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Cognitive control and word recognition speed influence the Stroop effect in bilinguals

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Bilinguals have been shown to be less susceptible to Stroop interference in their first language than monolinguals, though the cause is currently being debated. In two experiments, we explored how cognitive control and word recognition contribute to the Stroop effect by contrasting cognitive control (via a Simon arrow task), word recognition speed (via a Chinese/English word recognition task) and Stroop susceptibility (via a verbal Stroop task) between proficient and non-proficient Chinese–English bilinguals. Compared to non-proficient bilinguals, proficient bilinguals showed better cognitive control at inhibiting irrelevant information, and they were slower at recognising Chinese words but quicker at recognising English words. Critically, we also showed that proficient bilinguals showed a smaller Stroop effect than non-proficient bilinguals in Chinese but a comparable Stroop effect as non-proficient bilinguals in English. The results cannot be accounted for by cognitive control or word recognition speed alone; instead, they are best accommodated by assuming that cognitive control and word recognition speed jointly determine the Stroop effect. Thus, we conclude that enhanced cognitive control and delayed word recognition combine to reduce Stroop effect in bilinguals as compared to monolinguals.

Keywords: Bilingualism; Stroop effect; Cognitive control; Word recognition.

With the continuous advancement of internationalisation and the deepening of international exchange, bilingualism (and multilingualism) has become a norm rather than an exception. Learning to speak a second language not only offers the opportunity of an additional communicative tool but also consumes time and energy. In more recent years, psychologists have also begun to investigate the advantages and disadvantages of bilingualism in relation to cognitive performance. Many researchers have shown that bilinguals enjoy enhanced cognitive control (Bialystok, 1999; Bialystok, Craik, & Luk, 2008; Costa, Hernandez, & Sebastian-Galles, 2008). According to these studies, bilinguals regularly switch between their two languages in daily life, and, in doing so, have to choose lexical items of the target language while inhibiting those from the undesired language. These routines gradually enhance the cognitive control in bilinguals as compared to monolinguals. In particular, it has been repeatedly demonstrated that bilinguals outperform their monolingual counterparts in tasks in which they have to attend to one dimension of information while ignoring other dimensions (Bialystok, 1999).

The Stroop task is often used to measure cognitive control (Stroop, 1935; see MacLeod, 1991, for a review). In the task, participants are slower and/or make more mistakes in naming the ink of a printed colour word when the ink name and the printed word are incongruent (e.g., the word *red* printed in blue) than when they are congruent (e.g., the word *red* printed in red). The Stroop effect occurs because participants automatically recognise the printed word while perceiving the ink colour, so when the printed word denotes a different colour from

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the colour of the ink, competition in conceptual encoding occurs (e.g., the semantic representation BLUE from the ink and the semantic representation RED from the printed word), resulting in delayed response or/and errors. Thus, in cases where the printed word and the ink colour name mismatch, participants need to inhibit the printed word in order to accurately produce the colour name; in other words, the magnitude of the Stroop effect depends on the extent to which participants inhibit the semantic access of the printed word. Recent research has suggested that the (intralingual) Stroop effect is reduced in bilinguals. Bialystok et al. (2008) showed that, compared to English monolinguals, English speakers speaking an additional language (e.g., French or Cantonese) exhibited less interference effect from the printed word when naming the colour name.

The reduction in the Stroop effect in bilinguals has been attributed to enhanced cognitive control in bilinguals (Bialystok et al., 2008). That is, language switching experience makes bilinguals more apt at inhibiting irrelevant information (e.g., the undesired language). In a Stroop task, then, bilinguals are better at inhibiting the irrelevant dimension of the stimulus (i.e., lexical semantic information), thus reducing the semantic interference from the irrelevant print words in the Stroop task. However, it should be noted that whether bilinguals have better cognitive control than monolinguals still remains a debate (see Hilchey & Klein, 2011, for a review). A recent study using a more comprehensive cognitive test failed to reveal any bilingual advantage (Paap & Greenberg, 2013; see also Kousaie & Phillips, 2012), while other studies showed that bilinguals' better cognitive control may be due to bilinguals' better economic condition, educational level (Morton & Harper, 2007). For instance, Morton and Harper (2007) showed that bilinguals and monolinguals performed similarly in the Simon task when intelligence and socioeconomic factors were controlled for between the monolingual and bilingual groups.

