Research report

Neural signatures of language co-activation and control in bilingual spoken word comprehension

Peiyao Chen [a,*], Susan C. Bobb [a,b], Noriko Hoshino [c], Viorica Marian [a]

[a] Department of Communication Sciences and Disorders, Northwestern University, Evanston, IL 60208, USA
[b] Department of Psychology, Gordon College, Wenham, MA 01984, USA
[c] Department of English Studies, Kobe City University of Foreign Studies, Kobe 651-2187, Japan

ARTICLE INFO

ABSTRACT

To examine the neural signatures of language co-activation and control during bilingual spoken word comprehension, Korean-English bilinguals and English monolinguals were asked to make overt or covert semantic relatedness judgments on auditorily-presented English word pairs. In two critical conditions, participants heard word pairs consisting of an English-Korean interlingual homophone (e.g., the sound /mu:n/ means "moon" in English and "door" in Korean) as the prime and an English word as the target. In the homophone-related condition, the target (e.g., "lock") was related to the homophone's Korean meaning, but not related to the homophone's English meaning. In the homophone-unrelated condition, the target was unrelated to either the homophone's Korean meaning or the homophone's English meaning. In overtly responded situations, ERP results revealed that the reduced N400 effect in bilinguals for homophone-related word pairs correlated positively with the amount of their daily exposure to Korean. In covertly responded situations, ERP results showed a reduced late positive component for homophone-related word pairs in the right hemisphere, and this late positive effect was related to the neural efficiency of suppressing interference in a non-linguistic task. Together, these findings suggest 1) that the degree of language co-activation in bilingual spoken word comprehension is modulated by the amount of daily exposure to the non-target language; and 2) that bilinguals who are less influenced by cross-language activation may also have greater efficiency in suppressing interference in a non-linguistic task.

© 2017 Elsevier B.V. All rights reserved.

1. Introduction

Bilinguals' two languages have been shown to be simultaneously active during listening, reading, and speaking, even when only one language is explicitly required (e.g., Colomé and Miozzo, 2010; Marian and Spivey, 2003; Schwartz and Kroll, 2006; Thierry and Wu, 2007). This parallel activation has been shown to facilitate lexical access (e.g., Hoshino and Kroll, 2008; Van Hell and Dijkstra, 2002), as well as to interfere with language processing in bilingual comprehension (e.g., Dijkstra et al., 2000; Lagrou et al., 2011). To date, research has shown that when bilinguals process *visual* words, they experience language co-activation and use inhibitory control to resolve competition from the non-target language (Durlik et al., 2016; Macizo et al., 2010; Martín et al., 2010). However, it is less clear to what extent bilinguals draw on these same processing mechanisms during *spoken* word comprehension.

Here, we present evidence for the neural signatures of language co-activation and control in bilingual spoken word comprehension.

1.1. Language co-activation in bilingual visual and spoken word comprehension

Interlingual homographs and homophones, words that share visual and auditory forms but not meanings across languages, are often used to investigate language co-activation in bilingual visual and spoken word comprehension. In bilingual visual word comprehension studies, lexical decision times for homographs have been found to differ from those for non-homographs, suggesting that bilinguals activate lexical-semantic information in both languages non-selectively (e.g., De Groot et al., 2000; Dijkstra et al., 1998). In bilingual spoken word comprehension, homophones have been predicted to affect language co-activation differently than homographs. This prediction was based on the reasoning that spoken words, unlike written words, carry phonemic and subphonemic information that might produce a stronger cue to language

* Corresponding author.
E-mail address: peiyaochen@u.northwestern.edu (P. Chen).

membership and thus limit cross-linguistic phonological activation in bilinguals (Ju and Luce, 2004). However, when using homophones in an auditory lexical decision task, Lagrou et al. (2011) found that Dutch-English bilinguals showed delayed response times to homophones compared to non-homophones, regardless of the target language of the task. This result parallels effects found with homographs in bilingual visual word comprehension and suggests that lexical-semantic co-activation caused by interlingual homophones is similar to co-activation caused by homographs.

It is possible that the orthographic and typological similarity of the two languages (Dutch and English) used in Lagrou et al. (2011) boosted language co-activation in their study. Previous studies have suggested that orthographic information is activated during bilingual spoken word comprehension (Mishra and Singh, 2014; Veivo and Järvikivi, 2013). It is therefore possible that the observed lexical co-activation may have been partly driven by the orthographic overlap between homophones in the two languages. The current study used interlingual homophones between Korean and English, two languages that do not share a script, to examine whether lexical-semantic co-activation still occurs when orthographic overlap is completely eliminated.

1.2. Inhibitory control in bilingual language processing

To investigate the involvement of inhibitory control in bilingual visual word comprehension, Macizo and colleagues developed a negative priming paradigm in which Spanish-English bilinguals were instructed to make semantic relatedness judgments on English word pairs. In two similar behavioral studies (Macizo et al., 2010; Martín et al., 2010), Spanish-English bilinguals showed slower response times to homograph word pairs (e.g., *pie-toe*, "pie" meaning "foot" in Spanish) when compared to unrelated word pairs (e.g., *log-toe*). This result indicated that bilinguals co-activated the Spanish meaning of "pie," which interfered with their semantic judgment in English. More importantly, bilinguals were also slower when judging translation equivalent word pairs (e.g., *foot-finger*, where "foot" is the English translation of the Spanish word "pie") following homograph word pairs (e.g., *pie-toe*) as compared to those following unrelated word pairs (e.g., *log-toe*). The authors interpreted the prolonged response time on the second word pair as reflecting a recovery process in which participants suppressed the homograph's Spanish meaning (e.g., "foot" for "pie") during the presentation of the first word pair (e.g., *pie-toe*) and subsequently had to overcome the inhibition in order to judge the semantic relatedness of the second word pair (e.g., *foot-finger*). These findings are compatible with the *Inhibitory Control* model (IC model, Green, 1998) and the *Bilingual Interactive Activation* model (BIA, Dijkstra and Van Heuven, 1998), although the specific loci of the inhibitory processes might differ based on the two models. Because the current study did not aim to determine the specific locus of inhibitory control, the term inhibitory control throughout this paper refers to a domain-general inhibitory control process.

Other studies in bilingual visual word comprehension have provided further evidence of the involvement of inhibitory control and have also revealed the time course and scope of inhibitory control. In a follow-up study to Macizo et al. (2010), Martín et al. (2010) manipulated the intervals between homograph word pairs (e.g., *pie-toe*) and translation equivalent word pairs (e.g., *foot-hand*) and found that the inhibitory control effect disappeared between 500 ms and 750 ms. However, a recent study using a similar design suggests that inhibitory processes in bilingual visual word comprehension could last more than 1000 ms, at least when bilinguals have limited proficiency in their L2 (Durlik et al., 2016). This same study also suggests that inhibition may extend beyond the non-target language translation equivalent to the whole semantic category to which the homograph's meaning in the non-target lan-

guage belongs. More specifically, Durlik et al. (2016) found that the presentation of word pairs such as "pie-toe" not only slowed down the subsequent processing of "foot" but also delayed the following processing of "hand." These findings of inhibitory processes in bilingual visual word recognition seem to resemble those in language production, where the effect of inhibition has been considered long-lasting and widespread (Guo et al., 2011; Misra et al., 2012; Rossi et al., in preparation).

While these behavioral studies provide some evidence for the involvement of inhibitory control in bilingual visual word comprehension, it is difficult to assess the immediate impact of inhibition early in processing (i.e., during the initial presentation of homograph word pairs) by measuring prolonged response times in subsequent trials (i.e., translation word pairs). If inhibition occurs during the processing of homograph word pairs, online measures such as ERPs on the initial homograph word pairs alone should be sufficient to capture the inhibitory control process. In fact, Hoshino and Thierry (2012) used ERPs to investigate language co-activation and control in bilingual visual word comprehension. They compared ERPs of word pairs that were related to homographs' Spanish meanings (e.g., *toe-pie*, "pie" meaning "foot" in Spanish) with words pairs that were unrelated (e.g., *rug-pie*). They found that word pairs related in Spanish elicited a smaller N400 than unrelated word pairs, which indicated the activation of homograph meanings in Spanish. However, an attenuated effect on the late positive component (LPC) in the following time window indicated that homograph meanings in the non-target language did not receive further explicit processing. These ERP findings suggest that the activation of homograph meanings is language non-specific and that inhibitory processes may prevent further interference from the non-target language in bilingual visual word comprehension.

In contrast to visual word comprehension, the involvement of inhibitory control in bilingual spoken word comprehension has only been explored in an indirect way. Blumenfeld and Marian (2013) found that bilinguals with better inhibitory control showed increased co-activation during the early stages of spoken word comprehension and decreased co-activation immediately before the selection of a target word. Similarly, better inhibitory control has also been associated with decreased between-language competition among relatively low-proficient bilinguals (Mercier et al., 2014). These findings indicate that individual differences in inhibitory control in a non-linguistic task might be related to the efficiency of resolving interference from the non-target language, and they provide indirect evidence for the possible involvement of inhibitory control in bilingual spoken word recognition. Previous research has emphasized the role that negotiating language competition may play in shaping the bilingual cognitive architecture, mainly during bilingual production (see Kroll, 2008; Kroll and Bialystok, 2013, for reviews). Our aim was to assess the neural evidence for control processes when bilinguals hear one of their languages using a task that explicitly requires inhibitory control, thereby contributing to a comprehensive view of language control in bilingualism across modalities.

1.3. ERP indexes of language co-activation and control

The N400 has been used as a reliable neural index of language co-activation because of its sensitivity to semantic congruency and phonological repetition. Thierry and Wu (2007) asked Chinese-English bilinguals to perform semantic relatedness judgments on English word pairs. Unknown to these bilinguals, the phonological overlap between the Chinese translations of the prime and target (of a word pair) was manipulated. A reduced N400 was found for unrelated word pairs with the phonological overlap in Chinese when compared to other unrelated word pairs

without such overlap, indicating the activation of phonological information in the non-target language. Additionally, the N400 effect also indexes the cross-language semantic congruency effect caused by semantic co-activation of interlingual homographs (Hoshino and Thierry, 2012).

