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Disparate bilingual experiences modulate task-switching advantages: A diffusion-model analysis of the effects of interactional context on switch costs

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ABSTRACT

Drawing on the adaptive control hypothesis (Green & Abutalebi, 2013), we investigated whether bilinguals' disparate interactional contexts modulate task-switching performance. Fifty-eight bilinguals within the single-language context (SLC) and 75 bilinguals within the dual-language context (DLC) were compared in a typical task-switching paradigm. Given that DLC bilinguals switch between languages within the same context, while SLC bilinguals speak only one language in one environment and therefore rarely switch languages, we hypothesized that the two groups' stark difference in their interactional contexts of conversational exchanges would lead to differences in switch costs. As predicted, DLC bilinguals showed smaller switch costs than SLC bilinguals. Our diffusion-model analyses suggest that DLC bilinguals' benefits in switch costs are more likely driven by task-set reconfiguration than by proactive interference. Our findings underscore the modulating role of the interactional context of conversational exchanges in task switching.

1. Introduction

Bilinguals are unique in their practice of flexible language-switching between two or more languages. Given that the neurocognitive mechanisms that underlie bilinguals' language switching and task switching are partially shared (e.g., Abutalebi & Green, 2007; Weissberger, Gollan, Bondi, Clark, & Wierenga, 2015), the question arises as to whether bilinguals' qualitatively different language-switching practices affect their task-switching ability to switch back and forth between multiple tasks, operations, and mental sets (Monsell, 2003).

Bilinguals' task-switching abilities have been studied by using a typical task-switching paradigm that considers both switch costs and mixing costs, which have been found to implicate different control mechanisms (Braver, Reynolds, & Donaldson, 2003). Specifically, switch costs—i.e., the actual cost of switching between different task sets—arise from local control mechanisms that involve transient task-set reconfiguration (Rogers & Monsell, 1995) and proactive interference from previous task sets (Wylie & Allport, 2000). Mixing costs—i.e., the cost of monitoring and coordinating multiple streams of incoming information—entail activation of global and sustained control mechanisms (Rubin & Meiran, 2005). Because of the conceptual overlap between bilinguals' language- and task switching, it has been suggested that bilingualism attenuates task-switching costs. In recent years, however, the question of whether bilingualism confers benefits on task switching has been debated, and findings have been inconsistent. For instance, some studies have found bilingual advantages in switch costs (Prior & MacWhinney, 2010), while others report bilingual advantages in mixing costs (Gold, Kim, Johnson, Kryscio, & Smith, 2013; Wiseheart, Viswanathan, & Bialystok, 2014). Moreover, recent attempts to replicate these effects found neither switch- nor mixing-cost advantages, even among bilinguals who frequently switch languages (Hernández, Martin, Barcelo, & Costa, 2013; Paap & Greenberg, 2013; Paap & Sawi, 2014). These inconsistencies highlight the need for a more rigorous, theory-driven approach.

The adaptive control hypothesis (Green & Abutalebi, 2013) postulates that bilinguals' interactional contexts of conversational exchanges implicate different demands on bilinguals' language control and adaptively alter their cognitive-control abilities. Specifically, (a) the *dual-language* context (DLC)—in which bilinguals use two languages within the same context (e.g., both L1 and L2 at home and work)—requires a more taxing level of

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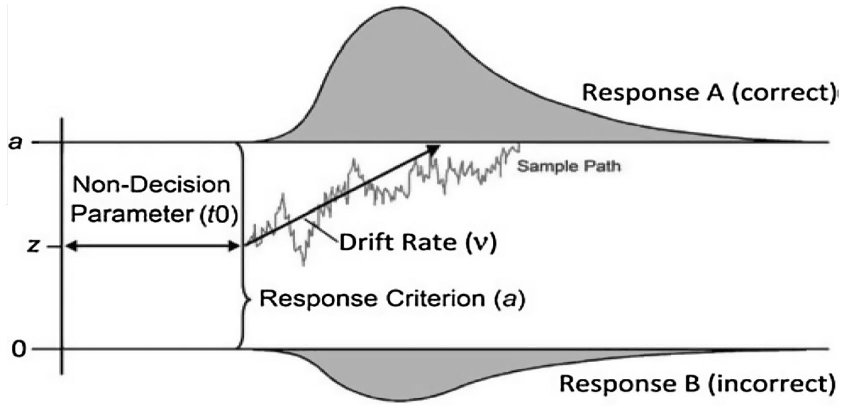

Fig. 1. Diffusion process underlying the diffusion model. The model assumes that decisions are based on the accumulation of information over time until a response boundary is reached and a motor response elicited (Ratcliff, 1978). By using both response latency and accuracy, the diffusion model decomposes the decision process into several meaningful parameters. Specifically, drift rate (v) quantifies the speed of information uptake and stimulus difficulty, which map onto participants' processing ability; larger values represent fast and accurate responses. The drift rate is the mean slope of the counter, and differences in drift rate between switch trials and non-switch trials are thought to reflect proactive interference in task switching. Boundary separation (a) quantifies the speed–accuracy trade-off, with a larger value indicating a conservative decision characterized by slow reaction time and high accuracy. Starting point (zr) quantifies a priori bias in decision thresholds, ranging from 0 to 1, with a value of 0.5 indicating the absence of a priori decisional bias. The decision process begins at the starting point, where information is accumulated until a response boundary is reached. Lastly, non-decision time (t_0) quantifies the duration of all non-decisional processes, such as encoding and response execution. Non-decision processes occur before and after the actual decision phase and are thought to reflect the reconfiguration processes in task switching (see Voss et al., 2013, for a practical introduction to diffusion models; see Schmitz & Voss, 2012, for their use in a task-switching paradigm). Adapted from Schmitz and Voss (2012, p. 226).

language control, and therefore should better facilitate task-switching performance than either (b) the *single-language* context (SLC)—in which bilinguals speak only one language in one environment and therefore rarely switch languages (e.g., L1 at home and L2 at work)—or (c) the *dense code-switching* context (i.e., intrasentential code-switching)—in which bilinguals routinely mix linguistic elements (e.g., words) of two languages within a single utterance.