An alternative account for the reduced intralingual Stroop effects in bilinguals is that bilinguals have delayed speed at recognising the printed word. Note that bilinguals often use their two languages in their daily life, but monolinguals only use a single language. Hence, bilinguals have reduced frequency of use in either language than monolinguals, and therefore bilinguals have slower word recognition compared to monolinguals. For example, Bialystok et al. (2008) showed that bilinguals were outperformed by their monolingual counterparts in verbal tasks such as lexical recognition. Bilinguals also had poorer word recognition through noise (Rogers, Lister, Febo, Besing, & Abrams, 2006) and experienced more tips of the tongue and more failures in word retrieval as compared to monolinguals (Gollan, Bonanni, & Montoya, 2005). All these studies point to the conclusion that the bilinguals' reduced frequency of use in either of their languages hinders word recognition. Therefore, in a Stroop task, bilinguals may be slower at recognising the printed word (e.g., slower semantic access of the word *red*). Such a delay in lexical processing in bilinguals can then lead to reduction or even elimination of the interference from the irrelevant lexical information (the Stroop effect), as the Stroop effect has been shown to be very sensitive to the temporal availability of the incongruent information (the incongruent lexical semantics). For instance, it was demonstrated that the Stroop effect is maximal when the incongruent word is presented at the same time or immediately preceding or following the colour, and it gradually decreases as a function of the temporal delay of the incongruent word (e.g., Glaser & Glaser, 1982). This suggests that the delay in word recognition of the incongruent word in bilinguals alone can account for the reduced Stroop effect without appealing to enhanced cognitive control.

So, is the reduced Stroop effect in bilinguals due to their enhanced cognitive control as a result of frequent language switches, their slower word recognition as a result of diminished frequency of use in either of their languages, or a combination of the two? To resolve this issue, we compared proficient and non-proficient bilinguals of Mandarin Chinese (L1; referred to as Chinese henceforth) and English (L2) in both a Chinese Stroop task and an English Stroop task. On one hand, proficient bilinguals have more experience in switching between the two languages than non-proficient bilinguals and should therefore have better cognitive control. Hence, if the reduced Stroop effect in bilinguals is caused by enhanced bilingual cognitive control alone, we should expect proficient bilinguals to be less susceptible to the Stroop effect in both languages than non-proficient bilinguals.

On the other hand, speed of word recognition may also affect the Stroop effect. Being more proficient in L2 means more lexical exposure, which should as a result speed up L2 word recognition. For instance, L2 proficiency has been shown to affect L2 semantic processing (Kotz & Elston-Güttler, 2004). There is also evidence that bilinguals have slower word processing in their L1 or more dominant language as compared to monolinguals. Lehtonen and Laine (2003) showed that Finnish-Swedish bilinguals were slower in a lexical decision task in their L1 (Finnish) than Finnish monolinguals (see also Lehtonen et al., 2012). Bialystok et al. (2008) showed that lexical access was compromised in bilinguals as compared to that in monolinguals. These results are in line with the frequency account (e.g., Gollan, Fennema-Notestine, Montoya, & Jernigan, 2007; Gollan, Montoya, Cera, & Sandoval, 2008) that bilinguals who are more proficient in L2 should correspondingly have less exposure to their L1 than less proficient bilinguals, and thus should have slower word recognition in their L1. Given that proficient bilinguals have quicker word recognition in English and slower word recognition in Chinese, on the word recognition account, proficient bilinguals in our study should

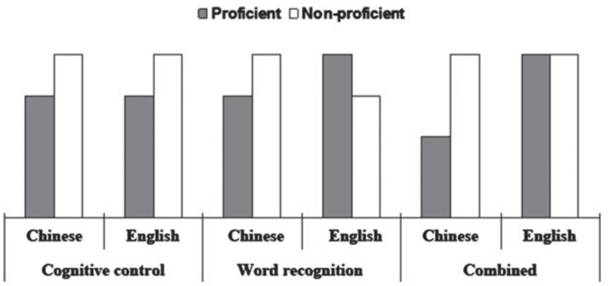

Figure 1. Predicted relative Stroop effect sizes in name the ink colour of a printed Chinese colour word and English colour word for proficient and non-proficient Chinese–English bilinguals by different accounts of Stroop effect reduction in bilinguals. On the cognitive control account, proficient bilinguals should exhibit smaller Stroop effect than non-proficient bilinguals in both languages. On the word recognition account, the Stroop effect should be smaller in Chinese words but greater in English words for proficient bilinguals than for non-proficient bilinguals. On the combined account, proficient bilinguals should exhibit smaller Stroop effect in Chinese words than non-proficient bilinguals but they should have comparable effects in English words.

have stronger Stroop effect in English but smaller Stroop effect in Chinese than non-proficient bilinguals.

