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Novel Evidence for the Bilingual Advantage: Effects of Language Control on Executive Function in Balanced and Unbalanced Dual-Language Users

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Abstract

Bilinguals' need to monitor and inhibit non-relevant languages over a relevant one confers advantage in cognitive control. No studies have demonstrated that the dual-language control process directly contributes to the bilingual cognitive advantage. We utilized a novel language control manipulation paradigm where 83 English-Chinese bilingual adults completed a reading and comprehension task in either single-language (low-language-control) or dual-language (high-language-control) prior to performing nonverbal executive control tasks (Stroop, task-switching, and n-back). Results showed that language control had significant effects on subsequent cognitive performance, depending on whether the participants were regular dual language users or not. In the dual-language condition, but not the single-language condition, participants who used both languages regularly demonstrated a smaller mixing cost in task-switching and a greater sensitivity in n-back detection compared to participants who did not. This suggests that dual language control utilizes similar resources as executive function and frequent dual language use enhances this resource.

Keywords: bilingualism; cognitive resources; task mixing; working memory; adults

Introduction

Research evidence suggests that the ability to speak more than one language confers an advantage in cognition, specifically in executive control. Executive control refers to a set of top-down mental processes such as the ability to inhibit impulses, monitor and update working memory representations and task switching (Miyake et al., 2000). The evidence for the bilingual advantage in executive control (henceforth bilingual advantage) is robust and is seen across the lifespan from young children to the elderly across several executive control tasks (e.g., Bialystok, Craik, & Luk, 2008; Macnamara & Conway, 2013).

Why would being bilingual have positive consequences to executive control? The transfer from bilingualism to enhanced executive control is likely a two-step process.

First, for a bilingual, different languages are activated in parallel during language processing (e.g., Crinion et al., 2006). Increased executive control resources are therefore needed to monitor this parallel activation and prevent cross-linguistic interference. Various executive control processes are hypothesized to be necessary for language control in different interactional contexts (Green & Abutalebi, 2013). For example, a bilingual speaker must maintain a task goal and inhibit the non-relevant language when speaking in one language rather than another. These processes are akin to updating and inhibition components in the Miyake et al. (2000) model of executive control. The cognitive demands on such processes are likely to increase in a dual-language context whereby both languages known to a bilingual are used and switched within a conversation. Such codeswitching acts (i.e., switching between languages) add another dimension of control necessary for disengagement from a prior language and engagement of the language in use. Neuroimaging studies have shown overlapping neural substrates between language control and nonverbal executive control (e.g., De Baene, Duyck, Brass, & Carreiras, 2015; Rodríguez-Pujadas et al., 2014).

Second, the control processes associated with language control in bilingual speakers are hypothesized to adapt to the demands imposed on them, in turn enhancing domain-general cognitive control (e.g., Bialystok & Craik, 2010; Green & Abutalebi, 2013). Behavioral evidence indicates that executive control processes implicated in language control such as updating, interference suppression and shifting are enhanced in bilinguals (e.g., Morales, Calvo, & Bialystok, 2013; Wiseheart, Viswanathan, & Bialystok, 2014). Neuroimaging work suggests that bilingual language control exerts neuroplastic effects both structurally and functionally in brain areas of importance for executive control (e.g., Klein, Mok, Chen, & Watkins, 2014). Bilinguals show reduced activation relative to monolinguals when performing conflict and inhibitory control tasks in the anterior cingulate (Rodríguez-Pujadas et al., 2014), indicating greater neural efficiency. These findings suggest that bilingual speakers may hold larger cognitive resources because of the adaptive language control processes.

A more specific account has been put forward recently, that these general "spill-over" positive effects of bilingualism in executive control skills may be due to the dual language switching behavior that bilinguals regularly engage in, which represents a skillful control of language use (e.g., Prior & Gollan, 2011; Yim & Bialystok, 2012). For example, Soveri, Rodriguez-Fornells, and Laine (2011) found that higher self-reported daily language switching frequency is associated with reduced task-mixing cost in adults from 30 to 75 years old. In addition, Yow and Li (2015) demonstrated that bilinguals who used both languages regularly have lower Stroop interference effects and task mixing costs than those who used one language significantly more than the other language. This bilingual advantage based on how often a bilingual uses both languages is also apparent across the lifespan from childhood to the elderly. Specifically, Thomas-Sunesson, Hakuta, and Bialystok (2016) showed that the more balanced Spanish-English bilingual young children were in their language proficiency between two languages, the better they performed in working memory and conflict resolution.