To test those theoretical predictions, we operationalized bilinguals' interactional contexts according to two primary perspectives that closely reflect the complexity of bilingualism in Singapore. First, we assume that DLC bilingualism is the bipolar opposite of SLC bilingualism, both of which fall along a bipolar continuum. Namely, each point on the continuum is influenced by the extent of both DLC and SLC bilingualism: If one's DLC bilingualism is high, his or her SLC bilingualism is likely low. Second, because of the prevalence of English-based creole in Singapore,[1] both DLC and SLC bilinguals likely perform intrasentential code-switching, which signifies the dense code-switching context; in particular, DLC more likely implicates the dense code-switching context. Therefore, DLC or SLC are not clearly separable from the dense code-switching context, and dividing bilinguals into three groups according to different interactional contexts is not straightforward.

Because of these constraints, we examined the impact of bilinguals' interactional contexts as follows. First, we examined whether DLC and SLC differ in switch costs. Consistent with the adaptive control hypothesis, we expected that DLC bilinguals would have smaller switch costs than SLC bilinguals, because DLC bilinguals' complex language-set reconfiguration should be conducive to transient task-set reconfiguration, which is regarded as the primary mechanism of switch costs. Second, given that both DLC and SLC are related to the dense code-switching context, we used regression analysis to examine its relative importance to DLC and SLC in predicting switch costs, while controlling for important individual factors.

Our other important goal was to elucidate the cognitive processing that underlies switch costs in particular. Although the multiple-component model of task switching proposes that switch costs arise from task-set reconfiguration and proactive interference (Mayr & Kliegl, 2003; Ruthruff, Remington, & Johnston, 2001), the literature on bilingualism has not clearly identified the specific cognitive components linked to bilingual advantages in task switching. Therefore, we employed the stochastic diffusion model (Ratcliff, 1978) to decompose switch costs into specific cognitive components. Using this model in the task-switching paradigm, recent studies have reported that differences in the non-decision time parameter (t_0) between switch trials and non-switch trials are related to the early phase of a task switch, which involves task-reconfiguration processes, whereas differences in drift rate (v) between switch trials and non-switch trials are associated with the later stage of task switching, which entails proactive interference (Mansfield, Karayanidis, Jamadar, Heathcote, & Forstmann, 2011; Schmitz & Voss, 2012, 2014). This model, therefore, allows us to examine whether the locus of bilingual advantages in switch costs is pertinent to either task-set reconfiguration or proactive interference (see Fig. 1).

2. Method

2.1. Participants

One hundred and thirty-three bilinguals (female = 89) from a university in Singapore participated for extra course credit or S $13.[2] In addition to English, bilingual participants spoke a variety of languages, which includes Chinese ($n = 110$), Malay ($n = 8$), Indonesian ($n = 1$), Hindi ($n = 3$), Tamil ($n = 3$), Malayalam ($n = 1$), Vietnamese ($n = 5$), Korean ($n = 2$). Using a 5-point Likert scale (1 = *never*, 5 = *always*), participants reported on two items regarding the extent to which they used two languages within the same context (DLC bilingualism) and in different contexts (SLC bilingualism;

[1] Singapore bilinguals speak an English-based creole language, "Singlish," which has been substantially influenced by loan words from Mandarin dialects, Malay, and Tamil (Wong, 2004). Therefore, Singlish involves frequent practice of intrasentential code-switching in everyday conversation. For example, bilinguals in Singapore may sometimes insert a Malay word, *makan*, into a single English utterance—e.g., "Let's find some place to *makan* [eat]."

[2] Five participants were excluded from the analysis for the following reasons. Two had extremely high mixing costs (5.6 and 4.8 *SD* from the overall mean of mixing costs); two violated the model fit when running the diffusion-model analyses ($p = .005$ and $.013$); and one had substantial negative switch costs (−190 ms) in non-decision parameters (t_0).

Table 1
Characteristics of dual-language context (DLC) and single-language context (SLC) bilinguals.

	DLC bilinguals ($n = 75$)	SLC bilinguals ($n = 58$)	t
Age	21.41 (1.81)	21.95 (2.84)	−1.32
Years of formal education	13.92 (2.07)	14.37 (1.91)	−1.29
Paternal education level[a]	3.95 (1.20)	3.90 (1.25)	0.24
Maternal education level[a]	3.65 (1.01)	3.84 (1.07)	−1.06
Monthly household income[b]	3.65 (2.23)	3.67 (2.42)	−0.05
Nonverbal intelligence standard score (KBIT-2)[c]	108.23 (14.24)	109.18 (15.00)	−0.37
Shipley Vocabulary Test score	30.80 (3.23)	30.84 (3.33)	−0.08
O level mother-tongue subject score[d]	8.23 (1.81)	8.07 (1.62)	0.50

Note: SDs are shown in parentheses.
[a] Parental education level was rated on a scale of 1 (*none*) to 6 (*master's or PhD*).
[b] Household income was rated on a scale of 1 (*less than S$2500*) to 9 (*more than S $20,000*), with intervals of S$2500.
[c] Five participants did not participate in a subsequent test session that assessed nonverbal intelligence (DLC bilinguals = 71; SLC bilinguals = 57).
[d] All O-level students in Singapore are required to take one mother-tongue subject (e.g., Mandarin, Malay, Hindi, or Tamil) other than English. The subject includes examination on written, oral, listening, and comprehension skills, and scores range from 1 (F9) to 9 (A1). Fourteen participants did not provide their scores.