Of course, a third possibility is that the reduced Stroop effect is a combined result of both enhanced cognitive control and more effortful word recognition in bilinguals. In this case, with slower word recognition in Chinese as well as better cognitive control, proficient bilinguals should be less susceptible to the Stroop effect in Chinese than non-proficient bilinguals. However, in an English Stroop task, while better cognitive control should reduce the Stroop effect for proficient bilinguals, such a reduction will be offset by the increase in Stroop susceptibility caused by proficient bilinguals' quicker access of the irrelevant lexical semantic information. Therefore, proficient and non-proficient bilinguals should behave similarly in the English Stroop task. Figure 1 captures the predictions of these three accounts concerning the Stroop effect in different languages in the two proficiency groups.

In Experiment 1, we compared the Stroop effects between proficient and non-proficient Chinese–English bilinguals in both their languages. We employed a verbal Stroop task in which participants named the ink colour of a printed Chinese colour word in Chinese (the Chinese Stroop task) or the ink colour of a printed English colour word in English (the English Stroop task), in a blocked design. Trials included congruent ones (in which the ink name and the printed word coincided) and incongruent ones (in which they did not coincide).

Finally, there is also some suggestion that cognitive performance is affected by socioeconomic variables such as economic condition and educational background (Morton & Harper, 2007). In present study, all participants completed the Raven Intelligence Test and surveys on their socioeconomic, linguistic, cultural and ethnic backgrounds to ensure that our non-proficient bilinguals and proficient bilinguals were comparable in these key variables. Thus, in the present study, any difference in cognitive control between the two proficiency groups should be attributed to bilingualism rather than socioeconomic upbringing.

EXPERIMENT 1

Method

Participants

Thirty proficient and 30 non-proficient Chinese–English bilinguals took part in the study. All the proficient Chinese–English bilinguals were English majors in a Chinese university and had passed the Test for English Majors Grade 4 (TEM-4) (an English proficiency test which English-major college students in China are expected to pass at the end of their second year). They used English in most of their course modules and also in their daily life. The non-proficient bilinguals were non-English major university students, and none of them had yet passed the College English Test Band 4 (CET-4) (an English proficiency test which non-English major Chinese college students are expected to pass at the end of their second year). They only used English in their English course and seldom needed to use it in their daily life. Informed consent was obtained from all participants before the experiment.

The results of the Raven Intelligence Test revealed no difference between the proficient and non-proficient groups ($p = .914$). The results of the background survey showed that there was no difference in socioeconomic, cultural or ethnic backgrounds between the two groups ($ps > .05$). Furthermore, all participants spoke Chinese (i.e., Mandarin) as a first language and began to learn English in school when they were 12 or 13 years old.

Procedure

The Stroop task only included congruent and incongruent conditions. There were also two blocked language conditions. Participants named the colour of printed Chinese words in Chinese in one block and the colour of printed English words in English in the other, with the order of the blocks counterbalanced across participants. Each block consisted of 24 trials of red, green and blue printed words (*red*, *green* or *blue*) in either the congruent or the incongruent condition. All trials within a block were randomly presented.

E-Prime was used to carry out the experiment. A trial began with a fixation point lasting for 300 milliseconds at the center of the screen. Then a word (printed in red, blue or green) appeared and participants named the colour aloud in Chinese (for Chinese words) or English (for

TABLE 1
Mean RTs (milliseconds) and SDs in different Stroop conditions for two proficiency groups in Experiment 1

	Proficient		*Non-proficient*	
	Congruent	*Incongruent*	*Congruent*	*Incongruent*
Chinese Stroop task	513 ± 80	719 ± 102	501 ± 107	761 ± 112
English Stroop task	536 ± 65	765 ± 101	558 ± 97	815 ± 136