Bilinguals often differ from each other in language proficiency and usage frequency of each of their languages, as well as language switching behavior. These differences in language usage behavior might lead to different neural and cognitive consequences due to the executive control processes implicated in language control. However, it is currently unknown whether active engagement in language control activities would have a positive or negative impact on bilingual speakers' performance in nonverbal tasks tapping executive control processes. No studies have experimentally manipulated language control to determine its effects on executive control. This present study aims to explore this question and to further understand the mechanisms underlying the effects of language control on executive control.

In the current study, we manipulated active engagement in language control by introducing a novel reading and comprehension task. In the single-language condition, participants read articles and answered questions in only English. In the dual-language condition, participants read and answered questions intermixed in English and Chinese, which would induce higher cognitive demands on language control compared to those in the single-language condition. Following the reading comprehension task, participants completed three executive control tasks (i.e., Stroop, number-letter task-switching, and n-back) to assess different executive control components (i.e., inhibition, shifting, and updating, respectively) (e.g., Miyake et al., 2000). If the engagement in language switching behavior indeed caused a higher cognitive demand (in the dual-language condition), then it could be expected that less cognitive resources would be available for integrating the text information, resulting in lower performance in the comprehension test. We also hypothesized that participants' performance in the subsequent executive control tasks would be negatively affected if they were in the dual-language condition, as cognitive resources would be depleted for these participants who had to engage in greater language control.

Since previous studies indicate that bilinguals who regularly use both languages may have a protective advantage in cognitive control, current participants who are balanced bilinguals (defined as either a balanced use or a balanced level of proficiency in two language systems) would be less likely to be affected by the language control manipulation than those who are unbalanced bilinguals.

Method

Participants

Eighty-three undergraduates (56 females, M_{age} = 22.60, *SD* = 1.83, range = 19 - 25) were recruited from the authors' university. All participants are Chinese Singaporeans and have been living in Singapore since they were born. Singapore is a multilingual country with English as the main official language. The bilingual policy in Singapore encourages citizens to be proficient in both English and a mother tongue, which is Chinese for the participants of this study. All participants provided written informed consent prior to their participation and received credit points or reimbursement for their time of participation.

Materials and Measures

Language Background Questionnaire (LBQ) This questionnaire asked participants to name all the languages that they know and to provide details about each of the listed languages (e.g., age of language acquisition, language proficiency, usage frequency, and language switching habits). For language proficiency, participants rated their proficiency in listening, reading, speaking and writing for each language on a 10-point scale (1 = *not proficient* to 10 = *very proficient*). We defined most and second most proficient language based on the two languages that have the highest average rating across these four domains. Usage frequency for each of the languages was assessed by asking participants to approximate the percentage they use each language when communicating with different groups of people (e.g., family members, colleagues, friends) in different contexts in a typical week. The usage of all different languages would add up to 100%. In addition, participants rated on a 5-point scale (1 = *never* to 5 = *always*) for nine questions relating to how frequent they switch languages during discourse. A higher score therefore indicates more frequent language switching.

We followed the procedures in Yow and Li (2015) to estimate the individual differences in the degree of bilingualism:

(I) Balanced Proficiency: Most proficient language rating minus second most proficient language rating; a metric of balanced bilingualism of relative competency between participants' most and second most proficient languages.

(II) Balanced Usage: Frequency of most used language minus frequency of second most used language; a metric of balanced bilingualism of relative usage frequency between participants' most used and second most used languages.

For both measures, a score closer to 0 indicates more balance between two languages. Conversely, a higher score indicates more dominant proficiency or use in one language over the other. See Table 1 for all key language variables, including details between the balanced and unbalanced users related to the current study. Differences between the balanced and unbalanced users are reported as this is of interest in the current study.