Table 2
Self-report language background of DLC and SLC bilinguals.

	DLC bilinguals ($n = 75$)	SLC bilinguals ($n = 58$)	t
Age of second language (L2) acquisition	3.17 (2.42)	3.98 (2.98)	−1.73[†]
Age of L2 fluency[a]	8.69 (4.33)	9.91 (4.27)	−1.62
Recent L1 exposure (%)	63.07 (27.52)	61.62 (29.49)	0.29
Recent L2 exposure (%)	33.33 (26.45)	33.47 (39.86)	−0.03
L1 exposure for the past 5 years (%)	60.68 (22.03)	61.05 (25.84)	−0.09
L2 exposure for the past 5 years (%)	35.23 (20.80)	33.43 (25.05)	0.45
Daily usage of L1 (%)	65.27 (29.04)	66.24 (31.24)	−0.19
Daily usage of L2 (%)	32.35 (29.18)	30.03 (31.12)	0.44
L1 self-reported proficiency			
Speaking	8.24 (1.79)	8.41 (1.36)	−0.61
Comprehension	8.47 (1.55)	8.78 (1.34)	−1.21
Reading	8.37 (1.75)	8.05 (2.13)	0.96
L2 self-reported proficiency			
Speaking	6.95 (2.04)	6.67 (2.24)	0.74
Comprehension	7.40 (1.87)	7.26 (2.02)	0.42
Reading	6.49 (2.41)	6.28 (2.66)	0.49

Note: SDs are shown in parentheses.
[†] $p < .10$.
[a] Data from one participant is missing.

reverse coded), respectively (see Appendix B). Scores on these two items were summed to produce the composite score for DLC bilingualism ($M = 5.80$; $SD = 1.69$), which takes SLC bilingualism into consideration. Using the mean split of this, participants were divided into groups of DLC ($n = 75$; $M \geqslant 6$) and SLC bilinguals ($n = 58$; $M < 6$). Participants' demographic and language characteristics are shown in Tables 1 and 2.

2.2. Color–shape switching task

Similar to the typical color–shape switching task used in previous studies (e.g., Paap & Greenberg, 2013), participants were instructed to respond to either the color (red or green) or shape (circle or triangle) of a target, with respect to the given cue (the color gradient or a row of small black shapes). For the diffusion-model analysis, we made two modifications. First, we employed overlapping response mapping, which required participants to press the left key for both "green" and "triangle" and the right key for both "red" and "circle" (counterbalanced across participants). Second, we employed 100% stimulus–response incompatible trials for two bivalent target stimuli (green circle and red triangle); i.e., no stimulus matched a response on both color and shape.

Participants began with one practice block (30 trials), followed by two pure blocks (color and shape, counterbalanced across participants), and then four mixed blocks that included an equal number of task-switch and task-repeat trials. Each main block consisted of 50 randomized trials with a maximum of four consecutive trials of the same task. For each trial, a fixation cross appeared for 350 ms, followed by a blank screen (150 ms). The cue then appeared 2.8° above the fixation cross (250 ms), followed by the target. Both the cue and the target remained on the screen until the participant responded, which was followed by an inter-trial interval (850 ms). Participants received feedback (a beep) for incorrect responses.

2.3. Background measures

A subtest of the Kaufman Brief Intelligence Test (KBIT-2; Kaufman & Kaufman, 2004) was used to measure nonverbal intelligence. General verbal ability was assessed by the Shipley Vocabulary Test (Shipley, 1986), and language background by a questionnaire adapted from the Language Experience and Proficiency Questionnaire (Marian, Blumenfeld, & Kaushanskaya, 2007) and the Language History Questionnaire (Li, Zhang, Tsai, & Puls, 2014).

3. Results

3.1. Background measures

DLC and SLC bilinguals did not differ in nonverbal intelligence, general vocabulary, demographic profiles, or various language-background variables (Tables 1 and 2). The two groups differed significantly, however, in variables related to DLC and SLC bilingualism, intrasentential and intersentential code-switching, all $ps < .01$ (Table 3).

3.2. Task-switching costs

Overall accuracy rates were high for both pure and mixed blocks and did not differentiate DLC and SLC bilinguals, all $ts < 1$ (Table 4). Preliminary analyses of accuracy showed that bilinguals' interactional contexts (DLC, SLC) moderated neither switch costs nor mixing costs, $Fs < 1$. Therefore, no other analyses were performed for accuracy. Response time (RT) that were either below 200 ms or above 5000 ms or 2.5 *SD* above or below each participant's mean were excluded separately for pure blocks and mixed-task blocks. Separate analyses were performed for switch costs and mixing costs.

Regarding switch costs, a repeated-measures mixed-factor ANOVA was performed with Interactional Context (DLC vs. SLC) as a between-participant factor and Switching (switch vs. repeat) as a within-participant factor. We found significant main effects of Interactional Context, $F(1,131) = 4.63$, $p = .033$, $\eta_p^2 = .034$, and Switching, $F(1,131) = 506.94$, $p < .001$, $\eta_p^2 = .795$. The interaction between Interactional Context and Switching was also significant, $F(1,131) = 8.94$, $p = .003$, $\eta_p^2 = .064$, suggesting that bilinguals' interactional contexts modulate switch costs. Follow-up analyses showed that DLC bilinguals were significantly faster than SLC bilinguals in switch trials, $F(1,131) = 6.55$, $p = .012$, $\eta_p^2 = .048$, but not in repeat trials, $p = .155$.