With respect to the neural signatures of the inhibitory control in language processing, the picture is less clear. While some previous studies have identified the N2 effect to index inhibition during bilingual language production (e.g., Misra et al., 2012), no specific inhibitory-related component (e.g., N2 or P3) has been found in the domain of bilingual language comprehension. Instead, given the results in Hoshino and Thierry (2012), we focused on the late positive component (LPC) as a potential index of the consequence of exerting language inhibition. The LPC has been found in a wide range of studies and is considered to reflect explicit and elaborate processing of stimuli that require additional cognitive resources (e.g., Osterhout and Holcomb, 1993; Paller et al., 1995; Rugg et al., 1988). Hoshino and Thierry (2012) observed an increased LPC only for word pairs that were related within language and not across languages, suggesting that cross-language relatedness did not receive further processing because of language inhibition. Since the current study used a similar design as in Hoshino and Thierry (2012), we also focused on these previously identified N400 and LPC effects.

1.4. The present study

In the present study, we used Korean-English homophones to investigate language co-activation and control during bilingual spoken word comprehension. Korean-English bilinguals and English monolinguals were asked to judge the semantic relatedness of two English words while their EEGs were recorded. In the homophone-related (across language) condition, homophones were paired with a word that is semantically unrelated to the English meaning but related to the Korean meaning of the homophones (e.g., *moon – lock*, where /mu:n/ means "door" in Korean). In the homophone-unrelated condition, homophones were paired with a word that is semantically unrelated to both English and Korean meanings of the homophones (e.g., *moon – tree*). The homophone-related and homophone-unrelated conditions used the exact same physical stimuli and required "No" responses; therefore, any neural or response differences between these two conditions can be attributed to their cross-linguistic relatedness. We predicted that the homophone-related (across language) condition would elicit a reduced N400 when compared to the homophone-unrelated condition. Unlike Hoshino and Thierry (2012), in the current study, interlingual homophones were used in the homophone-related across languages and the homophone-unrelated conditions. Thus, we predicted that the LPC would be larger for the homophone-related condition than for the homophone-unrelated condition due to greater cognitive demands in resolving cross-linguistic competition.

Bilinguals' language profile and inhibitory control ability have been shown to influence the extent to which bilinguals co-activate their two languages (see Chen and Marian, 2016; Van Hell and Tanner, 2012, for reviews) and effectively manage competition from the non-target language (Blumenfeld and Marian, 2013; Mercier et al., 2014). Therefore, we examined the effects of individual differences in language profile and in inhibitory control on the neural signatures of language co-activation in bilingual spoken word comprehension. In particular, we predicted that higher language proficiency and greater language exposure in the non-target language would increase the degree of language co-activation. To measure participants' inhibitory control ability, we employed a non-linguistic, simplified flanker task (Luk et al., 2010, see Fig. 1). The flanker task measures several different types
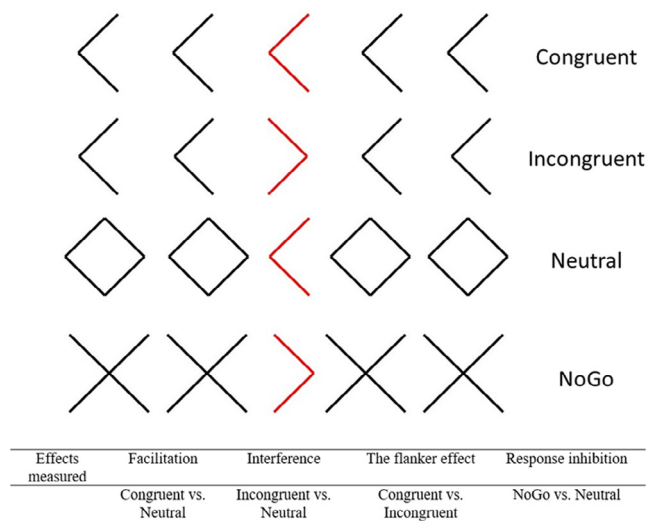

Fig. 1. Examples of four conditions and the effects measured in the simplified flanker task.

of cognitive control process. A facilitation effect, which is indexed by the difference between the congruent and neutral conditions, reflects the extent to which participants benefit from utilizing congruent information. An interference effect, the difference between the incongruent and neutral conditions, indicates the amount of interference participants experience (Luk et al., 2010). Lastly, the flanker effect can be calculated by comparing the congruent and incongruent conditions and is often used as a measure of cognitive control ability (e.g., Costa et al., 2008). In the current study, we were particularly interested in participants' ability to resolve interference, as reflected in the difference between the incongruent and the neutral conditions[1]. Neurally, we focused on the P300, a component which has been used as an index of cognitive effort and attentional resources (for a review see Polich, 2007). In the flanker task, the more difficult incongruent condition often elicits a larger P300 than the easier congruent and neutral conditions that do not generate interference (e.g., Clayson and Larson, 2011; Groom and Cragg, 2015). Furthermore, a smaller P300 effect is linked to higher efficiency in resolving conflicts and interference in the incongruent condition (Pratt et al., 2011; Wu and Thierry, 2013). We predicted that bilinguals' efficiency in resolving non-linguistic interference (i.e., RT differences or the P300 effect between the incongruent and neutral condition) would influence bilinguals' performance on the linguistic task.

2. Results

2.1. Behavioral results of the semantic judgment task

In NoGo conditions (covertly responded situations), the accuracy rates of successfully withholding responses were very high in all conditions (equal to or higher than 99%). In Go conditions (overtly responded situations), only trials to which participants responded correctly were included in the analysis of response times. Accuracies and response times were analyzed for homophones and non-homophones separately, using mixed-effects models as implemented in the lme4 library (version, 1.1–11,

---

[1] The difference between the incongruent and the neutral conditions may be a better measure of inhibitory control than the flanker effect (i.e., the difference between the congruent and the incongruent conditions) because the flanker effect conflates facilitation of congruent information and resistance to interference from incongruent information (see Schroeder et al., 2016, for a discussion).

Table 1

Behavioral results of the Go condition in the semantic judgment task (standard errors are in the parentheses).

Group	Conditions	Accuracy/%	Response time/ms
Bilinguals	Homophone-related	86.2 (2.6)	1219 (34)
	Homophone-unrelated	88.5 (2.0)	1226 (36)
	Control-related	86.4 (1.3)	1093 (29)
	Control-unrelated	84.8 (2.7)	1189 (35)
Monolinguals	Homophone-related	92.3 (1.8)	1088 (35)
	Homophone-unrelated	92.7 (2.4)	1095 (37)
	Control-related	88.4 (1.3)	999 (30)
	Control-unrelated	93.0 (1.6)	1087 (36)

Bates et al., 2015) in R (version 3.2.3, R Core Team, 2015). Fixed effects included group (bilinguals vs. monolinguals) and relatedness (related vs. unrelated), which were both coded with contrast coding. The models also included the maximal random effects structure justified by the data using a backward-fitting procedure (Barr et al., 2013). The descriptive accuracy and response time data are presented in Table 1.

2.1.1. Non-homophone controls

For accuracy, a main effect of group ($\beta = -0.67$, $SE = 0.22$, $Z = -2.99$, $p < 0.005$) showed that monolinguals ($M = 90.7\%$) were more accurate than bilinguals ($M = 85.6\%$). The interaction between group and relatedness was marginally significant ($\beta = 0.85$, $SE = 0.46$, $Z = 1.83$, $p = 0.07$). Further comparisons showed that monolinguals responded to unrelated word pairs ($M = 93.0\%$) more accurately than to related word pairs ($M = 88.4\%$, $\beta = -0.95$, $SE = 0.46$, $Z = -2.08$, $p < 0.05$), while bilinguals did not respond differently across conditions ($Z < 1.4$, $p > 0.17$). In the analysis of

response times, both the main effects of relatedness ($\beta = -0.09$, $SE = 0.02$, $t = -4.70$, $p < 0.001$) and group were significant ($\beta = -0.1$, $SE = 0.04$, $t = -2.13$, $p < 0.05$), where related word pairs ($M = 1046$ ms) were responded to faster than unrelated word pairs ($M = 1127$ ms), and monolinguals ($M = 1038$ ms) were overall faster than bilinguals ($M = 1134$ ms). No other main effects or interactions reached significance.

2.1.2. Homophones

The main effect of group was marginally significant in the analysis of accuracies ($\beta = -0.079$, $SE = 0.41$, $Z = -1.92$, $p = 0.06$) and was significant in the analysis of response times ($\beta = 0.13$, $SE = 0.05$, $t = 2.69$, $p < 0.01$), suggesting that monolinguals were more accurate and faster (M = 92.5%, M = 1092 ms) than bilinguals (M = 87.4%, M = 1223 ms).

2.2. ERP data of the semantic judgment task

The averaged ERPs were generated for each participant by only including trials that were responded to correctly. Early components such as P1, N1, and P2 appeared similar across all conditions. None of the analyses of these early components revealed significant differences between groups or between related and unrelated word pairs ($ps > 0.1$). No significant interactions between group and relatedness or between group and response type (Go/NoGo) were found in any of the early time windows ($ps > 0.08$).