Reading Comprehension Task This task was administered as a manipulation of language control. Participants were randomly assigned to a single-language condition (i.e., ***SL***; *n* = 38) or a dual-language condition (i.e., ***DL***; *n* = 45). For both conditions, participants read four passages pertaining to current events happening at the authors' university (two before executive control tasks and two after).

Table 1: Language background measures.

Language variable	Overall Mean (SD) n = 83	Balanced users Mean (SD) n = 40	Unbalanced users Mean (SD) n = 39*
Age of first acquired language	2.23 (1.51)	2.35 (1.29)	2.00 (1.69)
Age second acquired language	2.79 (1.75)	2.40 (1.26)	3.08 (2.10)
Most proficient language proficiency rating	8.49 (1.29)	8.47 (1.10)	8.47 (1.48)
Second most proficient language proficiency rating	6.54 (1.76)	7.36 (1.34)	5.63 (1.80)
Frequency of most used language	0.76 (0.19)	0.66 (0.93)	0.91 (0.58)
Frequency of second most used language	0.21 (0.17)	0.32 (0.09)	0.09 (0.06)
Balanced proficiency (Most proficient *minus* 2nd most proficient)	1.95 (1.84)	1.11 (1.00)	2.84 (2.16)
Balanced usage (Most used *minus* 2nd most used)	0.55 (0.34)	0.35 (0.17)	0.82 (0.11)
Language switching	25.96 (4.26)	26.60 (4.60)	25.11 (3.91)

*Note: Four participants did not provide their usage frequency for their languages. Hence, we were not able to categorize them as balanced or unbalanced users.

Participants assigned to the SL condition read passages presented in English only. The English reading passages are suitable for students in grade 12 (between grade 11 to 13), based on Flesch-Kincaid readability tests performed online (https://readability-score.com). The English passages contained on average 332.75 words (range = 305 to 366 words). In the DL condition, participants were presented with passages intermixed in English and Chinese. The passages contained 438.5 words on average (range = 406 to 458 words). Only inter-sentential switches (i.e., switching from English to Chinese sentence and vice versa) were used (M = 13.5 switches, range = 11 to 15).

After reading each passage, participants were required to answer eight questions in oral and then written form. For each passage, four questions required an oral response and four required a written response. However, four were filler questions (two oral and two written) that were not scored. Participants were given one point for each correctly answered question (not including the filler questions). A maximum score a participant can receive is therefore four. Participants could answer in either English or Chinese for any of the questions, regardless of whether they are in the SL or DL condition. The questions were all presented on the computer screen. The passages remained on screen for the participants to refer to if needed.

In the SL condition, all questions were posed in English only. In the DL condition, participants were presented the questions in English and then Chinese in alternating fashion. For each of the four questions posed (oral and written), the answers could only be found in the passage printed in the opposite language. In other words, for a question posed in English, its corresponding answer is printed in Chinese in the passage and vice versa. This therefore necessitated participants in the DL condition to engage in codeswitching to answer the questions.

The sum of all correct responses was calculated for each form of questions (oral or written) and for each two passages before or after the executive control tasks as DVs (dependent variables) from this task.

Executive Control Tasks We selected three tasks, color-word Stroop, number-letter switching, and n-back, to measure executive control components of inhibition, mental-set shifting, and information updating and monitoring, respectively (Miyake et al., 2000; see Yow & Li, 2015 for details about stimuli design and procedure for each of the tasks).

In the Stroop task, participants were required to indicate the color that the stimuli were printed in and ignore the color names. The dependent measure in this task is the Stroop effect, taken as the difference in response time (RT) between the incongruent and neutral trials. Greater Stroop effects reflect the poorer inhibition.

In the letter-number switching task, participants saw number-letter pairs and either determined if the number was even or odd or if the letter was a vowel or consonant. The DVs for this task are switch cost and mixing cost. Switch cost reflects more transient control processes to updating goals or task demands, while mixing cost reflects cognitive control in actively maintaining representations of multiple task demands.