Table 3
Language switching variables of DLC and SLC bilinguals.

	DLC bilinguals ($n = 75$)	SLC bilinguals ($n = 58$)	t
Intersentential code-switching frequency[a]	2.97 (0.96)	2.34 (0.93)	3.80***
Intrasentential code-switching frequency[b]	3.57 (0.87)	3.02 (1.03)	3.36**
Index of intersentential code-switching[c]	2.82 (1.06)	2.25 (0.92)	3.29**
Index of intrasentential code-switching[d]	3.39 (0.93)	2.78 (1.07)	3.47**
Composite score of DLC bilingualism[e]	7.04 (0.98)	4.21 (0.87)	17.34***
Index of SLC bilingualism[f]	62.18 (24.48)	78.98 (16.94)	−4.47***

Note: SDs are shown in parentheses.
* $p < .05$.
** $p < .01$.
*** $p < .001$.
[a] General frequency of bilinguals' code-switching between sentences (1 = *never*, 5 = *always*).
[b] General frequency of bilinguals' code-switching within sentences (1 = *never*, 5 = *always*).
[c] Aggregated intersentential code-switching frequency relative to time spent across four different situations—home, school, work, and others (see Appendix B for more detail).
[d] Aggregated intrasentential code-switching frequency relative to time spent across four different situations (see Appendix A).
[e] Overall DLC bilingualism in consideration of SLC bilingualism. The value is computed by summing participants' responses on two items regarding DLC bilingualism and SLC bilingualism, which is reverse coded. Scores range from 2 to 10, with a higher score indicating a greater degree of DLC bilingualism.
[f] Estimate of a SLC bilingual's relative use of L1 over other languages, given the amount of time spent across four different situations. This score ranges from 0 to 100, with 100 indicating perfect SLC bilingualism (see Appendix B).

Table 4
Reaction times, accuracy rates, and task-switching costs in the color–shape switching task.

	Reaction time (RT)			Accuracy		
	DLC bilinguals	SLC bilinguals	t	DLC bilinguals	SLC bilinguals	t
Type of trials						
Pure	393 (66)	405 (93)	−0.88	.98 (.02)	.98 (.02)	−0.04
Repeat	716 (162)	757 (171)	−1.43	.95 (.08)	.96 (.04)	−0.79
Switch	915 (201)	1018 (260)	−2.56*	.87 (.11)	.89 (.09)	−0.85
Switch costs	199 (95)	260 (139)	−2.99*	−.08 (.06)	−.08 (.05)	−0.57
Mixing costs	322 (150)	351 (150)	−1.11	−.02 (.07)	−.02 (.04)	−0.84

Note: SDs are shown in parentheses.

Regarding mixing costs, a similar repeated-measures mixed factor ANOVA was performed with Interactional Context and Mixing (pure vs. repeat). We found a significant main effect of Mixing, $F(1,131) = 660.36$, $p < .001$, $\eta_p^2 = .834$, but neither the main effect of Interactional Context ($p = .151$) nor its interaction with Mixing ($p = .269$) was significant. Together, our results demonstrate that DLC bilingualism confers benefits on switch costs, but not on mixing costs.

3.3. Diffusion-model analysis of switch costs

We performed diffusion-model analysis by focusing on switch and repeat trials in the mixed blocks. In our analysis, only drift rate (v) and non-decision time (t_0) were allowed to vary freely over task-switch and task-repeat trials. Boundary separation (a) and starting point (zr) were held constant across trials to increase the model's parsimony and fit (Voss, Nagler, & Lerche, 2013). Similarly, variability parameters and response-execution differences (d) were fixed to zero, except for the inter-trial variability of non-decision components ($st0$), which were held constant across trials (Voss et al., 2013). Parameters were estimated using Fast-dm for each participant, with the Kolmogorov–Smirnov (KS) statistic for optimization of parameters (Voss & Voss, 2007, 2008). Overall, the KS statistic did not reveal any suspicious fit ($ps > .20$), and parameter estimates of the diffusion model fit the empirical RT distributions closely (Appendix C).

Drift rate and non-decision time were submitted to repeated-measures mixed-factor ANOVAs with Interactional Context and Switching (switch vs. repeat). For non-decision time, we found a significant main effect of Switching, $F(1,131) = 373.62$, $p < .001$, $\eta_p^2 = .74$, and an interaction effect between Interactional Context and Switching, $F(1,131) = 4.61$, $p = .034$, $\eta_p^2 = .034$. However, for drift rate, we found only a significant main effect of Switching, $F(1,131) = 159.50$, $p < .001$, $\eta_p^2 = .427$. Neither the effect of Interactional Context nor its interaction with Switching was significant, $Fs < 1$. These results did not change when we excluded either 23 bilinguals who speak English and a language(s) other than Chinese or 5 participants whose IQ scores were missing; in either case, interactional context significantly modulated switch costs in RT and non-decision time, $ps < .05$. Together, these results suggest that the source of DLC bilinguals' advantages in switch costs are likely driven by their better ability to deal with task-set reconfiguration rather than proactive interference (Table 5). For boundary separation, we found significant group differences $t(131) = 2.06$, $p = .041$, suggesting SLC bilinguals' conservative (slower) responses than DLC bilinguals. However, given that zero-order correlations of boundary separation with the composite score of DLC ($r = -.132$, $p = .129$) and the index of SLC bilingualism ($r = .07$, $p = .455$) were not significant, this suggests that group differences in boundary separation could be a statistical artifact of the median-split procedure (MacCallum, Zhang, Preacher, & Rucker, 2002). Lastly, for starting point, the groups did not differ, $t(131) = 1.29$, $p = .199$, suggesting that the groups were similar in terms of a priori decision bias.