2.2.1. Non-homophones

The significant main effect of relatedness emerged during the 400–450 ms time window and lasted during all remaining time
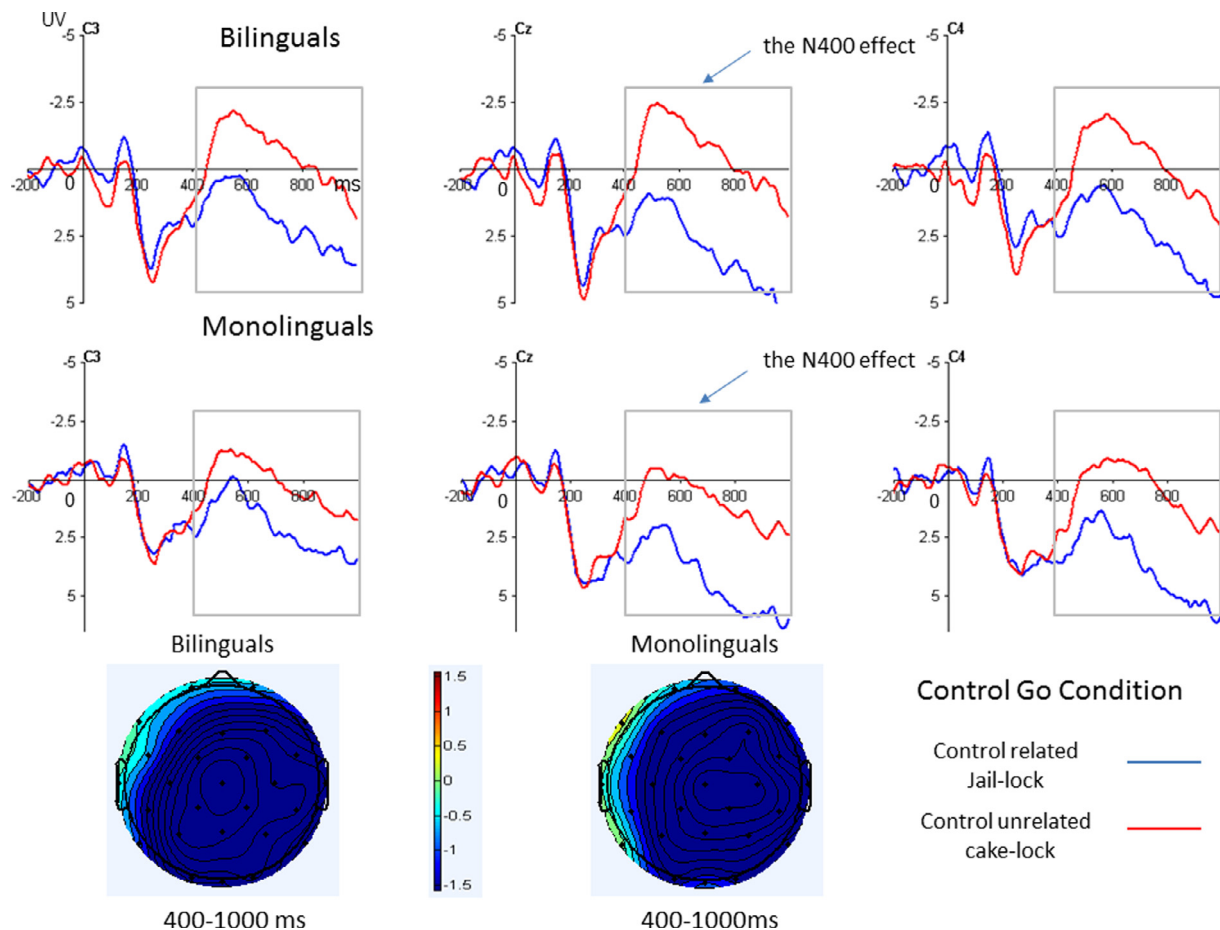

Fig. 2. ERPs and difference waves elicited by control-related and control-unrelated word pairs in the Go condition.
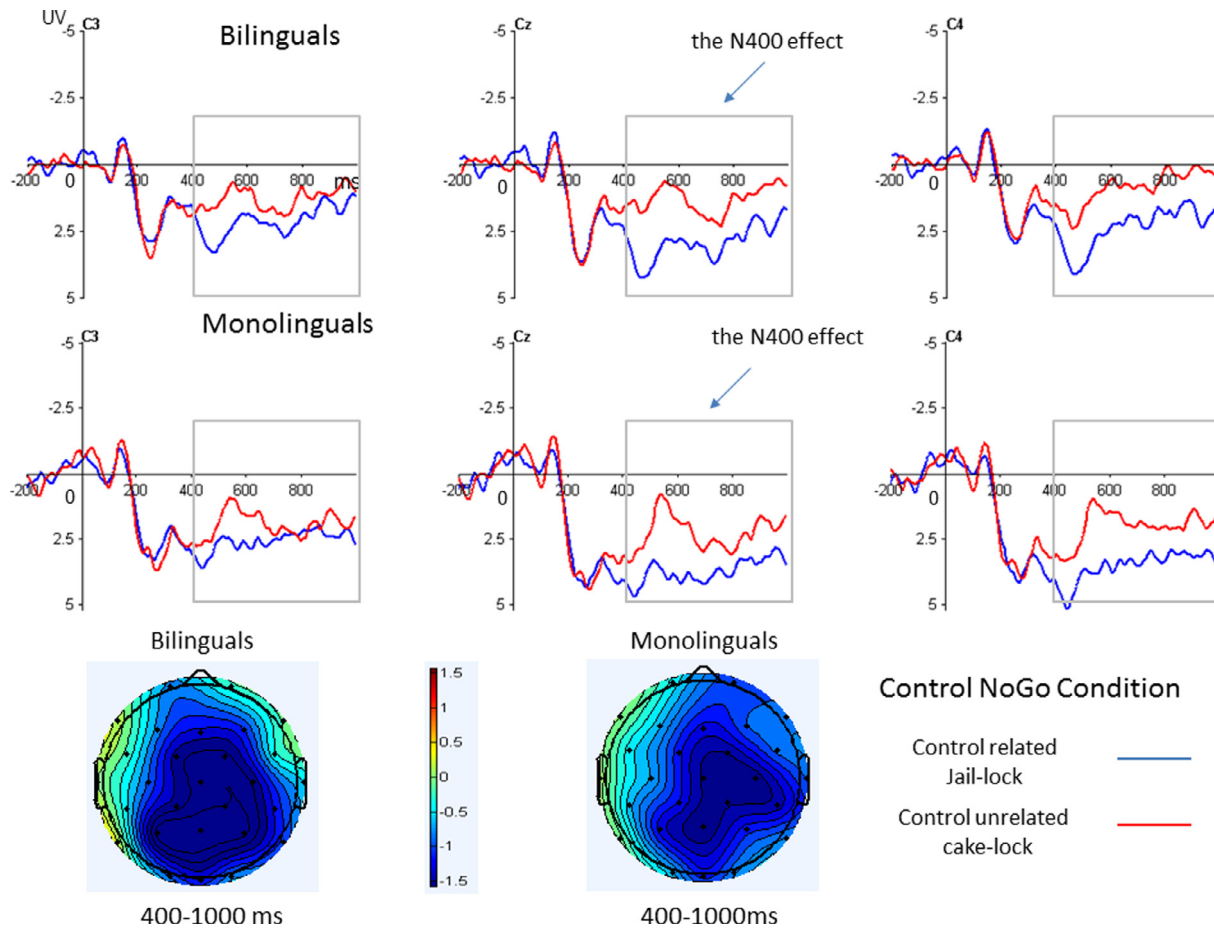
Fig. 3. ERPs and difference waves elicited by control-related and control-unrelated word pairs in the NoGo condition.

windows in both Go and NoGo conditions (see Fig. 2 and Fig. 3). Therefore, we re-calculated the mean amplitude of each condition in the 400–1000 ms time window and submitted it to a 2 (group: monolinguals vs. bilinguals) × 2 (relatedness: related vs. unre-lated) × 8 (electrode) ANOVA in both Go and NoGo conditions. In both conditions, the main effect of relatedness was significant (Go: $F(1,37) = 51.71$, $p < 0.001$, $\eta_p^2 = 0.58$; NoGo: $F(1,37) = 14.21$, $p = 0.001$, $\eta_p^2 = 0.28$). Planned comparisons showed that the main effect of relatedness was significant for both bilinguals (Fs $(1,19)$ > 7.61, $ps < 0.05$, $\eta_p^2 s > 0.28$) and monolinguals (Fs $(1,18) > 6.78$, $ps < 0.05$, $\eta_p^2 s > 0.27$) in both Go and NoGo conditions.

2.2.2. Homophones
2.2.2.1. Homophone Go condition.
The main effects of relatedness or group x relatedness interactions did not reach significance in any of the 50 ms time windows between 350 to 1000 ms. Planned com-parisons within each group did not reveal any significant effects ($Fs < 2.83$, $ps > 0.1$, see Fig. 4).

Next, we evaluated the influence of language proficiency and daily language exposure (Luk and Bialystok, 2013), as well as indi-vidual differences in inhibitory control (Blumenfeld and Marian, 2013; Mercier et al., 2014) on the N400 language co-activation effect. In order to examine the N400 effect, we computed mean amplitude differences (averaged across eight electrodes in the ROI analysis) between the two homophone conditions (subtracting the mean amplitude of homophone related condition from the mean amplitude of the homophone unrelated condition) in the 350–500 ms time window (Hoshino and Thierry, 2012) and

500–1000 ms time window. While neither language proficiency in Korean nor the inhibitory control measure correlated with the N400 effect in either time window ($rs < 0.36$, $ps > 0.14$), we found that the amount of Korean exposure was positively correlated with the mean amplitude difference of the two homophone conditions (the N400 effect) in the 500–1000 ms time window ($r = 0.47$, $p = 0.038$, two-tailed, see Table 2). This indicates that increased daily exposure to the non-target native language (Korean) resulted in greater language co-activation in bilinguals (see Fig. 5). Impor-tantly, language proficiency in Korean and daily language exposure were not correlated with each other ($r = 0.03$, $p > 0.9$, see Table 2).