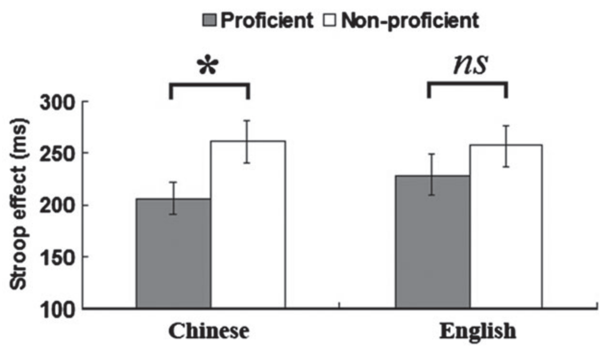

Figure 2. Stroop effects (difference in RTs between the congruent and incongruent conditions) for the two bilingual groups in the Chinese and the English Stroop task. Error bars show *SE*s.

English words). The word disappeared at the onset of a participant's verbal response. If participants failed to respond within 2000 milliseconds after the word onset, the word automatically disappeared and the trial was discarded. There was a 200 milliseconds inter-stimulus interval.

Results

One participant in the proficient bilingual group was excluded from analysis for having an error rate higher than 25%. Again, for each group, we rejected RTs over 2.5 standard deviations (*SD*s) away from the mean. The mean RTs in different conditions for two language groups are presented in Table 1.

We used the difference in RTs between the incongruent condition and the congruent condition as a measure of the Stroop effect. The Stroop effect was significantly smaller for proficient bilinguals than for non-proficient bilinguals in the Chinese Stroop task, $t(57) = 2.187$, $p = .033$, $d = .579$, but such a difference was absent from the English Stroop task, $t(57) = 1.004$, $p = .320$, $d = .266$ (see Figure 2).

We further examined the error rates in the Stroop tasks. The difference in error rates between the incongruent and congruent conditions was similar for the proficient and non-proficient bilinguals in both the Chinese Stroop task, 2% vs. 4%, $t(57) = 1.439$, $p = .156$, $d = .377$, and the English Stroop task, 2% vs. 2%, $t(57) = .088$, $p = .930$, $d = .025$. These results thus excluded the possibility that the RT patterns reported above were a result of speed–accuracy trade-off.

In Experiment 1, non-proficient bilinguals exhibited stronger susceptibility to the Stroop effect in Chinese than proficient bilinguals, while both groups were equally susceptible to the Stroop effect in English. The pattern of results thus cannot be explained by cognitive control alone, which would predict a smaller Stroop effect for proficient bilinguals (due to their enhanced cognitive control) than non-proficient bilinguals in both the Chinese and the English Stroop tasks. Furthermore, the results are not entirely compatible with the word recognition account, which would predict a smaller Stroop effect in Chinese but a larger Stroop effect for proficient bilinguals than for non-proficient bilinguals. As we laid out in the introduction, the pattern of results is best accommodated in terms of both cognitive control and word recognition speed. That is, proficient bilinguals were better at their cognitive control and slower in Chinese word recognition and were thus less susceptible to Stroop effect in Chinese; however, in the English Stroop task, proficient bilinguals' reduction in the Stroop interference due to enhanced cognitive control was offset by the increased Stroop interference due to their quicker word recognition in English, leading to comparable Stroop effects for the proficient and non-proficient bilinguals.

EXPERIMENT 2

Though Experiment 1 showed that cognitive control and word recognition speed jointly contributed to Stroop effects in bilinguals, there were no direct tests of cognitive control and word recognition speed in these bilinguals. Experiment 2 had a twofold purpose. Firstly, we intended to replicate the Stroop effects we observed in Experiment 1, and secondly, we aimed to directly compare the two bilingual groups in cognitive control in a non-verbal Simon task and word recognition speed in a word recognition task.

Method

Participants

Twenty-four proficient and 24 non-proficient Chinese–English bilinguals from the same populations as in Experiment 1 took part in the study. None of them had participated in Experiment 1. As in Experiment 1, results of the Raven Intelligence Test and the background surveys showed no difference in intelligence, socioeconomic, cultural or ethnic backgrounds between the two groups (*ps* > .05). Self-ratings of Chinese and English proficiency (on a 7-point scale; 1 = *very non-proficient*, 7 = *very proficient*) showed that the proficient bilinguals (5.00 ± .78) had similar Chinese proficiency compared to the non-proficient bilinguals (5.08 ± .78) ($p > 0.05$), but they (4.67 ± .70) had higher English proficiency than non-proficient bilinguals (3.50 ± .59) ($p < .001$).

