]. According

to Cohen' s (1992) criteria, small, medium, and large effect sizes are demarcated at 0.2, 0.5, and 0.8 respectively, indicating that the found effect size was small. Further testing of the three components of executive control—interference suppression, response inhibition, and cognitive flexibility—showed no significant between-group differences (Q = 1.95, p = 0.377). Response inhibition (58 data sets) had a comprehensive effect size g = 0.21, 95% CI [0.03, 0.39], which was significant; cognitive flexibility (75 data sets) had a comprehensive effect size g = 0.14, 95% CI [-0.04, 0.33], which included 0 and was not significant; interference suppression (182 data sets) had a comprehensive effect size g = 0.08, 95% CI [0.01, 0.15], which was significant. After correcting for publication bias, the comprehensive effect size for response inhibition became g = -0.17, 95% CI [-0.36, 0.03], which was not significant.

3.4 Moderator Effect Tests

Main effect tests only found small effect sizes in the interference suppression component, but this does not rule out the possibility that response inhibition and cognitive flexibility may show bilingual advantages under specific conditions. Therefore, moderator effect tests were conducted separately for bilingual advantage effects in interference suppression, response inhibition, and cognitive flexibility.

3.4.1 Moderating Effects on Bilingual Advantage in Response Inhibition (Under Publication Bias)

Moderator effect tests for bilingual advantage in response inhibition were affected by publication bias and met the criteria of at least 4 studies per subgroup for subgroup analysis and at least 6 studies for meta-regression analysis (Fu et al., 2011). Specific subgroup analysis results are shown in Table 2 . Moderator effect tests for bilingual advantage in response inhibition found that the moderating effect of second language proficiency was significant (Q = 16.14, p < 0.001), with proficient/highly proficient bilinguals (51 data sets) showing an effect size g = 0.26, greater than other proficiency levels (5 data sets) with g = -0.35, with the former reaching the small effect size range. The moderating effect of sample size was not significant (Q = 0.04, p = 0.838), but small-sample studies showed an effect size g = 0.23, reaching the small effect size range and greater than large-sample studies' effect size g = 0.19. The moderating effect of language family type was not significant (Q = 2.51, p = 0.113), but different language family types showed an effect size g = 0.33, reaching the small effect size range and greater than same language family types' effect size g = 0.06. The moderating effect of participant age was not significant (Q = 0.93, p = 0.334). The moderating effect of age of second language acquisition was not significant (Q = 0.04, p = 0.834). The moderating effect of socioeconomic status was not significant (Q = 1.02, p = 0.313). The moderating effect of publication year was not significant; meta-regression analysis of publication year (b = -0.01, 95% CI [-0.07, 0.05]; z = -0.29, p = 0.773) showed that publication year could not

significantly predict bilingual advantage in response inhibition.

3.4.2 Moderating Effects on Bilingual Advantage in Cognitive Flexibility

Moderator effect tests for bilingual advantage in cognitive flexibility met the criteria of at least 4 studies per subgroup and at least 6 studies for meta-regression analysis (Fu et al., 2011). Specific subgroup analysis results are shown in Table 3 . Moderator effect tests found that the moderating effect of participant age was significant (Q = 10.48, p = 0.001), with participants under 18 years (32 data sets) showing an effect size (g = 0.46) greater than participants 18 years or older (43 data sets) with (g = -0.12). The moderating effect of publication year was significant; meta-regression analysis of publication year (b = 0.06, 95% CI [0.00, 0.12]; z = 2.08, p = 0.037) showed that publication year could significantly predict bilingual advantage in cognitive flexibility, and between-group differences in publication year were significant (Q = 42.78, p < 0.001), as were within-group differences (Q = 402.81, p < 0.001). The moderating effect of sample size was not significant (Q = 1.25, p = 0.264). The moderating effect of age of second language acquisition was not significant (Q = 0.00, p = 0.951). The moderating effect of language family type was not significant (Q = 0.01, p = 0.911). The moderating effect of second language proficiency was not significant (Q = 3.21, p = 0.073). The moderating effect of socioeconomic status was not significant (Q = 0.61, p = 0.437).