3.4. Regression analyses on switch costs

Four hierarchical regression analyses were conducted to assess the importance of various predictors of switch costs (in both RT and non-decision time). In all models, paternal education, verbal ability, and nonverbal intelligence were controlled in Step 1 (see Table 6). In Step 2, the index of intrasentential code-switching—i.e., the proxy measure of a dense code-switching context—was added simultaneously with an additional predictor for each regression model: the composite score of DLC bilingualism (Model 1), the index of SLC bilingualism (Model 2), the index of intersentential code-switching (Model 3), and the frequency of intersentential code-switching (Model 4).

Two primary results were noteworthy. First, we found that the composite score of DLC bilingualism and the index of SLC bilingualism—variables that represent the continuum of single- and dual-language contexts—emerged as significant predictors of switch costs, while the index and frequency of intersentential code-switching were only moderately significant. Second, unlike intersentential code-switching and DLC bilingualism, which negatively predicted switch costs, intrasentential code-switching positively predicted (i.e., exacerbated) switch costs.

4. Discussion

Our study demonstrates that bilinguals' DLC facilitates switch costs but not mixing costs. Furthermore, our diffusion-model anal-

Table 5
Diffusion model parameter estimates.

Parameter	DLC bilinguals	SLC bilinguals	t
Drift rate (v)			
Repeat trials	1.92 (0.64)	1.90 (0.68)	0.23
Switch trials	1.38 (0.55)	1.28 (0.49)	1.09
Non-decision time (t_0)			
Repeat trials	0.27 (0.08)	0.26 (0.07)	0.56
Switch trials	0.40 (0.10)	0.43 (0.10)	−1.49
Boundary separation (a)	1.83 (0.42)	2.00 (0.50)	−2.06*
Starting point (zr)	0.53 (0.08)	0.55 (0.09)	−1.29
Inter-trial variability of non-decision components ($st0$)	0.20 (0.08)	0.19 (0.09)	0.24

Note: SDs are shown in parentheses.

ysis demonstrates that DLC bilinguals' advantages in switch costs are primarily driven by group differences in non-decision time—which is related to task-set reconfiguration—rather than drift rate, which is related to proactive interference. Our findings highlight the importance of bilinguals' interactional contexts in examining bilingual advantages in task switching.

Our results elucidate potential causes of previous studies' inconsistencies in three respects. First, although the frequency-related values of intersentential code-switching reflect important aspects of the DLC context, they may be less reliable predictors of switch costs than the composite score of DLC bilingualism and index of SLC bilingualism. This is because the mere frequency of intersentential code-switching may not sufficiently capture the complex nature of the control processes involved in language switching. For example, the cognitive demand for intersentential code-switching can be moderated by who initiates the discourse. In general, self-initiated intersentential code-switching seems less taxing than other-initiated intersentential code-switching, because the former permits sufficient preparation time to reconfigure language sets, while the latter is triggered unexpectedly and occurs rapidly, and therefore imposes greater demands on language-set reconfiguration and proactive inhibition. Accordingly, the mere frequency of language switching may not be an adequate proxy measure of bilinguals' interactional context.

Second, our finding that intrasentential and intersentential code-switching predict switch costs in the opposite direction underscores the importance of the typology of code-switching. Intrasentential code-switching is voluntary and implicates opportunistic planning—i.e., using whatever comes most readily to hand (e.g., Gollan & Ferreira, 2009; Green & Abutalebi, 2013). Therefore, intrasentential code-switching facilitates language production by lightening the cognitive load of language-set reconfiguration (Gollan, Kleinman, & Wierenga, 2014). This contrasts with intersentential code-switching, which requires more taxing language control that leads, in turn, to adaptive cognitive control. Hence, a greater reliance on intrasentential code-switching likely mitigates one's ability to exercise task-set reconfiguration and eventually impairs switch costs. Our finding corroborates previous studies (e.g., Festman, Rodriguez-Fornells, & Münte, 2010; Rodriguez-Fornells, Krämer, Lorenzo-Seva, Festman, & Münte, 2012), in that not only unconscious but also conscious self-directed code-switching is associated with reduced executive functioning. Further investigation is warranted to examine different types of code-switching (Green & Wei, 2014), which appears to demand a different extent of control processing. Together, our findings highlights potential factors that can account for the mixed findings previously reported.

Lastly, previous studies' inconsistent results can be attributed in part to methodological differences. Given that our color–shape switching task included two modifications—i.e., overlapping response mapping and 100% stimulus–response incompatibility—it is noteworthy that these modifications may have enhanced the task's sensitivity to group differences in task-set reconfiguration. Previous studies have suggested that overlapping response mapping places greater demand on task-set reconfiguration than non-overlapping response mapping (Meiran, 2000, 2008), because switch trials in overlapping response mapping require participants to recode the response key to match different aspects of the stimulus (for a review, see Kiesel et al., 2010). Moreover, unlike previous studies that employed 50% incompatible trials (e.g., Gold et al., 2013), using 100% incompatible trials requires response recoding on all switch trials, which may further impose greater demand on task-set reconfiguration. We have summarized the procedural details of previous studies in Table 7.

Table 6
Multiple regression analyses on switch costs with interactional contexts as predictors.