In the n-back task, participants completed two blocks of 2-back and two blocks of 3-back test trials. The dependent measures in this task are d' calculated separately for 2 and 3-back, reflecting detection sensitivity according to the signal detection theory.

General Procedure

All tasks were administered individually in a quiet room at the authors' university. Participants first completed the LBQ. Participants then performed the two reading comprehension tasks and subsequently completed three executive control tasks: Stroop task, task-switching and n-back task, programmed in MATLAB (Version 7.10). The order of the Stroop and task-switching task was counterbalanced between participants but the n-back task was always performed last. When all the executive control tasks were completed, participants completed two other reading comprehension tasks. Visual stimuli were presented to participants from about 70cm via a 23-inch monitor with a refresh rate of about 60Hz. For the executive control tasks, participants were instructed to respond as quickly and as accurately as possible. Each experimental session took about 1.5 to 2 hours.

Results

Prior to data analyses, we screened the data from all executive control tasks to remove incorrect trials as well as trials with those RTs shorter than 200ms or longer than 3000ms. These discarded trials amounted to less than 6% (3% - 5%) of the total number of trials for each task. We also discarded DVs (Stroop interference RT, switch cost RT, mixing cost RT, 2-back *d'* and 3-back *d'*) of interest that were greater or less than 2.5 SDs from the group mean. These outliers were rare and amounted to about 2% of the total number of data points. These data trimming procedures are typical in studies using similar experimental tasks.

We performed a median split on balanced proficiency and balanced usage to categorize participants into balanced and unbalanced proficient groups as well as balanced and unbalanced dual-language users. This is to directly compare these groups and subsequently perform analyses to determine the effect of proficiency and usage interactions on executive control. As participants' language switching could potentially confound the relationship between language usage and proficiency on our executive control measures, we controlled for its effects by entering language switching as a covariate in separate analyses of covariance.

Reading Comprehension Performance

We first performed 2 (time: reading comprehension before and after executive control tasks) x 2 (response type: oral and written) x 2 (condition: SL and DL) x 2 (balanced usage: balanced and unbalanced) x 2 (balanced proficiency: balanced and unbalanced) mixed ANCOVA with language switching as a covariate to determine whether performance in the reading comprehension task differed as a function of time, bilingualism, response type and condition. Importantly, this also allowed us to perform a manipulation check to determine if the DL condition was indeed more cognitively demanding than the SL condition.

There was a Condition effect, $F(1, 63) = 21.71$, $p < .001$, $\eta_p^2 = 0.26$. This was qualified by a Condition x Balanced Usage interaction, $F(1, 63) = 4.14$, $p = .05$, $\eta_p^2 = 0.06$. Specifically, unbalanced language users' reading comprehension performance was poorer when required to codeswitch in the DL condition ($M = 11.80$) compared to the SL condition where codeswitching was not required ($M = 13.56$), $t(36) = 2.34$, $p = .03$. Similarly, balanced users performed poorer in reading comprehension in the DL ($M = 10.22$) than in the SL condition ($M = 14.12$).

There was also a Time effect, $F(1, 63) = 8.10$, $p = .01$, $\eta_p^2 = 0.11$, indicating that participants performed better in the reading comprehension task following ($M = 3.18$) the executive control tasks than before ($M = 3.06$). This was however qualified by a Time x Language Switching interaction. We followed up this significant interaction with a median split of language switching and compared the reading comprehension scores for frequent and infrequent language switchers. While the infrequent language switchers performed better ($M = 6.57$) after the executive control tasks than before ($M = 5.87$), $t(36) = -3.03$, $p = .01$, the frequent language switchers performed equally well before ($M = 6.13$) and after ($M = 6.16$) the executive control tasks, $t(37) = -0.1$, $p = .93$. This suggests infrequent switchers but not the frequent switchers gained from a prior practice in the reading comprehension task. No other main effects or interactions approached or were statistically significant.

Overall, the significant main effect of condition showed that the dual-language condition was more demanding and indicated that our manipulation was successful in increasing executive control load.