Procedure

The Stroop task. The Stroop task was the same as used in Experiment 1 with the following modifications. It included not only the within-language conditions we had in Experiment 1, but also between-language conditions. In the within-language conditions, participants named the ink colour of English words in English and the ink of Chinese words in Chinese. In the between-language conditions, they named the ink colour of Chinese words in English and the ink colour of English words in Chinese. So there were four blocks in total. Each block consisted of 48 trials of a word (*red*, *green* or *blue*) in either the congruent condition (e.g., the word *red* printed in red) or the incongruent condition (e.g., the word *red* printed in green or blue). Before each block, the participants received an instruction telling them which language to use in naming the colour of the printed words. All the other aspects of the task were the same as in Experiment 1.

The word recognition task. The experimental stimuli consisted of 42 English words and 42 Chinese single-character words selected from Li, Mo, Wang, Luo, and Chen's (2009) study. Half of the words referred to living things and the others referred to non-living things. There were no translation equivalent pairs between the Chinese and English words. Another twenty participants who were non-English major university students were recruited to rate the familiarity of the words on a 7-point scale (0 = *very unfamiliar*, 6 = *very familiar*). The results showed that all the mean scores for each word were greater than 4, suggesting that participants recognised all the words we selected. In addition, participants were familiar with both the Chinese words (5.66 ± .24) and English words (5.41 ± .05).

The task was carried out in E-Prime. Chinese words presented in one block and English words presented in another. A fixation was presented for 500 milliseconds, followed by a target word. Participants were instructed to make a "living" judgement by pressing the key "F" if the word referred to something living (e.g., animal or plant) or part of a living thing (e.g., hand) and to make a "non-living" judgement by pressing the key "J" if the word referred to something non-living (e.g., boat). The word disappeared at the onset of a participant's keyboard response. If participants failed to respond within 2000 milliseconds after the word onset, the word automatically disappeared and the trial was discarded. There was a 250 milliseconds inter-stimulus interval.

The Simon arrow task. Following previous research using Simon arrow task (Bialystok et al., 2008), we included three blocks. The first block was a control condition. An arrow pointing ether left or right was presented in the center of the screen and, depending on the direction of the arrow, participants were instructed to press the left or right response key ("F" or "J" on the keyboard) as quickly as possible. The arrow disappeared at key press. This block included 48 trials. In the second block, the stimulus were same as the first block, but the participants were instructed to press the response key in the direction opposite to that indicated by the arrow head. This block thus measured response inhibition. In the third block, an arrow (pointing either left or right) was presented on the left or right side of the screen, thus creating either a congruent trial in which the direction and position of the arrow corresponded, or an incongruent trials in which they conflicted. Participants were instructed to press a (left or right) response key to indicate the direction indicated by the arrow head, regardless of the side of the screen on which the arrow appeared. This block was a measure of inhibition control and it contained 48 congruent and 48 incongruent trials randomly presented. The task was also carried out in E-Prime.

Results

Mean error rates in all conditions for all participants in three tasks were less than 25%. For each group, we rejected RTs that were over 2.5 *SD*s away from the mean in each block.

Results of the Stroop task

The mean RTs in different Stroop conditions for two language groups are presented in Table 2. We used the difference in RTs between the incongruent condition and the congruent condition as a measure of the Stroop effect. The Stroop effect was significantly smaller for proficient bilinguals than for non-proficient bilinguals when naming the colour of Chinese words both in Chinese, $t(46) = 2.132$, $p = .038$, $d = .628$, and in English, $t(46) = 4.14$, $p < .001$, $d = 1.184$, but there was no such a group difference in naming the colour of English words either in Chinese, $t(46) = .020$, $p = .984$, $d = .006$ or in English, $t(46) = .256$, $p = .601$, $d = .155$ (see also Figure 3).