3.4.3 Moderating Effects on Bilingual Advantage in Interference Suppression

Moderator effect tests for interference suppression met the criteria of at least 4 studies per subgroup and at least 6 studies for meta-regression analysis (Fu et al., 2011). Specific subgroup analysis results are shown in Table 4 . Moderator effect tests found that the moderating effect of language family type was not significant (Q = 1.11, p = 0.292), but different language family types showed an effect size g = 0.15, greater than same language family types' effect size g = 0.07. The moderating effect of sample size was not significant (Q = 0.17, p = 0.682). The moderating effect of participant age was not significant (Q = 3.65, p = 0.056). The moderating effect of age of second language acquisition was not significant (Q = 0.07, p = 0.787). The moderating effect of second language proficiency was not significant (Q = 1.01, p = 0.315). The moderating effect of socioeconomic status was not significant (Q = 0.09, p = 0.956). The moderating effect of publication year was not significant; meta-regression analysis of publication year (b = 0.01, 95% CI [-0.01, 0.03]; z = 0.83, p = 0.408) showed that publication year could not significantly predict bilingual advantage in interference suppression.

Note: represents heterogeneity test results; K represents the number of effect sizes; 95% CI is the 95% confidence interval for subgroup effect size Hedge' s g, the same below.

[Table content appears corrupted in original and cannot be meaningfully reconstructed]

4.1 Bilingual Advantage Effects in Interference Suppression and Response Inhibition

By separating interference suppression and response inhibition components from traditional inhibitory control, this study found that the bilingual advantage effects they exhibit indeed differ. Interference suppression showed a small but stable bilingual advantage. Subgroup analysis of various moderating variables for interference suppression showed that no moderating variables affected its bilingual advantage effect. In contrast, the bilingual advantage in response inhibition disappeared after controlling for publication bias. Similar to these results, Lehtonen et al. (2018) found that bilingual advantage in inhibitory control was affected by publication bias. Gunnerud et al. (2020) also found that bilingual advantage in inhibitory control disappeared after controlling for publication bias. These meta-analytic results align with our findings, all indicating that bilingual advantage effects in response inhibition are not stable.

The finding that interference suppression has bilingual advantage effects is supported by existing empirical research and theoretical hypotheses. Previous research on bilingual children found that participants showed bilingual advantages in total reaction time for mixed tasks containing both congruent and incongruent responses (Hilchey & Klein, 2011). This study used reaction time for incongruent trials or reaction time difference between incongruent and congruent trials as indicators for interference suppression, similarly finding bilingual advantages in corresponding task responses. Furthermore, some studies created different experimental conditions within the same task framework (e.g., face tasks) to compare bilinguals' and monolinguals' performance on different executive control components, finding that bilinguals showed more interference suppression advantages but no significant differences from monolinguals in response inhibition, and that higher second language proficiency was associated with stronger interference suppression (Bialystok & Viswanathan, 2009; Fan Xiaoyue et al., 2012). Only a few studies found that immediate language switching environments could promote non-proficient bilinguals' response inhibition while hindering their interference suppression. Researchers suggest that short-term language switching experimental contexts and long-term bilingual switching experience have different effects on executive control. Experimentally induced language switching tasks force bilinguals to constantly suppress dominant language responses, temporarily enhancing their response inhibition abilities (Liu Cong et al., 2016). These findings indirectly reflect that bilinguals' stronger interference suppression ability is not task-driven but results from long-term language control, providing evidence for the internal mechanism of interference suppression bilingual advantage.

According to the inhibitory control hypothesis, language control and executive control rely on similar control mechanisms. Whether competition between dif-

ferent languages or competition between different stimuli or responses in non-linguistic conflict tasks, both essentially require monitoring of conflicting information and enhancement of target information (Chang Xin et al., 2017). Compared with monolinguals, bilinguals need to establish representational systems different from their native language in their minds, constantly monitor environmental information when using both languages, and switch target languages at any time. Long-term bilingual switching experience exercises bilinguals' interference suppression abilities. However, in most language contexts, bilinguals do not need to suppress habitual dominant language responses, thus failing to show differences from monolinguals in response inhibition-related tasks. Based on extensive existing research, this study systematically summarized different types of task paradigms and various moderating variables through meta-analysis, avoiding limited explanatory power from single experimental studies due to task contexts and sample sizes, and further verifying that language control shares cognitive mechanisms with the enhancement process reflected by interference suppression.

In summary, this study not only found bilingual advantage effects in executive control but, more importantly, tested the necessity of separating interference suppression and response inhibition from traditional inhibitory control. After separation, only interference suppression showed stable bilingual advantage effects, while response inhibition bilingual advantage effects were unstable. Given that no study has yet proposed a bilingual advantage hypothesis specifically for the interference suppression component, these findings provide new ideas and reference for future research in related fields, suggesting that more specific examination of differences in bilingual advantage effects across executive control components is needed, particularly requiring more quantitative research results to explore and test the bilingual advantage effect and its internal mechanism in interference suppression.