	Response time						Non-decision time					
	B	$SE\ B$	Beta	t	Tolerance	VIF	B	$SE\ B$	Beta	t	Tolerance	VIF
Step 1: Control variables												
Paternal education	0.75	9.08	0.01	0.08	0.98	1.03	3.28	6.65	0.05	0.49	0.98	1.03
KBIT-2	0.17	0.76	0.02	0.22	0.98	1.03	0.06	0.56	0.01	0.11	0.98	1.03
Shipley	−3.46	3.30	−0.09	−1.05	1.00	1.00	−1.98	2.42	−0.07	−0.82	1.00	1.00
Step 2: Language-switching variables												
Model 1												
Index of intrasentential code-switching	21.80	11.25	0.19	1.94†	0.80	1.25	16.17	8.39	0.19	1.93†	0.80	1.25
Composite score of DLC bilingualism	−22.86	6.81	0.32	−3.36**	0.83	1.21	−12.50	5.08	−0.24	−2.46*	0.83	1.21
Model 2												
Index of intrasentential code-switching	16.54	11.70	0.14	1.41	0.78	1.28	16.11	8.50	0.19	1.90†	0.78	1.28
Index of SLC bilingualism	1.17	0.53	0.22	1.98†	0.78	1.28	0.90	0.39	0.23	2.29*	0.78	1.28
Model 3												
Index of intrasentential code-switching	24.05	14.01	0.21	1.71†	0.55	1.83	19.86	10.25	0.23	1.94†	0.55	1.83
Index of intersentential code-switching	−26.03	13.82	−0.22	−1.88†	0.56	1.78	−17.96	10.11	−0.21	−1.78†	0.56	1.78
Model 4												
Index of intrasentential code-switching	21.10	13.25	0.18	1.59	0.61	1.63	16.47	9.72	0.19	1.69†	0.61	1.63
Frequency of intersentential code-switching	−24.32	13.48	−0.20	−1.80†	0.64	1.56	−14.45	9.89	−0.16	−1.46	0.64	1.56

Note: KBIT-2 assessed nonverbal intelligence; Shipley assessed general verbal abilities; DLC = dual-language context; SLC = single-language context; response time and non-decision time were measured in ms; each model was independent.
† $p < .10$.
* $p < .05$.
** $p < .01$.

Table 7
Summary of studies examining bilingual benefit using a color–shape switching task in a task-cueing paradigm.

Study	Participants	Number of trials	Cue	CSI (ms)	RCI (ms)	Response mapping[a]	RC[b] (%)	Task-switching outcome
Garbin et al. (2010)	Bilinguals ($n = 19$) Monolinguals ($n = 21$)	60 trials (30 mixed-switch and 30 mixed-repeat)	Verbal	0	2000	Overlapping	50	Switch costs advantages in bilinguals
Prior and MacWhinney (2010)	Bilinguals ($n = 47$) Monolinguals ($n = 45$)	288 trials (144 pure–repeat, 72 mixed-switch and 72 mixed-repeat) sandwich design	Non-verbal	250	850	Non-overlapping	100	Switch costs advantages in bilinguals
Prior and Gollan (2011)	Spanish–English bilinguals ($n = 41$) Mandarin–English bilinguals ($n = 43$) Monolinguals ($n = 47$)	288 trials (144 pure–repeat, 72 mixed-switch and 72 mixed-repeat) sandwich design	Non-verbal	250	850	Non-overlapping	100	Relative switch costs advantages after controlling for parents' educational level in Spanish–English bilinguals but not in Chinese–English bilinguals
Hernández et al. (2013; experiment 3)	Bilinguals ($n = 38$) Monolinguals ($n = 39$)	288 trials (144 pure–repeat, 72 mixed-switch and 72 mixed-repeat) sandwich design	Non-verbal	250	850	Non-overlapping	100	No bilingual advantages
Paap and Greenberg (2013)	Bilinguals ($n = 109$) Monolinguals ($n = 144$)	288 trials (144 pure–repeat, 72 mixed-switch and 72 mixed-repeat)	Non-verbal	250	850	Non-overlapping	100	No bilingual advantages
Gold et al. (2013) Experiment 1	Older adult bilinguals ($n = 15$) Older adult monolinguals ($n = 15$)	240 trials (80 pure–repeat, 80 mixed-switch, 80 mixed-repeat)	Verbal	150	200	Overlapping	50	Mixing costs advantages in bilinguals
Experiment 2	Older adult bilinguals ($n = 20$) Younger adult bilinguals ($n = 20$) Older adult monolinguals ($n = 20$) Young adult bilinguals ($n = 20$)	240 trials (80 pure–repeat, 80 mixed-switch, 80 mixed-repeat)	Verbal	150	200	Overlapping	50	No bilingual advantages
Paap and Sawi (2014)	Bilinguals ($n = 58$) Monolinguals ($n = 62$)	288 trials (144 pure–repeat, 72 mixed-switch and 72 mixed-repeat)	Non-verbal	250	850	Non-overlapping	100	No bilingual advantages
Wiseheart et al. (2014)	Bilinguals ($n = 31$) Monolinguals ($n = 37$)	150 trials (50 pure–repeat, 50 mixed-switch and 50 mixed-repeat)	Non-verbal	0	1000	Overlapping	0	Mixing costs advantages in bilinguals
Mor, Yitzhaki-Amsalem, and Prior (2014)	Bilinguals with ADHD ($n = 20$) Bilinguals control ($n = 20$) Monolingual with ADHD ($n = 20$) Monolingual control ($n = 20$)	288 trials (144 pure–repeat, 72 mixed-switch and 72 mixed-repeat) sandwich design	Non-verbal	250	850	Non-overlapping (100%)	100	No bilingual advantages
Houtzager, Lowie, Sprenger, and De Bot (2015)	Bilinguals ($n = 50$) Monolinguals ($n = 50$)	192 trials (96 pure–repeat, 48 mixed-switch, and 48 mixed-repeat)	Non-verbal	650	850	Non-overlapping (100%)	100	Switch costs advantages in bilinguals
Current study	DLC bilinguals ($n = 75$) SLC bilinguals ($n = 58$)	300 trials (100 pure–repeat, 100 mixed-switch and 100 mixed-repeat)	Non-verbal	250	850	Overlapping	0	Switch costs advantages in DLC bilinguals

Notes: CSI = cue-to-stimulus interval; RCI = response-to-cue interval; RC = response compatibility; DLC = dual-language context; SLC = single-language context.