Executive Control Performance

Inhibition A 2 (balanced proficiency) x 2 (balanced usage) x 2 (condition) ANCOVA with language switching as a covariate to account for unintentional switching in language use as a potential confound was conducted. Language switching was not significantly related to Stroop effect ($p = .53$). There was a significant Balanced Proficiency x Condition interaction, $F(1,65) = 4.22$, $p = .04$. Follow up comparisons however showed no significant difference in Stroop interference effects between the two conditions amongst balanced proficient bilinguals ($p = .095$). This was similar for the unbalanced proficient bilinguals ($p = .22$). No other significant effects were found (all *p*s > .43).

Shifting The switch cost and mixing cost in task-switching were evaluated in a similar way. There were no significant main effects or interactions on the switch cost (all *p*s > .23). In contrast, for the mixing cost, the Balanced Usage x Condition interaction was significant, $F(1, 67) = 4.87$, $p = .03$, $\eta_p^2 = 0.07$ (see Figure 1). In the SL condition, no significant differences were found between balanced and unbalanced dual language users in mixing cost ($p = .26$). However, in the DL condition, the balanced users had a significantly smaller mixing cost than the unbalanced users ($p = .04$). These results suggest that codeswitching in the DL condition negatively affected unbalanced participants in task mixing but not on balanced usage participants.

Updating On the 2-back trials, there was a significant Balanced Usage x Condition interaction on the sensitivity to targets, $F(1, 67) = 4.48$, $p = .04$, $\eta_p^2 = 0.06$ (see Figure 2). Follow up comparisons revealed that although there was no difference in 2-back *d'* between balanced and unbalanced users in the SL condition ($p = .31$), 2-back *d'* differed between the two groups in the DL condition ($p = .047$). This demonstrated that codeswitching adversely affected information updating (in 2-back) for the unbalanced users, but had no effect on the balanced users.

On the 3-back trials, a significant main effect of balanced usage was evident, $F(1, 68) = 6.17$, $p = .02$, $\eta_p^2 = 0.08$. This main effect was qualified by a Balanced Usage x Condition interaction, $F(1, 68) = 4.80$, $p = .03$, $\eta_p^2 = 0.07$. Similar as the 2-back task, no significant differences in performance were found between balanced and unbalanced dual-language users in the SL condition ($p = .84$). However, balanced users had significantly higher 3-back *d'* scores compared to unbalanced dual language users in the DL condition ($p = .001$). This indicates that balanced dual language users were less affected by codeswitching than did their unbalanced counterparts (see Figure 3). Additionally, a significant balanced proficiency main effect was found for the 3-back *d'* scores, $F(1, 68) = 5.72$, $p = .02$, $\eta_p^2 = 0.08$. The Balanced Usage x Balanced Proficiency interaction was also significant, $F(1, 68) = 6.91$, $p = .01$, $\eta_p^2 = 0.09$.

Discussion

This study investigated the effects of language control on domain-general executive control in bilingual adults who differed in the degree of bilingualism. By implementing a novel language control manipulation and adopting an individual differences approach to study the bilingual advantage, we found that (1) engaging bilingual speakers in a dual-language context (involving codeswitching) increased cognitive load and interfered with information organization and integration, resulting in poorer comprehension performance, (2) increased cognitive demands on language control depleted general executive control resources and negatively impacted executive control components such as maintenance of mental representations and sensitivity to targets, and (3) effects of language control on executive control were modulated by factors that influenced the exposure and opportunity for bilingual speakers to practice language control in daily life.

When required to codeswitch prior to performing executive control tasks, participants who were balanced dual language users demonstrated smaller mixing cost and better target discrimination compared to those unbalanced users. These results suggest that a more balanced use of two languages may function as a cognitive reserve that would mitigate the effects of language control on executive control, i.e., balanced bilinguals may have larger cognitive resources for executive control than less balanced bilinguals. This advantage is likely due to balanced dual language users having more opportunity to be involved in interactional contexts where both languages are used with different speakers, and the constant need to monitor and control attention to the target language system over the competing other language, which in turn lead to the development of larger cognitive resources for adaptive language control processes.