4.2 Influencing Factors of Bilingual Advantage in Cognitive Flexibility

The executive control hypothesis proposes that cognitive flexibility reflects the ability to switch between different tasks. Since bilinguals often need to flexibly switch between native and second languages according to speaking contexts and conversational partners, and language switching shares common cognitive components with task switching, language switching can promote bilinguals' cognitive flexibility (Donnelly, 2016). Although this study did not find an overall bilingual advantage in cognitive flexibility, participant age and publication year moderated the bilingual advantage effect in cognitive flexibility, indicating conditional bilingual advantages in this component.

First, similar to previous findings that younger bilingual participants show better performance on executive control tasks than older participants (Bialystok et al., 2008), this study similarly found that child bilinguals showed bilingual advantages in cognitive flexibility, while adult bilinguals did not. Cognitive flex-

ibility develops rapidly in early childhood, approaching adult levels by age 10, and remains relatively stable in young and middle adulthood (Anderson, 2002; Cepeda et al., 2001). Since child bilinguals' cognitive flexibility is in a period of rapid development, with abilities for rule and task switching continuously and rapidly improving, bilingual switching experience and language learning training have more significant promoting effects on cognitive flexibility. Through moderator analysis of age, this study found that age is closely related to bilingual advantage in executive control. On one hand, the effect of second language experience on bilingual advantage in executive control differs with bilinguals' age development, with bilingual experience promoting executive control abilities more in children than in adults, and different components of executive control having different age development stages and plasticity. On the other hand, the finding that age only moderated cognitive flexibility bilingual advantage but not interference suppression also indicates that interference suppression has a more stable relationship with language control, unaffected by age. Second, publication year also moderated cognitive flexibility bilingual advantage. More recent publication years showed more obvious bilingual advantage results. Further testing found significant differences in research results across publication years. These results indicate that bilingual advantage research conclusions differ substantially across years, suggesting that future research should pay more attention to longitudinal developmental changes in bilingual advantage research results to avoid drawing partial or biased conclusions from being overly influenced by short-term research trends.

4.3 Effects of Moderating Variables on Bilingual Advantage in Executive Control

This study newly included language family type as a moderating variable and found that whether native and second languages belong to the same language family type affects bilingual advantage effects in executive control to some extent. However, contrary to the non-language-specific extraction theory hypothesis that same language family types would produce more significant language transfer effects, this study found that different language family types showed larger effect sizes than same language family types, and response inhibition showed bilingual advantages when native and second languages belonged to different language family types.

Although more direct research evidence is lacking to compare cognitive advantage performance between bilinguals of different versus same language family types, these findings still have important implications. When bilinguals' two languages belong to different language family types, their executive control functions are more likely to benefit from bilingual use experience. A possible reason for this result is that because the second language to be learned differs substantially from the native language, learners need to expend more cognitive resources and effort to complete control and switching between different languages, thus their executive control functions receive more exercise and improvement during

this process. Future research could further investigate the specific influence of language family type by setting up control groups of different and same language family types to compare how language family type affects bilingual advantage effects in different executive control components.

By comparing moderating variables for bilingual advantages across different executive control components, only second language proficiency showed a moderating effect on response inhibition. Proficient or highly proficient bilinguals showed bilingual advantages in response inhibition compared with less proficient bilinguals. Although numerous studies have found that second language proficiency is a direct factor affecting bilinguals' language switching (Wu Junjie et al., 2018; Magezi et al., 2012), this study indicates that differences between high and low second language proficiency individuals in executive control are more reflected in response inhibition. The influence of second language proficiency on response inhibition advantage aligns with research hypotheses and further confirms that interference suppression and response inhibition components are independent, with essentially different bilingual advantages. On one hand, bilinguals' language control shows a closer relationship with interference suppression; regardless of high or low proficiency, language use experience significantly promotes interference suppression abilities and enhances enhancement-based cognitive processing, thus second language proficiency does not moderate interference suppression bilingual advantage effects. On the other hand, because most bilinguals do not need to frequently suppress dominant language responses, overall advantage effects in response inhibition are not significant, but this effect is moderated by second language proficiency. For proficient bilinguals, especially balanced bilinguals, who frequently need to switch language responses according to changing contexts, bilingual advantage effects can be shown in both interference suppression and response inhibition. Research has found that professional interpreters show better performance than general bilinguals and monolinguals on various executive control-related tasks including inhibitory control and working memory—the "interpreter advantage effect" — indicating that frequent bilingual switching promotes both enhancement-based and inhibition-based processing abilities (Wen & Dong, 2019).