2.2.2.2. Homophone NoGo condition.
A marginally significant main effect of relatedness was found in the 700–750 ms time window, showing that the homophone-unrelated condition elicited a larger positivity than the homophone-related condition ($F(1,37) = 4.08$, $p = 0.051$, $\eta_p^2 = 0.1$, see Fig. 6). The interaction between group and relatedness was not significant ($F < 1$, $p > 0.6$). Planned compar-isons showed that the relatedness effect was only significant in bilinguals ($F(1,19) = 4.83$, $p = 0.041$, $\eta_p^2 = 0.20$), but not in monolinguals ($F(1,18) < 1$, $p > 0.35$). Visual inspection of the scalp distribution suggested potential lateralization of this effect during the 600-800 ms time window. Therefore, we added hemisphere as an additional factor and performed a 2 (relatedness: related vs. unrelated) × 2 (group: bilingual vs. monolingual) × 2 (hemisphere: left vs. right) × 3 (electrode: CP1, C3, and P3, vs. CP2, C4, and P4) ANOVA over the 600–800 ms time window. A significant interac-tion between hemisphere and relatedness emerged ($F(1,37)$ $= 9.76$, $p = 0.003$, $\eta_p^2 = 0.21$). Planned comparisons within each
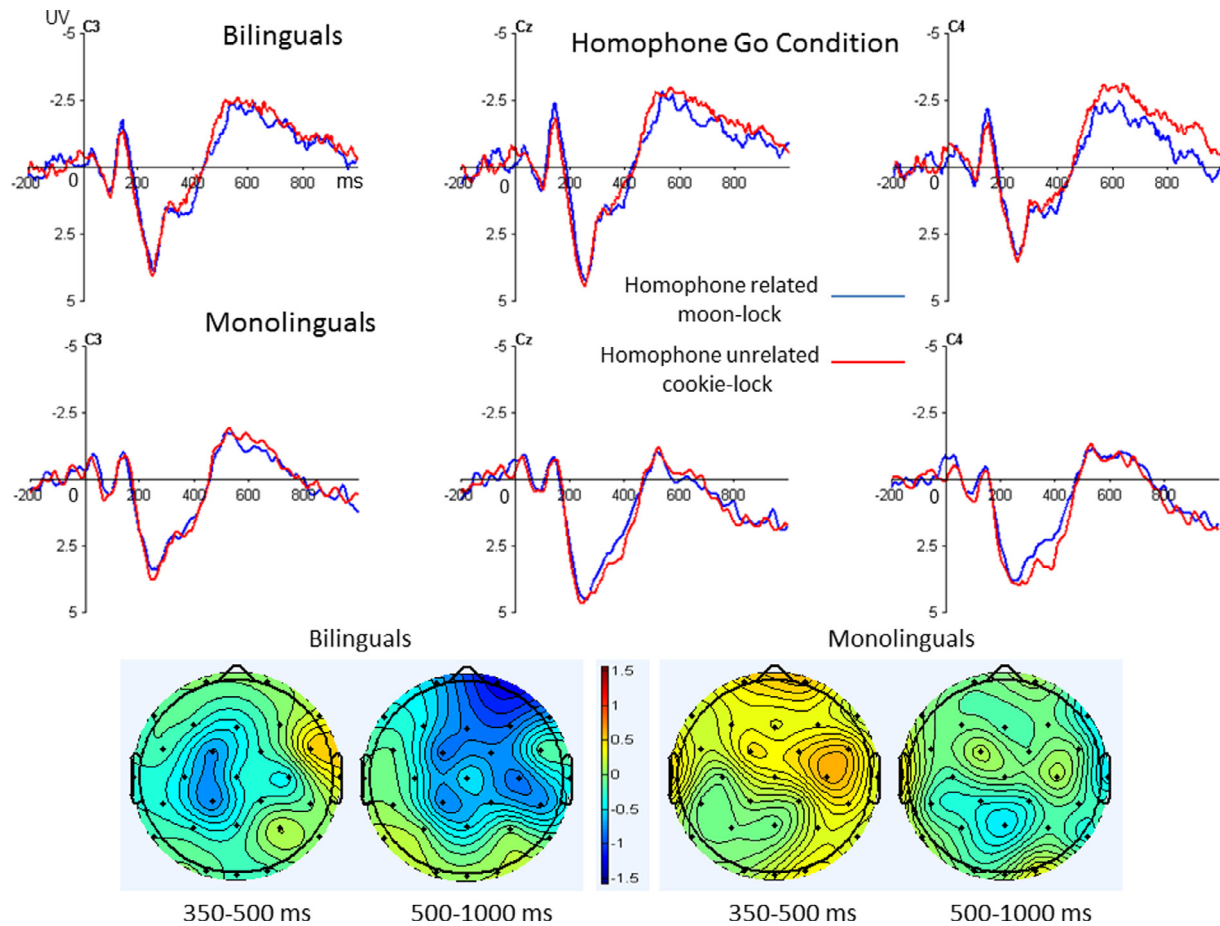
Fig. 4. ERPs and difference waves elicited by homophone-related and homophone-unrelated word pairs in the Go condition.

Table 2
Correlations among ERP effects in the semantic judgment task, measures of language profile and neural efficiency in the flanker task in Korean-English bilinguals.

Variables	The N400 effect (co-activation)	The LPC effect (language control)	Korean proficiency	Korean exposure		The P300 effect (inhibitory efficiency)
The N400 effect	–	−0.19	−0.31	0.47[*]	0.31	
The LPC effect		–	−0.14	−0.02	0.52[*]	
Korean proficiency			–	0.03	−0.03	
Korean exposure				–	0.09	
The P300 effect					–	

[*] $p < 0.05$

language group showed that the hemisphere × relatedness interaction was significant in bilinguals ($F(1,19) = 8.25$, $p = 0.01$, $\eta_p^2 = 0.30$), but not in monolinguals ($F(1,18) = 2.20$, $p > 0.15$), and that the three-way interaction between group, hemisphere and relatedness was not significant ($F(1,37) = 1.37$, $p = 0.25$). Further comparisons revealed that bilinguals elicited larger positive-going waves for the homophone-unrelated condition than for the homophone-related condition in the right hemisphere ($F(1,19) = 6.32$, $p = 0.021$, $\eta_p^2 = 0.25$), but not in the left hemisphere ($F(1,19) < 1$, $p > 0.6$). No difference between the two homophone conditions was found for monolinguals in either the left or right hemisphere ($Fs(1,18) < 1$, $ps > 0.5$). Next, we examined the relationship between this right-lateralized late positive effect (subtracting the mean amplitude of the homophone-unrelated condition from that of the homophone-related condition across three electrodes in the right hemisphere) and individual differences in the amount of Korean exposure, language proficiency and inhibitory control.

We found that only the neural index of inhibitory control (i.e., the P300 effect between incongruent and neutral conditions in the flanker task) was correlated with the late positive effect ($r = 0.52$, $p = 0.028$, two-tailed, see Table 2), showing that a larger P300 difference was associated with a larger late positive effect (see Fig. 7).

2.3. Semantic rating and translation tasks

To ensure that the participants in the ERP study evaluated semantic relatedness of the critical word pairs similar to the participants in the norming study, we collected semantic ratings after the ERP session was completed (on a 0–7 scale, where 0 = not related at all, and 7 = highly related). For bilinguals, the average rating of homophone-related across languages word pairs (which should be judged as unrelated in English) was 0.22 ($SD = 0.027$) when evaluated in English, and the average rating of
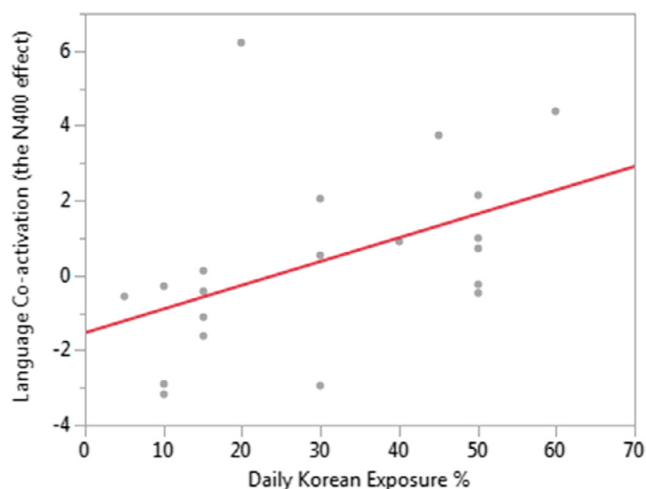
Fig. 5. Correlation between the N400 effect and the amount of daily Korean exposure in Korean-English bilinguals.

homophone-unrelated word pairs was 0.22 (SD = 0.025). For the English monolinguals, the average rating for homophone-related across languages word pairs was 0.54 (SD = 0.060) and 0.56 (SD = 0.061) for homophone-unrelated word pairs. Although monolinguals had an overall slightly higher rating than bilinguals, both groups determined that the relatedness of two homophone conditions (both unrelated when considering only the English meaning of homophones) were comparable. Finally, bilingual par-

ticipants were also asked to translate all the critical English word stimuli into Korean. The average accuracy of the translation task was high (M = 91%, SD = 7%), confirming that bilingual participants knew the English words that were used in the critical conditions and were able to judge the semantic relatedness correctly.

2.4. Behavioral results of the flanker task

The behavioral results of the flanker task are summarized in Table 3. The accuracies for the congruent, incongruent and neutral conditions were high (equal to or higher than 97.5%) for both bilinguals and monolinguals (no further accuracy analyses were conducted because of the lack of variability in these three conditions). In the response time analysis, a 2 (group: bilinguals vs. monolinguals) × 3 (condition: congruent, incongruent, and neutral) mixed repeated-measures ANOVA was performed with only correctly responded trials. The main effect of condition was significant, $F(2, 66) = 104.19$, $p < 0.001$, $\eta_p^2 = 0.76$. Further comparisons showed that the congruent condition was faster than the neutral condition ($p < 0.001$), and the incongruent condition was slower than the neutral condition ($p < 0.001$). However, neither the main effect of group nor the interaction between group and condition was significant ($Fs < 1$).