[a] Overlapping response mapping occurs when each response key is assigned to two responses (e.g., both " green" and "triangle") from the color vs. shape tasks, while non-overlapping response mapping occurs when each response key is assigned to only one response (e.g., green).

[b] RC (response compatibility) indicates the proportion of trials where the stimulus and response are compatible in the color–shape switching task. For instance, on compatible trials, the bivalent stimulus (e.g., "green triangle") correctly matches the response associated with "green" and "triangle."

Although we found that DLC and SLC bilinguals do not differ in mixing costs, one might argue that DLC bilinguals should have greater advantages in mixing costs because they experience greater demands on goal maintenance and conflict monitoring. We argue, however, that given the high prevalence of bilingualism in Singapore (Dixon, 2005), our SLC bilinguals may still—although to a relatively lesser degree—engage monitoring of their language environment, and therefore both SLC and DLC bilinguals can have comparable mixing costs. For instance, SLC bilinguals who speak only Chinese at home must still monitor sudden conversational intrusions from a new interlocutor—e.g., conversing by phone in the caller's language. Furthermore, given mixing costs' greater malleability and sensitivity to training effects than switch costs (e.g., Prior & Gollan, 2013; Strobach, Liepelt, Schubert, & Kiesel, 2011), it is likely that bilingualism readily confers benefits on mixing costs to a relatively comparable degree for both DLC and SLC bilinguals. On procedural grounds, the absence of group differences in mixing costs is less likely to be attributed to our administration of pure blocks prior to mixed blocks. We did not find any systematic practice effects between the first two pure blocks. Although only the first mixed block showed relatively faster RTs than other mixed blocks, RTs were quickly stabilized across subsequent mixed blocks. Additionally, when we recalculated mixing costs by using only the second pure block as the baseline to account for any potential practice effect, we still obtained the same results.

In conclusion, using a theoretical framework, our study closes a gap in the literature regarding the critical importance of including bilinguals' interactional contexts and different types of language switching when studying bilingual advantages in task switching.

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Appendix A

A.1. Index of intersentential code-switching

Intersentential code-switching is the language switching that occurs between sentences. The index of intersentential code-switching yields an overall estimate of bilinguals' intersentential code-switching, aggregated across four different situations (home, school, work, and others). Participants reported the percentage of time they spent at home, school, work, and in other situations as well as the frequency of intersentential code-switching (1 = *never*, 5 = *always*) in each situation. The following formula was used to derive the index for intersentential code-switching:

$$\sum_{i=1}^{4} \frac{p_i \times s_i}{100}$$

where p_i is the amount of time bilinguals spent across four different situations, and s_i is the value of intersentential code-switching within each situation.

A.2. Index of intrasentential code-switching

Intrasentential code-switching is the language switching that occurs within a sentence. The index of intrasentential code-switching yields an overall estimate of bilinguals' intrasentential code-switching, aggregated across four different situations (home, school, work, and others). Participants reported the percentage of time they spent at home, school, work, and in other situations as well as the frequency of intrasentential code-switching (1 = *never*, 5 = *always*) in each situation. The following formula was used to derive the index for intrasentential code-switching:

$$\sum_{i=1}^{4} \frac{p_i \times m_i}{100}$$

where p_i is the amount of time spent in each context, and m_i is the frequency of intrasentential code-switching within a particular situation.

Appendix B

B.1. Composite score of dual-language context bilingualism

Composite score of dual-language context (DLC) bilingualism reflects the extent to which two languages are used within the same situation in general. The value is computed by summing participants' responses on two items regarding DLC bilingualism and single-language context bilingualism, which is reverse coded. Scores range from 2 to 10, with a higher score indicating a greater degree of DLC bilingualism.

B.2. Index of single-language context bilingualism

The index of single-language context (SLC) bilingualism estimates the extent to which one language (e.g., L1) is used in one situation, as opposed to the usage of another language (e.g., L2) in a separate situation. Participants reported the percentage of time they spent at home, school, work, and in other situations as well as the percentage of time they used L1 and L2 (and, potentially, L3 and L4) in each situation. Total percentage of all languages should be 100%. The following formula was used to derive the index for SLC bilingualism:

$$\sum_{i=1}^{4} \frac{p_i \times c_i}{100}$$

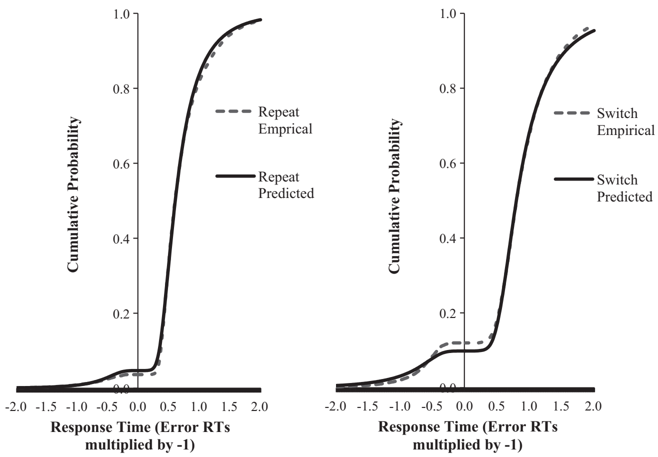
$$c_i = |(|(|(\textit{Percentage of } \mathrm{L1} - \textit{Percentage of } \mathrm{L2})| - \textit{Percentage of } \mathrm{L3})| - \textit{Percentage of } \mathrm{L4})|$$

where p_i is the amount of time spent in each context, and c_i is the absolute discrepancy between the percentage of time L1 was used and the total percentage of time other languages were used.