Although sample size did not significantly moderate interference suppression, response inhibition, or cognitive flexibility, small-sample studies still showed a trend of larger bilingual advantage effect sizes than large-sample studies. Small-sample studies of response inhibition and cognitive flexibility both showed bilingual advantage effects, indicating that small-sample studies are more likely to find bilingual advantages—a result consistent with previous research conclusions (Paap et al., 2015). A possible reason for this result is that small-sample studies more easily obtain highly proficient bilinguals and are also affected by publication bias, suggesting that future research should be more cautious about how sample size and sample representativeness may affect bilingual advantage effect results. Additionally, for age of second language acquisition and socioeconomic status, neither showed significant moderating effects, possibly due to different descriptions and division standards in original literature. For age of second lan-

guage acquisition, some studies defined it as age of first exposure to the second language (Escobar et al., 2018), while others defined it as age of second language acquisition (Gonçalves et al., 2021). Moreover, data on second language acquisition before age 3 are particularly scarce, and previous research using age 12 as a cutoff also failed to find moderating effects of acquisition age (Lehtonen et al., 2018). Therefore, whether age of second language acquisition can moderate bilingual advantage in executive control still requires more quantitative research evidence. Furthermore, unlike Gunnerud et al. (2020), who found that bilingual children from middle socioeconomic status backgrounds showed more bilingual advantages, this study did not find a moderating effect of socioeconomic status. Since most studies lack unified standards for measuring socioeconomic status, the education years and academic qualifications of participants or their parents used in this study cannot fully represent socioeconomic status levels, and most included participants were from middle socioeconomic status backgrounds with scarce data from low and upper-middle socioeconomic status, potentially biasing results.

4.4 Research Implications and Limitations

By separating interference suppression and response inhibition from traditional inhibitory control and incorporating moderating variables such as age and language family type, this study further examined whether stable bilingual advantage effects exist in executive control and their influencing factors and specific conditions. The findings provide multiple implications for future work. First, stable bilingual advantages were found in the interference suppression component, unaffected by moderating variables, while response inhibition showed no bilingual advantage after separation, demonstrating that distinguishing interference suppression and response inhibition is feasible and necessary, and that their bilingual advantage effects indeed differ. Future research should more carefully examine different advantage effects of interference suppression and response inhibition. Second, the study found that second language acquisition across different language family types has greater potential promoting effects on executive control, particularly response inhibition, suggesting that future research should pay more attention to possible relationships between second language acquisition with greater linguistic distance and executive control. Additionally, although this study did not find moderating effects of second language acquisition age, it showed that participant age has obvious effects on executive control, particularly cognitive flexibility, with children showing more bilingual advantages than adults. Future research might consider the duration of second language acquisition and use as an influencing factor for bilingual advantage in executive control.

Given research constraints and technical limitations, this study has several shortcomings. First, it only examined bilingual advantages in three components of executive control—interference suppression, response inhibition, and cognitive flexibility—without including other components such as working memory or se-

lective attention. Second, due to limitations in the number of original studies included, some subgroup analyses had unbalanced data across groups, potentially affecting analysis results. Additionally, based on existing literature search methods, this study could not include non-English foreign language literature in the analysis, potentially causing loss of research data from specific regional and language backgrounds and limiting the generalizability of conclusions.

In conclusion, the overall bilingual advantage effect in executive control was marginally significant but disappeared after controlling for publication bias. Interference suppression showed a small but stable bilingual advantage, while response inhibition bilingual advantage was affected by publication bias. Age significantly moderated bilingual advantage effects in cognitive flexibility, with only child bilinguals showing cognitive flexibility advantages. The moderating effect of language family type was not significant, but different language family types showed bilingual advantages in response inhibition. These results support separating interference suppression and response inhibition in research and highlight the importance of age and language family type as moderating variables for bilingual advantage in executive control.

*Indicates literature included in the meta-analysis

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Appendix 1: Original Literature Included in Meta-Analysis and Coding Information

[Table content appears corrupted in original and cannot be meaningfully reconstructed]

Note: (1) In the category column: A = response inhibition, B = cognitive flexibility, C = interference suppression. (2) Group 1 is the bilingual group, Group 2 is the monolingual group.

Note: Figure translations are in progress. See original paper for figures.