2.5. ERP data of the flanker task

In the analysis of the P300 effect during the 500–750 ms time window, the main effect of condition was significant ($F(2, 66) = 27.03$, $p < 0.001$, $\eta_p^2 = 0.45$). Further comparisons showed that
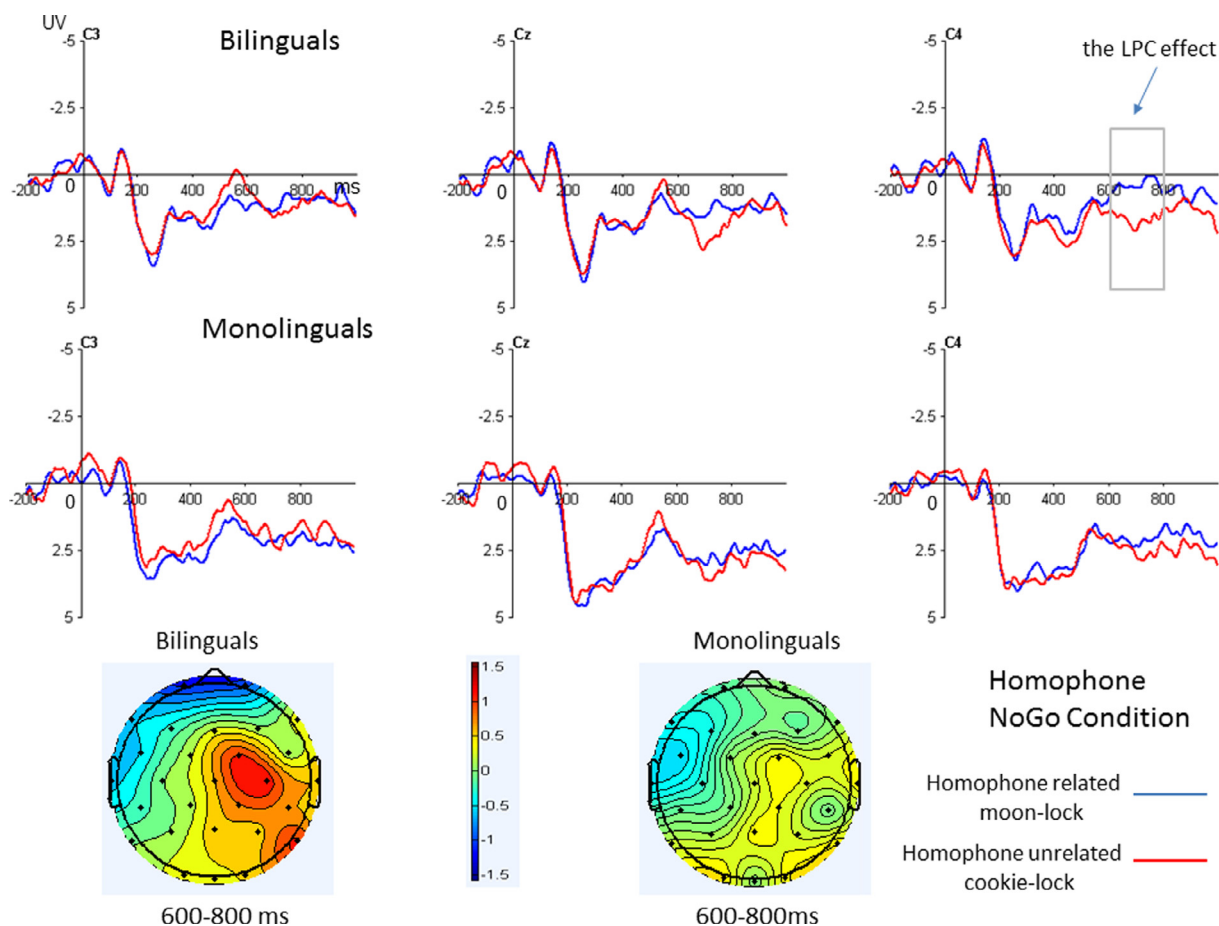

Fig. 6. ERPs and difference waves elicited by homophone-related and homophone-unrelated word pairs in the NoGo condition.
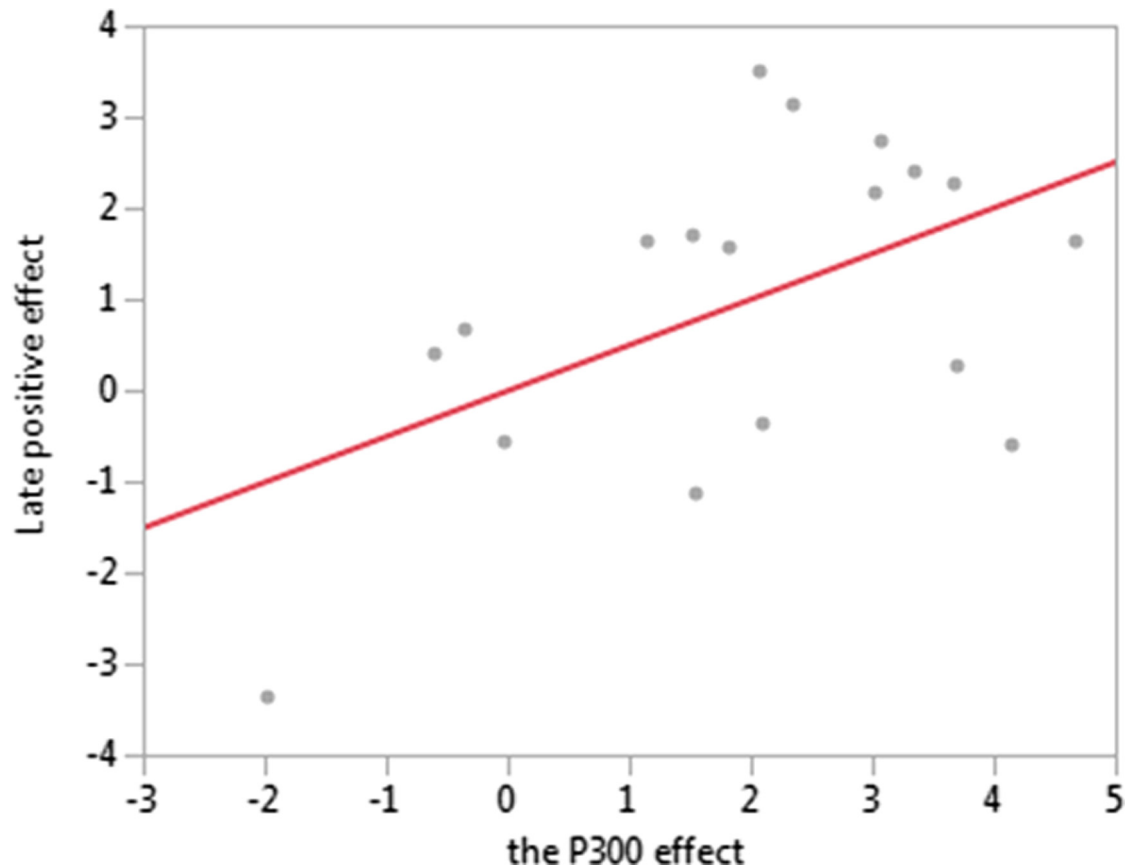
Fig. 7. Correlation between the late positive effect in the right hemisphere and the P300 effect (incongruent condition – neutral condition) in the Flanker task.

Table 3
Accuracies and response times of the four conditions in the flanker task (standard errors are in parentheses).

	Group	Congruent	Incongruent	Neutral	Nogo
Accuracy (% correct)	Bilinguals	98.3 (0.7)	97.9 (0.7)	99.0 (0.4)	93.0 (1.6)
	Monolinguals	99.8 (0.7)	97.5 (0.8)	99.3 (0.4)	90.7 (1.8)
Response time (in ms)	Bilinguals	537 (17)	601 (17)	557 (19)	NA
	Monolinguals	519 (18)	580 (17)	542 (20)	NA

the incongruent condition elicited a larger P300 than both the congruent condition ($p < 0.001$) and the neutral condition ($p < 0.001$). However, the group x condition interaction as well as the main effect of group was not significant ($Fs < 1.98$, see Fig. 8). We provide a more detailed description of the flanker ERP results in the Supplementary materials.

3. Discussion

The aim of the current study was to examine the neural signatures of language co-activation and control in bilingual spoken word comprehension. Comparisons were drawn between word pairs that were related within language (English), word pairs that were related across languages (English and Korean), and word pairs that were unrelated either within or across languages. In the comparison of word pairs that were related and unrelated within English, both bilinguals and monolinguals showed the classic semantic congruency effect, as indexed by the N400 effect. In the critical comparison between word pairs that were related across languages and that were unrelated, we found that the amount of language co-activation, as indexed by the size of the

N400 effect, increased as bilinguals had more daily exposure to the non-target native language. We also found that the allocation of cognitive resources differed depending on whether cross-language competition was present: word pairs that were related across languages received fewer cognitive resources than word pairs that were not related. Meanwhile, a smaller resource allocation difference (i.e., a smaller effect caused by cross-linguistic competition) was found to positively correlate with bilinguals' ability to resolve interference in the flanker task. These findings suggest that the degree of language co-activation in bilingual spoken word comprehension is influenced by bilinguals' daily language experience and that greater neural efficiency in resolving non-linguistic interference may make bilinguals less susceptible to cross-linguistic interference.