Appendix C

C.1. Graphical display of model fit

The graph displays overlaid predicted (parameter-based) and empirical cumulative distribution functions (cdfs) for both switch and repeat trials. Following the suggestion of Schmitz and Voss (2012), predicted and empirical cdfs were first computed for each participant and then averaged across participants. Correct and incorrect cdfs are combined, with latencies of correct responses plotted on the right side (with positive values) and latencies of incorrect responses plotted on the left side (with negative values). The intercept of the cdf reflects the percentage of inaccurate responses. A perfect fit is obtained if the predicted cdf falls on the empirical cdf line (Voss et al., 2013).



Appendix D

See Table D1.

Table D1
Correlation coefficients among language-switching variables.

	1	2	3	4	5	6
1. Composite score of DLC bilingualism	–					
2. Index of SLC bilingualism	−.424***	–				
3. Index of intersentential code-switching	.344***	−.480***	–			
4. Index of intrasentential code-switching	.379***	−.420***	.657***	–		
5. Frequency of intersentential code-switching	.376***	−.496***	.814***	.591***	–	
6. Frequency of intrasentential code-switching	.304***	−.384***	.614***	.637***	.678***	–

Note: DLC = dual-language context; SLC = single-language context.
*** $p < .001$.

Appendix E

E.1. Code-switching and interactional contexts questionnaire

Q1. How much time do you spend in each of the following situations, in general? Note that your answers should add up to 100%.

	Home	School	Work	Other than home, school and work
List percentage here				

E.2. Index of intersentential code-switching

Q2. How often do you switch languages between sentences when speaking at home (e.g., you speak one sentence in English and another sentence in Chinese).

Never ---------- Rarely ---------- Sometimes ---------- Most of the Time ---------- Always

Q3. How often do you switch languages between sentences when speaking at school (e.g., you speak one sentence in English and another sentence in Chinese)?

Never ---------- Rarely ---------- Sometimes ---------- Most of the Time ---------- Always

Q4. How often do you switch languages between sentences when speaking at work (e.g., you speak one sentence in English and another sentence in Chinese)?

Never ---------- Rarely ---------- Sometimes ---------- Most of the Time ---------- Always

Q5. How often do you switch languages between sentences when speaking in places other than home, school, and work (e.g., you speak one sentence in English and another sentence in Chinese)?

Never ---------- Rarely ---------- Sometimes ---------- Most of the Time ---------- Always

E.3. Index of intrasentential code-switching

Q6. How often do you mix words of different languages when speaking at home (e.g., when you have trouble finding a word in Chinese, you tend to immediately replace it with an English word instead, or vice versa)?

Never ---------- Rarely ---------- Sometimes ---------- Most of the Time ---------- Always

Q7. How often do you mix words of different languages when speaking at school (e.g., when you have trouble finding a word in Chinese, you tend to immediately replace it with an English word instead, or vice versa)?

Never ---------- Rarely ---------- Sometimes ---------- Most of the Time ---------- Always

Q8. How often do you mix words of different languages when speaking at work (e.g., when you have trouble finding a word in Chinese, you tend to immediately replace it with an English word instead, or vice versa)?

Never ---------- Rarely ---------- Sometimes ---------- Most of the Time ---------- Always

Q9. How often do you mix words of different languages when speaking in a situation other than home, school, or work (e.g., when you have trouble finding a word in Chinese, you tend to immediately replace it with an English word instead, or vice versa)?

Never ---------- Rarely ---------- Sometimes ---------- Most of the Time ---------- Always

E.4. Index of single-language context bilingualism

Q10. List the percent use of your native language and subsequently acquired language(s) at home. Put 0% if you do not use that particular language (note that your answers should add up to 100%).

	Native language	Second language	Third language	Fourth language	Fifth language
List percentage here					

Q11. How often do you use your native language and subsequently acquired language(s) at school? Put 0% if you do not use that particular language (note that your answers should add up to 100%).

	Native language	Second language	Third language	Fourth language	Fifth language
List percentage here					

Q12. List the percent use of your native language and subsequently acquired language(s) at work. Put 0% if you do not use that particular language (note that your answers should add up to 100%).

	Native language	Second language	Third language	Fourth language	Fifth language
List percentage here					

Q13. List the percent use of your native language and subsequently acquired language(s) in situations other than home, school, and work. Put 0% when you do not use that particular language (note that your answers should add up to 100%).

	Native language	Second language	Third language	Fourth language	Fifth language
List percentage here					

E.5. Composite score of dual-language context bilingualism

Q14. Do you speak two or more languages interchangeably within the same situation in general (e.g., using both English and Chinese at school)?

Never ---------- Rarely ---------- Sometimes ---------- Most of the Time ---------- Always

Q15. Do you speak only one language in one environment in general (e.g., using Chinese at home but English at school)?

Never ---------- Rarely ---------- Sometimes ---------- Most of the Time ---------- Always

Appendix F. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cognition.2016.01.016.

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