The interaction effects of balanced usage and language control condition were significant for only mixing cost and working memory updating, but not for Stroop interference

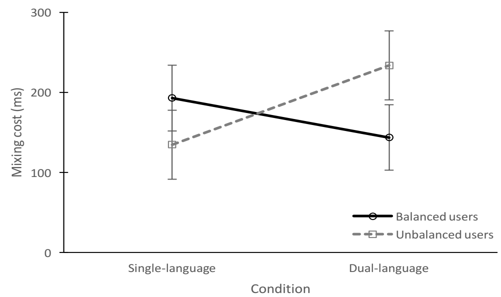

Figure 1. Mixing cost for balanced and unbalanced usage participants in single- and DL conditions. Error bars denote 95% confidence intervals.

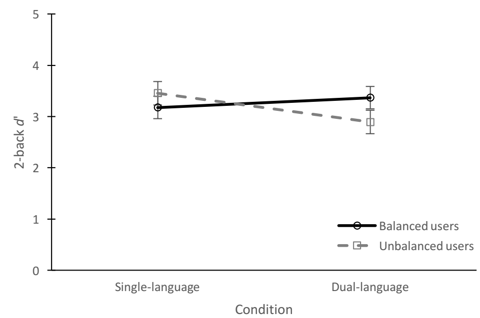

Figure 2. Performance in 2-back (*d'*) by balanced usage and condition. Error bars denote 95% confidence intervals.

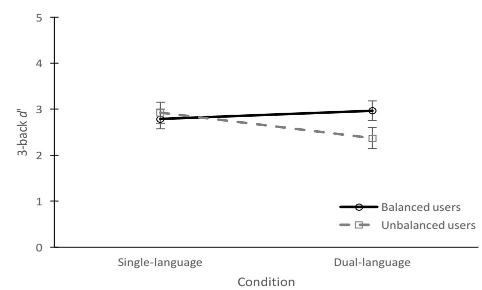

Figure 3. Performance in 3-back (*d'*) by balanced usage and condition Error bars denote 95% confidence intervals.

effect or switch cost, indicating that only some cognitive control processes were used in the current dual-language context. This is consistent with the adaptive control hypothesis proposing that the demand on different control processes varies as a function of the interactional context. For instance, it is hypothesized that, for bilingual speakers, both single-language and dual-language contexts increase the demands on interference control that was assessed by the Stroop task in this study. Thus, resources for inhibition may not be depleted in the dual-language context, even amongst unbalanced users. Our failure to find bilingual advantages in switch cost has been documented previously (e.g., Yow & Li, 2015). Being more balanced in dual language use may not have conferred an advantage to the transient switching cost because task switching is also akin to frequent topic changes during discourse, in which both balanced and unbalanced users are equally likely to engage in (Wiseheart et al., 2014). In contrast, mixing cost reflects global sustained control necessary for maintaining competing mental representations, which is akin to using different languages in dual-language contexts. Balanced dual language users may have developed a larger executive control resource to hold multiple language rules "on-line", preventing resource depletion following our codeswitching manipulation. Lastly, updating and monitoring is postulated to be necessary for maintenance of task goals during dual language discourse. Unbalanced dual language users who hold smaller working memory resources are therefore more affected in updating after having to codeswitch. Taken together, these results indicate that bilingual advantage is limited to certain but not all components within the Miyake et al. (2000) model.

One limitation inherent in our study is the use of self-report for language proficiency. Although this approach is consistent with many other studies (e.g., Wiseheart et al., 2014), we acknowledge that using self- report measures may result in less accurate proficiency ratings than objective measures. However, given that many participants may know more than two languages, objective measures of their language proficiency may not be feasible without substantially prolonging the experimental session.

In conclusion, we provide novel evidence showing that language control and executive control depend on shared resources by experimentally manipulating language control via codeswitching. Crucially, we provide evidence of the bilingual advantage in showing that bilinguals who are more balanced in dual language use have larger working memory and task mixing resources that buffered against performance decline following language control. Theoretically, our results add to the current understanding of the mechanism of the bilingual advantage in executive control: language and executive control share similar resources, and this shared resource can be enhanced by using more than one language equally frequently.

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