We found that greater exposure to the non-target language (native language) in daily life increased the degree of language co-activation in bilinguals. This result is comparable to a previous behavioral study in which bilinguals read sentences in their L2 embedded with homographs. In the study, Elston-Güttler et al. (2005) showed that during an English (L2) sentence reading task, German-English bilinguals who were exposed to the German (L1) version of a film (compared to the English version of the same film)
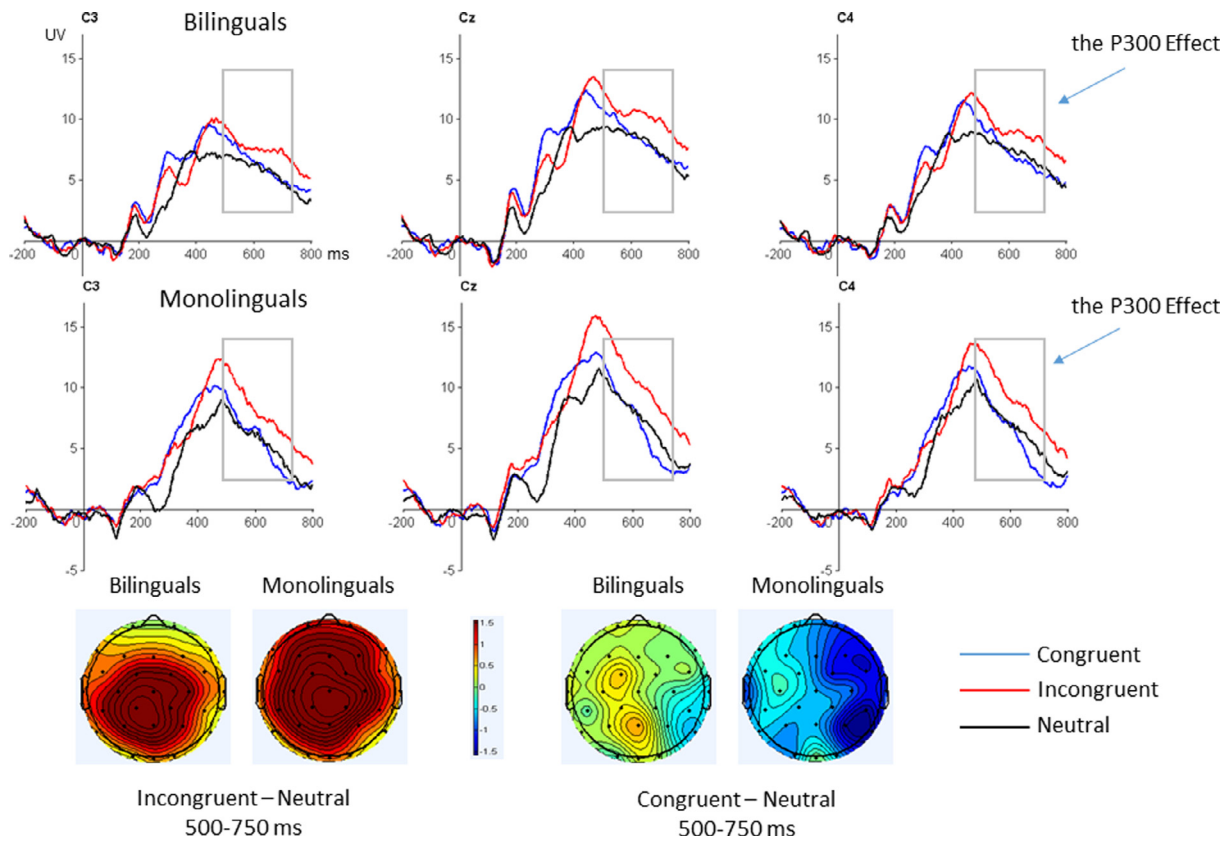
Fig. 8. ERPs and difference waves elicited by congruent, incongruent, and neutral conditions in the flanker task.

prior to the reading task accessed homophones' German meaning. According to the *Bilingual Interactive Activation* model (BIA and BIA +, Dijkstra and Van Heuven, 1998, 2002), the high daily exposure to the non-target language in the current study and brief exposure to the non-target language before the experiment in Elston-Güttler et al. (2005) would both increase the pre-activation level of the non-target language and increase the ease of accessing that language, thereby resulting in greater language co-activation in bilinguals. Taken together, these findings suggest that language co-activation in bilinguals could be very sensitive to fine-grained differences in the bilingual language experience. Thus, it might be more appropriate to consider bilinguals on a continuum of language experience, and future studies should use continuous measures instead of categorical measures to capture subtle individual differences (Luk and Bialystok, 2013; Van Hell and Tanner, 2012).

In the current study, we observed cross-linguistic semantic activation in interlingual homophones that do not overlap orthographically, suggesting that phonological similarity alone is sufficient to activate semantic information in the non-target language. This finding is consistent with the prediction of the *Bilingual Language Interaction Network for Comprehension of Speech* model (*BLINCS*, Shook and Marian, 2013). In *BLINCS*, the incoming auditory input first activates phonemes in both of a bilingual's languages as the phonological representation is shared across two languages. Activated phonemes are then mapped onto words in each language at the level of phono-lexical representation, and these words subsequently activate both semantic and ortho-lexical information. According to the *BLINCS* model, the activation of the ortho-lexical representation does not have a direct influence on the access of semantic information, and semantic co-activation occurs as long as two languages share phonological similarity. Consistent with the model, we observed that interlingual homophones with no

orthographic overlap still activated semantics in the non-target language.

However, the cross-linguistic semantic relatedness effect in the current study appeared later (i.e., the first visible difference appeared around 500 ms after stimulus onset) than the within-language semantic effect in non-homophone word pairs (i.e., around 400 ms). This finding suggests that a homophone's meaning in the non-target language might not be immediately accessible in bilingual spoken word comprehension, and is consistent with FitzPatrick and Indefrey (2014). They found that when listening in an L2, a homophone's meaning in the non-target language (L1) was only available after accessing the meaning in the target language L2. This delayed effect in bilingual spoken word comprehension contrasts with the co-activation of homograph meanings in bilingual visual word comprehension. In Hoshino and Thierry (2012), the cross-linguistic semantic effect (shown in word pairs that were related across languages) appeared in the same 350–500 ms time window as the semantic effect in the target language (shown in word pairs that were related within language). Taken together, these findings indicate a difference in the time course of semantic co-activation triggered by interlingual homophones and homographs. The time course difference of co-activation across auditory and visual modalities is likely caused by different degrees of overlap in interlingual homophones and homographs. Homographs overlap visually completely while homophones can vary in pronunciation because of the phonetic differences between languages (Kang and Guion, 2006). Therefore, it is likely that when hearing interlingual homophones, bilinguals need additional time to match these slightly different auditory inputs onto the phonological representations in the non-target language. Consequently, co-activation of the meanings in the non-target language was delayed. Another possible explanation is that a homophone's

semantic information in a given language is more closely linked to the native phonology (FitzPatrick and Indefrey, 2014); as a result, accessing a homophone's meaning in the L1 takes more time when it is presented with L2 pronunciation. Future studies can use homophone word pairs presented in Korean to Korean-English bilinguals to test this explanation.

In the time window of 600–800 ms in the NoGo condition, we observed an effect that resembles the LPC effect, which is often identified around 500 ms after stimulus onset. However, contradictory to our prediction, word pairs that contain cross-language competition elicited a smaller LPC than unrelated word pairs in the right hemisphere. It is not clear why we observed a reduced LPC for word pairs that were related across-languages because we expected cross-linguistic activation to increase the cognitive demand, which would result in an increased LPC. One tentative explanation is that bilinguals resolve cross-linguistic competition at the cost of semantic processing, resulting in a smaller LPC for cross-linguistically related word pairs. Critically, the difference in the homophone-related and -unrelated conditions suggests that the LPC is sensitive to the experimental manipulation of whether or not cross-language competition is present. If we consider the word pairs without cross-language competition as a baseline, then the difference between the baseline and the word pairs with cross-language competition can be used as an index of the interference which bilinguals experience. Therefore, a smaller difference between the conditions with and without cross-linguistic competition indicates that bilinguals experienced less influence or interference from cross-linguistic competition.

In the following correlation analysis between the non-linguistic flanker task and the linguistic semantic relatedness task, a smaller LPC effect between homophone related and unrelated word pairs was positively associated with a smaller P300 effect between incongruent and neutral conditions in the flanker task. A smaller P300 effect in the flanker task has been associated with more efficient cognitive processing where fewer cognitive resources are required (Pratt et al., 2011; Wu and Thierry, 2013). Therefore, the correlation between the LPC effect in the semantic judgment task and the P300 effect in the flanker task might indicate a link between the efficiency of suppressing non-linguistic interference and the interference bilinguals experience when they encounter cross-linguistic competition. It is plausible that bilinguals who were more efficient in managing interference in the non-linguistic task also experienced less linguistic interference, resulting in a smaller difference in resource allocation. These findings also indicate a potential link between the cognitive efficiency when facing interference in linguistic and non-linguistic tasks. While a number of studies have found greater cognitive efficiency in non-linguistic processing in bilinguals when compared with monolinguals (e.g., Bialystok, 2006; Bialystok and DePape, 2009; Costa et al., 2008; Luk et al., 2010; Schroeder et al., 2016), and attributed better inhibitory control abilities to bilingual language experience, the robustness of this causal relationship is under debate (see Paap et al., 2015, for different views). The current study provides the first neural evidence demonstrating that cognitive mechanisms might be similar across linguistic and non-linguistic processing, allowing for a potential bi-directional influence between language experience and non-linguistic abilities.

In the current study, we did not find behavioral differences between the homophone-related and homophone-unrelated conditions, which contrasts with bilingual visual word studies in which behavioral differences were observed (Durlik et al., 2016; Macizo et al., 2010; Martín et al., 2010). The current study constructed homophone word pairs in a very similar way to these behavioral studies (homophones with auditory presentation vs. homographs with visual presentation); therefore, a similar pattern of behavioral results was expected. Contrary to our expectations, bilinguals did

not show different response times between homophone-related (across languages) and homophone-unrelated conditions. This unexpected finding could be due to differences in simultaneous and sequential presentation across visual and auditory modalities. During the simultaneous presentation, bilinguals may have experienced difficulty resolving the interference because the *source* of the interference – homographs – was constantly shown on the screen before a decision was made (Durlik et al., 2016; Macizo et al., 2010; Martín et al., 2010). In the sequential presentation, the interval between the two words provided a buffering zone that made semantic interference manageable; therefore, no conflicts were detected by behavioral measures. Nevertheless, because of their excellent temporal resolution, ERP measures were still able to capture the language co-activation effect (see McLaughlin et al., 2004, for a similar dissociation).