The difference in error rates between the incongruent and congruent conditions was similar for the proficient and non-proficient bilinguals in naming the colour of Chinese words in Chinese, 6.8% vs. 8.0%, $t(46) = .584$, $p = .562$, $d = .169$, or English, 1.6% vs. .7%, $t(46) = .828$, $p = .412$, $d = .250$, and in naming the colour of English words in Chinese, .5% vs. 1.4%, $t(46) = 1.096$, $p = .279$, $d = .333$, or English, 3.9% vs. 5.4%, $t(46) = .827$, $p = .413$, $d = .263$. These results thus ruled out the possibility

TABLE 2
Mean RTs (milliseconds) and SDs in different Stroop conditions for two proficiency groups in Experiment 2

	Proficient		*Non-proficient*	
	Congruent	*Incongruent*	*Congruent*	*Incongruent*
Chinese Stroop task				
naming in Chinese	640 ± 72	781 ± 86	630 ± 66	812 ± 98
naming in English	661 ± 71	730 ± 73	668 ± 62	797 ± 59
English Stroop task				
naming in Chinese	658 ± 81	702 ± 85	660 ± 71	704 ± 81
naming in English	678 ± 72	816 ± 81	712 ± 73	857 ± 89

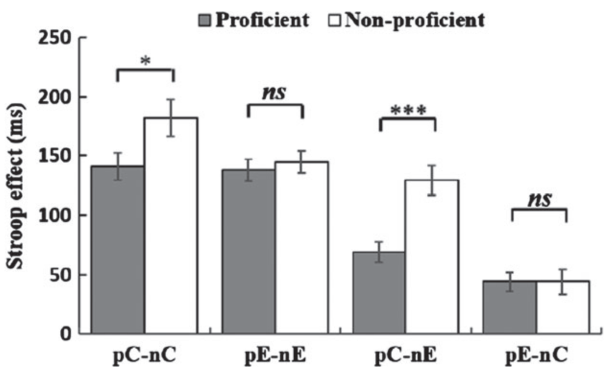

Figure 3. Stroop effects (difference in RTs between the congruent and incongruent conditions) for the two bilingual groups in different Stroop tasks. pC-nC refers to the condition in which the printed word was Chinese and the ink colour was named in Chinese; pE-nE refers to the condition in which the printed word was English and the ink colour was named in English; pC-nE refers to the condition in which the printed word was Chinese and the ink colour was named in English; pE-nC refers to the condition in which the printed word was English and the ink colour was named in Chinese. Error bars show SEs.

that the RT patterns reported above were a result of speed-accuracy trade-off.

We found that the Stroop effect was smaller for proficient bilinguals than for non-proficient bilinguals when naming the colour of Chinese words, but such a group difference was absent in naming the colour of English words, in both within-language condition and between-language condition. These results replicated the Stroop effects observed in Experiment 1.

Results of the word recognition task

The mean RTs in Chinese and English conditions for two language groups are presented in Table 3. The results showed that, compared to non-proficient bilinguals, proficient bilinguals responded quicker, $t(46) = 4.308$, $p < .001$, $d = 1.271$, and made fewer errors, $t(46) = 2.708$, $p = .009$, $d = .797$, at recognising English words, but they responded slower, $t(46) = 2.095$, $p = .042$, $d = .618$, and made similar number of errors, $t(46) = .137$, $p = .892$, $d = .041$, at recognising Chinese words. These findings suggest that proficient bilinguals were quicker and more accurate at recognising English words but slower at recognising Chinese words than non-proficient bilinguals.

TABLE 3
Mean RTs (milliseconds) and error rates in the word recognition task for the two proficiency groups in Experiment 2

	Proficient	*Non-proficient*
RT		
Chinese	646 ± 68	609 ± 50
English	814 ± 101	969 ± 145
Error rates		
Chinese	0.07 ± 0.05	0.07 ± 0.05
English	0.08 ± 0.05	0.14 ± 0.09

TABLE 4
Mean RTs (milliseconds) and SDs in the Simon task for two proficiency groups in Experiment 2

	Proficient	*Non-proficient*
Control	399 ± 51	394 ± 42
Response inhibition	459 ± 67	454 ± 67
Congruency	469 ± 49	473 ± 55
Non-congruency	504 ± 65	532 ± 39

Results of the Simon arrow task

The mean RTs in different Simon conditions for two language groups are presented in Table 4. As in Bialystok et al. (2008), response inhibition was operationalized as the RT difference between response inhibition condition and control condition, and inhibition control was calculated as the difference between incongruent condition and congruent condition. The results showed that non-proficient bilinguals produced a larger cost than proficient bilinguals in inhibition control, 59 milliseconds vs. 35 milliseconds, $t(46) = 2.138$, $p = .038$, $d = .630$, but the difference between proficient bilinguals and non-proficient bilinguals was not significant in response inhibition, 60 milliseconds vs. 60 milliseconds, $t(46) = .041$, $p = .968$, $d = .012$. The difference in error rates between the proficient and non-proficient bilinguals was similar in both response inhibition, 0.1% vs. 0.1%, $t(46) = .000$, $p = 1.000$, $d = 0.001$, and inhibition control, 4.5% vs. 2.5%, $t(46) = 1.037$, $p = .305$, $d = .303$, therefore ruling out the possibility that the RT patterns reported above were a result of speed–accuracy trade-off.