Using ERP measures, the current study revealed that the neural signatures of language co-activation and control differ across overtly and covertly responded conditions. In the overtly responded Go condition, an N400 effect (which is an index of language co-activation) was found, and this N400 effect correlated with daily exposure to the non-target language. In the covertly responded NoGo condition, a late positive effect (which is associated with the allocation of cognitive resources) was found, and this effect correlated with cognitive efficiency in the flanker task. The difference between the Go and NoGo conditions might suggest that bilinguals used different strategies for processing cross-linguistic related word pairs, depending on whether overt responses were required or not. In the Go condition, bilinguals were instructed to press the buttons in a timely manner; it is likely that this high-demand task prevented bilinguals from inhibiting the non-target language completely, resulting in language co-activation. In contrast, in the NoGo condition, where the task demand was low, bilinguals had more cognitive resources available for resolving cross-linguistic competition, which successfully prevented language co-activation. This might be the reason why we did not observe an N400 effect. However, when the comparison was made between word pairs with and without cross-language competition, we found that bilinguals allocated cognitive resource differently. Nevertheless, the results in the NoGo condition were different from those of a similar ERP study (Hoshino and Thierry, 2012), in which an N400 language co-activation effect was found. This discrepancy might be due to a difference in the presentation order of word pairs in the two studies. Hoshino and Thierry (2012) presented their homographs as the target of the word pairs while we presented homophones as the prime of the word pairs. It is possible that participants in the current study had more time and used more cognitive resources to prepare for and to subsequently resolve language co-activation. Therefore, we observed a component that is associated with allocation of cognitive resources instead of language co-activation.

In conclusion, the current study provides the first ERP evidence for language co-activation and control in bilingual spoken word comprehension. The results suggest that the degree of language co-activation is influenced by bilinguals' daily language experience, and bilinguals' neural efficiency when facing interference is comparable across linguistic and non-linguistic processing. These findings reveal that bilingual language processing is sensitive to individual differences in language experience and cognitive abilities.

4. Methods

4.1. Participants

Twenty Korean-English bilinguals and 19 native English monolinguals were included in the data analyses. All participants were

Table 4
Characteristics of the English monolingual and Korean-English bilingual participants. (Standard deviations are in the parentheses.)

Measure	Monolinguals	Bilinguals
Number	19 (4 male)	20 (3 males)
Age	22.4 (3.3)	21.7 (2.9)
L1 Proficiency	9.70 (0.6)	8.67 (1.2)
L2 Proficiency	1.56 (1.6)	9.1 (1.2)[***]
L1 Age of Acquisition	Birth	Birth
L2 Age of Acquisition	11.67 (4.3)	6.03 (2.5)[***]
Daily L1 Exposure (%)	98.3 (3.2)	30.0 (17.8)[***]
Daily L2 Exposure (%)	1.7 (3.2)	67.7 (18.0)[***]

[*] $p < 0.05$, [**] $p < 0.01$, [***] $p < 0.005$.

Table 5
Examples of the critical conditions in the semantic relatedness judgment task.

Critical Conditions	Examples	Required Responses	Number of trials
Homophone-related	moon (door) – lock soup (forest) – tree	No	56
Homophone-unrelated	moon (door) – tree soup (forest) – lock	No	56
Control-related	jail – lock leaf – tree	Yes	56
Control-unrelated	jail – tree leaf – lock	No	56

Note: Words in the parentheses indicate the Korean homophone meaning.

right-handed (assessed by the Edinburgh handedness inventory, Oldfield, 1971) and had normal or corrected to normal vision and normal hearing. None of them reported any neurological disorders. Participants gave informed consent prior to the experiment, which was approved by the Institutional Review Board. We included bilinguals who learned Korean as their native language and English as their second language, and monolinguals who learned English as their native language and had a second language proficiency lower than 4 on an 11-point scale (0–10, where 10 indicates native-like fluency). One Korean-English speaker and two English speakers were tested but excluded due to poor quality of the data (i.e., no early components could be identified in the averaged ERPs). Furthermore, one Korean-English speaker and two English speakers were excluded because too few trials remained after artifact rejection and exclusion of incorrect trials ($n < 25$ per condition).

The remaining 20 Korean-English speakers all started learning Korean at birth and English before the age of 11 (two of them reported acquiring Korean and English simultaneously). All bilingual participants lived in the U.S. at the time of testing. The remaining 19 English speakers were native speakers of English with minimal exposure to a second language, and none of them reported having any knowledge of Korean. All participants completed the *Language Experience and Proficiency Questionnaire* (*LEAP-Q*; Marian et al., 2007), a self-report questionnaire for assessing the language profile of multilingual participants. Participant demographics are summarized in Table 4.

4.2. Materials

4.2.1. Semantic judgment task

Fifty-six English-Korean homophones were selected. One doctoral-level psychologist who teaches English in Korea and two doctoral-level linguistics students who speak both languages were asked to rate the phonological similarity between the English pronunciation and Korean pronunciation of the homophone on a Likert scale from 1 to 10. The average rating of phonological similarity for the 56 homophones was 7.65 ($SD = 1.08$) out of 10 (see Appendix A for the list of homophones. A more detailed selection procedure is provided in the Supplementary materials).

From the 56 homophones, four types of word pairs were constructed for the critical conditions (see Table 5). (1) In the homophone-related (across language) condition, each of the 56 homophones (e.g., *moon*, meaning "door" in Korean) was paired with an English target word that was unrelated to the English homophone meaning but was related to the Korean homophone meaning (e.g., *lock*). (2) In the non-homophone control-related (within language) condition, each English target word (e.g., *lock*) that was generated for the homophone-related condition was paired with a new related English word (e.g., *jail*). (3) For the homophone-unrelated condition, homophones were paired with a different target word that was previously paired with another homophone in the homophone-related condition, resulting in

word pairs that were not related when considering both English and Korean homophone meanings. This pairing method ensured that the stimuli were exactly the same in the homophone-related and -unrelated conditions. (4) The control-unrelated condition was created in the same way by using the stimuli from the control-related condition. Therefore, each homophone appeared once in the homophone-related condition and once in the homophone-unrelated condition. Each non-homophone control word appeared once in the control-related and once in the control-unrelated condition. The targets were the same across all four conditions. In other words, each homophone and non-homophone control word was presented 4 times throughout the semantic relatedness judgment task, and the targets paired with them were presented 8 times.

The prime words in the homophone related and unrelated conditions and those in non-homophone control related and unrelated conditions were matched for length, lexical frequency, log-frequency, subtitle frequency, number of phonemes, number of syllables, and both orthographic and phonological neighborhood sizes (all $ps > 0.1$, see Table 6; lexical properties were obtained from The English Lexicon Project, Balota et al., 2007). The semantic relatedness of the word pairs was computed based on the Nelson Norms (Nelson et al., 1998). The average semantic relatedness of the word pairs in the homophone-related condition (when considering the Korean homophone meaning) did not differ from the average semantic relatedness of the control-related condition (0.13 vs. 0.13, $p > 0.9$). Because no norms existed to assess the degree of unrelatedness between word pairs in the homophone-related condition (when considering the English homophone meaning), homophone-unrelated condition and control-unrelated condition, a norming study was conducted. Each unrelated pair was rated on its semantic relatedness on a scale from 0 (not at all related) to 7 (completely related) by 22 native speakers of English. The average ratings of homophone-related, homophone-unrelated and control-unrelated word pairs were 0.58 ($SD = 0.54$), 0.59 ($SD = 0.48$), and 0.72 ($SD = 0.54$) respectively and there was no difference among the three conditions ($p > 0.27$). In addition to the critical conditions, we generated 224 filler pairs in a similar manner to the critical condition by selecting an additional 112 English words as filler primes and pairing each with two different filler target words that were selected from an additional set of 56 word. Of the 224 filler pairs, 168 word pairs were semantically related (required a "Yes" response in the semantic judgment task) and 56 word pairs were not semantically related (required a "No" response). Therefore, the number of word pairs requiring "Yes" and "No" responses was equal in the semantic relatedness judgment task.

In order to obtain both behavioral measures and response-free EEGs, all of the word pairs (both critical and filler word pairs) were

Table 6
Lexical characteristics of homophones and control words (standard deviation in parentheses).

Lexical characteristics	Homophones	Control words
Length	3.85 (0.9)	3.81 (0.7)
Frequency_HAL	68762.4 (150912)	45929.8 (101317)
Subtitle Word Frequency	295.88 (766)	142.83 (415)
Orthographic neighborhood	8.40 (6.5)	8.71 (5.0)
Phonological neighborhood	17.67 (9.4)	18.08 (9.8)
Number of phonemes	2.96 (0.6)	3.13 (0.6)
Number of syllables	1.19 (0.4)	1.08 (0.3)

presented once as a Go condition in which participants were asked to press a yes or no button to indicate their semantic relatedness judgment, and once as a NoGo condition where participants were asked to make silent judgments. Go and NoGo trials were randomly intermixed to maintain participants' attention (e.g., Hoshino and Thierry, 2012; Orgs et al., 2008). While interspersing Go and NoGo conditions potentially risked increasing the cognitive load of the task, this concern was mitigated by our experimental design in which the comparison occurred only within the Go or NoGo condition. If the additional cognitive load influences participants' performance, it should exert similar effects across all the Go and NoGo conditions.

To minimize repetition effects, the materials were divided into two equivalent sets so that no homophone words and no control words appeared in both related and unrelated conditions within the same set. In the first half of the semantic relatedness judgment task, one set of word pairs was presented in the Go condition and the other set of the word pairs was presented in the NoGo condition. In the second half of the semantic task, the two sets of word pairs were switched for Go and NoGo presentation; words previously presented in the Go condition were now presented in the NoGo condition and vice versa. There were four lists of word pairs in each half of the semantic task, and each unique word only appeared once in each list. Within each list, word pairs were presented in a randomized order. The number of word pairs from each condition, the number of word pairs requiring a Yes or No response, and the number of Go/NoGo responses within each block were balanced. The order of a set being presented first in the Go condition or first in the NoGo condition and the block order within a set were counterbalanced across participants.