Discussion

Several findings are worth discussing. First, we replicated the findings in Experiment 1 that proficient bilinguals exhibited less Stroop susceptibility than non-proficient bilinguals in Chinese but not in English. In addition, Experiment 2 further showed that such a language-specific group difference held for both the within- and the between-language Stroop task. Second, we provided direct evidence that our proficient bilingual participants were slower at recognising Chinese words but quicker at recognising English words than our non-proficient bilinguals, just as we hypothesised in Experiment 1. Such a finding is in line with the frequency account (e.g., Gollan et al., 2007, 2008; Ivanova & Costa, 2008), which proposes that bilinguals' speed in word recognition in a particular language is causally linked to their exposure to that language. Third, we also provided direct evidence that our proficient bilingual participants were better in cognitive control than our non-proficient bilingual participants, a finding consistent with that in Bialystok et al. (2008). More importantly, the above findings of cognitive control and word recognition speed thus provide a very compelling account for the Stroop effects we observed with our proficient and non-proficient bilinguals. That is, in Chinese, enhanced cognitive control and slower word recognition in proficient bilinguals led to smaller Stroop effect in Chinese as compared to non-proficient bilinguals, while in English, proficient bilinguals had not only better cognitive control but also quicker word recognition and the two cancelled each other out, leading to comparable Stroop effects for the proficient and non-proficient bilinguals.

GENERAL DISCUSSION

In our study, non-proficient bilinguals exhibited a stronger Stroop effect in naming the colour of Chinese (L1) colour words than proficient bilinguals, though both groups had comparable Stroop effects in naming the colour of English (L2) colour words. In addition, compared with non-proficient bilinguals, proficient bilinguals had quicker English word recognition and slower Chinese word recognition (as measured by the word recognition task), and better cognitive control (as measured by the Simon arrow task). These results support the account that cognitive control and word recognition speed in tandem constrain the magnitude of Stroop susceptibility. Proficient bilinguals' enhanced cognitive control (as compared to that of non-proficient bilinguals) reduced the Stroop effect in both their L1 and L2. Such a general reduction, is, however, modulated by different word recognition speeds in the two bilingual groups in a particular language. While proficient bilinguals' slower access of the irrelevant printed word in the Chinese Stroop task further reduced their susceptibility to the Stroop effect, their quicker recognition of the irrelevant printed word in the English Stroop task increased the Stroop effect, cancelling out the reduction caused by their enhanced cognitive control, hence no difference in the Stroop effect in English between the two bilingual groups. All together, these findings suggest that both cognitive control and word recognition affect the magnitude of the Stroop effect.

Stroop effects in bilinguals

Our finding that the Stroop effect is a combined result of cognitive control and word recognition suggests that the reduction of the Stroop effect in bilinguals is caused not only by their enhanced cognitive control (Bialystok et al., 2008), but also by their delayed word recognition. Bilinguals enjoy better cognitive control than monolinguals, which helps to better inhibit the interference of the irrelevant lexical semantic information from the printed word and in turn to reduce the Stroop interference. In addition, as bilinguals have slower word recognition than monolinguals due to their reduced frequency of use in either of their languages (e.g., Gollan et al., 2008), the recognition of the irrelevant word should be delayed, leading to a further reduction of the Stroop effect (e.g., Glaser & Glaser, 1982).

The size of the Stroop effect is related to word recognition speed, with faster or more automatic reading producing more interference and larger Stroop effects (MacLeod, 1991). Bialystok et al. (2008) also pointed out that the Stroop effect in bilinguals was correlated with their speed of word recognition. In other words, bilinguals with slower word recognition tended to have a smaller Stroop effect, a finding that our current results corroborate, that is, proficient bilinguals who had slower word recognition in Chinese manifested a smaller Stroop effect in Chinese than non-proficient bilinguals. Bialystok et al. (2008), however, found that even bilinguals with fast word recognition showed smaller Stroop effect than monolinguals with slow word recognition, a result they used to dispute the role of word recognition in the occurrence of the Stroop effect. Given our results, it is possible that, in Bialystok et al. (2008), the effect of cognitive control outweighed that of word recognition, hence still a smaller Stroop effect for the fast-reading bilinguals than the slow-reading monolinguals. However, the relative weights of the cognitive control and word recognition speed in Stroop task is beyond the scope of the current article and remains an interesting question for future research.

It is also interesting to note that, if language proficiency determines word recognition speed (as we showed here), there should be correlations among the individual differences in language proficiency, word recognition speed and the size of the Stroop effect. For instance, if a person is more proficient in L2, he/she should be quicker at recognising L2 words, which in turn would lead him/her to be more susceptible to the Stroop effect when naming the colour of L2 words. Though we showed such an effect for more proficient L2 speakers as a whole, we do not have an objective measure of individuals' language proficiency to test this prediction and can only leave this question for future studies.

The Stroop task has been frequently used to test cognitive control in bilinguals. Our study, however, implies that when the Stroop task involves the use of lexical information, word recognition should be taken into account. So a variety of experimental paradigms (e.g., the trail-making task, the Simon task and the flanker task, in addition to the Stroop task) should be used in order to avoid confounding factors (e.g., linguistic factors) and provide a better profile of cognitive control in bilinguals.

Enhanced cognitive control in bilinguals

Whether bilingualism really leads to enhanced cognitive control is being debated (e.g., Calvo & Bialystok, 2014; Hilchey & Klein, 2011). Though earlier research suggests that the regular practice by bilinguals to select the target language and inhibit the non-target language helps to boost their capacity of cognitive functioning (e.g., Bialystok, 1999; Bialystok et al., 2008; Costa et al., 2008), some more recent research either failed to replicate these results (e.g., Kousaie & Phillips, 2012; Paap & Greenberg, 2013) or suggests that the enhanced cognitive control is a result of better socioeconomic backgrounds in bilinguals (Morton & Harper, 2007). Our study suggests that the enhancement of cognitive control in bilinguals cannot be solely contributed to socioeconomic background differences between bilinguals and monolinguals. In our study, proficient bilinguals had better cognitive control than non-proficient bilinguals in both the Stroop task and the Simon arrow task, even though they had similar socioeconomic and IQ profiles. Therefore, we believe the better cognitive control in the proficient bilinguals was a result of their frequent language switching experience, as these bilinguals, but not the non-proficient ones, used both languages on a daily basis.

Such an explanation is consistent with the widely accepted account of bilinguals' advantage in cognitive control as a result of language control and selection (Fan, Flombaum, McCandliss, Thomas, & Posner, 2003). Both languages are active when bilinguals are engaged in using one of them (e.g., Thierry & Wu, 2007). Therefore, executive control is needed to select the target language, to avoid the interference of the other language, and to switch between the two languages, an experience that may enhance bilinguals' cognitive control (Bialystok, Shenfield, & Codd, 2000). Emmorey, Luk, Pyers, and Bialystok (2008) showed that though unimodal bilinguals who often needed to select one of languages for communication performed better at flanker tasks than monolinguals, bimodal bilinguals who were able to sign and speak at the same time (hence less or no need for language control and selection) did not differ from monolinguals, suggesting that enhanced cognitive control in the unimodal bilinguals stems from their frequent monitoring of and selection between their two languages. Furthermore, the control and selection account also receives support from cognitive neuroscience. For instance, in an MEG study, Bialystok et al. (2005) showed that the management of the two language systems in bilinguals led to systematic changes in frontal executive functions.

Summary

We found that proficient Chinese–English bilinguals exhibited weaker Stroop effect in Chinese than non-proficient counterparts because their enhanced cognitive control and delayed word recognition jointly reduced the interference of the irrelevant lexical content in a Stroop task; however, the two groups demonstrated comparable Stroop effects in English because the reduction in Stroop effect due to the proficient bilinguals' enhanced cognitive control was offset by the increase in Stroop effect due to their quicker word recognition in English. Therefore, the study suggests that the reduction in the (intralingual) Stroop effect in bilinguals as compared to monolinguals reflects a combined effect of both enhanced cognitive control and delayed word recognition in bilinguals. It also suggests that language proficiency influences both cognitive control and lexical processing in bilinguals.

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