4.2.2. Auditory Recordings

Auditory stimuli were produced by a female native speaker of American English using a Sennheiser PC360 microphone headset in a quiet room. Recordings were digitized as WAV files at a sampling rate of 44.1 kHz using the audio-editing software Audacity 2.0.6 (http://audacity.sourceforge.net). Individual stimuli were minimally processed to remove clicks using PRAAT (Boersma and Weenink, 2004) and were then run through a dynamic compressor in Audacity to reduce the range of the loudest sounds and bring them closer to the average.

4.2.3. The flanker task

The flanker task included four conditions (adapted from Luk et al., 2010, see Fig. 1). The participants were asked to respond to the center red arrow. In the congruent condition, the center arrow was surrounded by four arrows pointing in the same direction. In the incongruent condition, the center arrow was flanked by four arrows pointing in the opposite direction. In the neutral trials, the flanking stimuli were diamonds providing no directional information. Finally, in the no-go condition where the center arrow was surrounded by Xs, participants were asked to suppress their responses. There were 60 trials in each condition (30 trials with

center arrow facing left and 30 trials with center arrow facing right), resulting in 240 trials in total. The flanker task was divided into two equivalent sets with the same number of trials from each condition. Within each set, trials of different conditions were presented randomly.

4.3. Procedure

After informed consent was obtained, participants were prepared for EEG testing. Each participant was tested individually in a quiet room. Stimuli were presented using MATLAB (version 8.2, The MathWork Inc., Natick, MA, 2013) with PsychToolBox 3.0 (Brainard, 1997) on a Dell PC. In the semantic relatedness judgment task, auditory sound files of words were played via two magnetically shielded speakers. Each trial started with a fixation cross of 400 ms, followed by the first word while the fixation cross stayed on the screen. After a 400 ms interstimulus interval, the second word was played with a black or a red fixation cross on the screen. In the event of a black fixation cross, participants were asked to make their responses as accurately and quickly as possible by pressing one of two buttons on a two-handed game controller. In the event of a red fixation cross, participants were instructed to make a relatedness judgment silently. The black or red fixation cross disappeared after 1500 ms regardless of when the participants made their judgments. The inter-trial interval was 1000 ms (see Fig. 9). The corresponding hand for "Yes" and "No" was counterbalanced across participants. A practice of 12 word pairs that were not used for the formal experiment was given before the formal task, and the same 12 word pairs were repeated a second time for eye blink control practice. Participants were offered a break after every 96 trials.

After the semantic relatedness judgment task, participants completed the flanker task. In the flanker task, each trial started with a fixation of 500 ms, followed by a blank of 200 ms. The arrow and its flanking stimuli were presented for a maximum duration of 1500 ms and disappeared immediately after a response was made. The inter-trial-interval was 1000 ms. After the EEG session of the semantic relatedness judgment task and the flanker task, participants rated all the critical word pairs on a 0–7 scale, where 0 meant "not related at all" and 7 meant "highly related." Korean-English bilinguals also completed a translation task on the critical stimuli of the semantic judgment task. All participants then completed the Language Experience and Proficiency Questionnaire (LEAP-Q; Marian et al., 2007) and the NIH Toolbox Cognition Battery (NTCB, https://www.assessmentcenter.net/). The entire experimental session lasted approximately 3.5–4.5 h and all participants received monetary compensation for their participation.

4.4. Electroencephalogram recording and processing

The electroencephalogram was recorded from 30 Ag/AgCl active electrodes (Brain Vision antiCHamp and PyCorder, Brain Vision LLC) placed on the scalp according to the extended 10–20 system
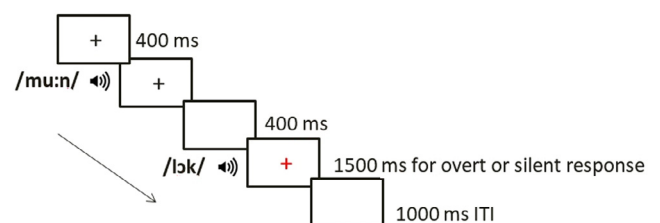

Fig. 9. A schematic representation of the procedure in the Semantic Relatedness Judgement Task.

(Pivik et al., 1993). Vertical and horizontal electrooculogram was recorded through two additional electrodes attached below the left eye and the corner of the right eye. All electrodes were referenced to the left mastoid online. Electrode impedances were kept below 15 kΩ. All channels were amplified with a band pass of 0.01–100 Hz and at a sampling rate of 500 Hz. Offline, EEG data were preprocessed using a combination of EEGLAB (version 13.3.2, Delorme and Makeig, 2004) and ERPLAB (version 4.0.3.1, Lopez-Calderon and Luck, 2014) under MATLAB (version 8.2, The Math-Work Inc., Natick, MA, 2013). After using independent component analysis to remove EEG components related to eye blinks (ICA function in EEGLAB, Delorme and Makeig, 2004), continuous EEGs were filtered with a band pass of 0.05–70 Hz (for statistical analyses), and were re-referenced to the averaged mastoid reference.

After re-referencing, the EEGs were segmented into epochs of 1200 ms, starting 200 ms before stimulus onset. Each epoch was baseline corrected for the 200 ms pre-stimulus interval. Finally, epochs containing artifacts were automatically discarded when the amplitudes exceeded a 100 µV threshold using a moving window of 200 ms in steps of 50 ms, or when simple voltage exceeded -120 µV and 120 µV in any channel.

4.4.1. Semantic relatedness judgment task

After excluding trials with incorrect responses or artifacts, the percentage of remaining trials in each condition was calculated: Homophone-related (85%), homophone-unrelated (85%), control-related (92%), and control-unrelated (93%) in the Go condition, and homophone-related (84%), homophone-unrelated (82%),

Appendix A

Word pairs in each critical condition.

Homophone-related (Korean meaning in parenthesis)		Homophone-unrelated		Control-related		Control-unrelated	
Bull (fire)	Hot	God	Pencil	Cool	Hot	Boy	Number
Ill (work)	Place	Talk	Bacon	Room	Place	Soap	Air
Talk (chin)	Bone	Ill	Shoe	Teeth	Bone	Rack	Cow
God (hat)	Coat	Bull	Coat	Fur	Coat	Rod	Pen
Book (drum)	Stick	Abbey	Short	Rod	Stick	Fur	Nerd
Oat (clothes)	Hanger	Tall	Warm	Rack	Hanger	Teeth	School
Abbey (father)	Man	Book	Water	Boy	Man	Cool	Spoon
Tall (hair)	Wash	Oat	Death	Soap	Wash	Room	Death
Pay (lung)	Air	Duck	Sweet	Fan	Air	Life	Place
Jug (enemy)	War	Goal	Skin	Fight	War	Lake	Pencil
Goal (valley)	River	Jug	Pen	Flood	River	Smart	Rose
Duck (virtue)	Truth	Pay	Brick	Liar	Truth	Wipe	Truth
Huge (toilet paper)	Tissue	Arm	School	Wipe	Tissue	Liar	Tissue
Arm (cancer)	Death	Huge	Parent	Life	Death	Fan	Wash
Easy (intellect)	Nerd	Autumn	Necklace	Smart	Nerd	Flood	Necklace
Mat (taste)	Sweet	Tongue	Ocean	Cake	Sweet	Rice	Tree
Tongue (empty)	Nest	Mat	Sick	Eagle	Nest	Fee	Brick
up (career)	School	Meal	Hanger	Fee	School	Eagle	Warm
Meal (wheat)	Field	Up	Paint	Rice	Field	Cake	Paint
Daisy (pig)	Bacon	Bar	Air	Ham	Bacon	Art	Ocean
Autumn (ice)	Water	Easy	Thread	Lake	Water	Fight	New
Bar (foot)	Shoe	Daisy	Truth	Box	Shoe	Cold	Nest
Evil (blanket)	Warm	Boot	Music	Cold	Warm	Box	Hanger
Boot (brush)	Paint	Evil	Under	Art	Paint	Ham	Rope
Choke (tip)	Pencil	Him	Number	Draw	Pencil	Idea	Lock
Soup (forest)	Tree	Jeep	Kiss	Leaf	Tree	Child	Bacon
Him (strength)	Energy	Choke	River	Power	Energy	Inch	Lobe
Jeep (house)	Brick	Soup	Bone	Wall	Brick	Dance	Sick
Key (height)	Short	Yet	Beach	Inch	Short	Power	Beach
Yet (old)	New	Key	Spoon	Idea	New	Draw	Thread
Sorry (sound)	Music	Deck	Fruit	Dance	Music	Wall	Fruit
Moon (door)	Lock	Cookie	Lock	Jail	Lock	Fork	Hot
Cookie (flag)	Pole	Moon	Lobe	Fish	Pole	Pearl	Energy
Oak (jade)	Necklace	Car	Bell	Pearl	Necklace	Fish	Bell
Deck (home)	Parent	Sorry	Field	Child	Parent	Leaf	Under
Car (knife)	Spoon	Oak	Cloud	Fork	Spoon	Jail	Water
Chill (seven)	Number	Jar	Positive	Age	Number	Sew	Positive
Bowl (cheek)	Kiss	Mall	Tree	Lip	Kiss	Low	Sweet
Jar (ruler)	Pen	Chill	Pole	Ink	Pen	Tone	Coat
Top (tower)	Bell	Panel	Feather	Tone	Bell	Ink	Short
Sun (line)	Rope	Top	Man	Hang	Rope	Age	Cloud
Panel (needle)	Thread	Goat	War	Sew	Thread	Fog	War
Gray (yes)	Positive	Gray	Energy	Sure	Positive	Pillow	River
Goat (flower)	Rose	Bee	Stick	Wine	Rose	Wine	Feather
Say (bird)	Feather	Bowl	Nest	Pillow	Feather	Peach	Shoe
Mall (horse)	Cow	Meat	Swear	Beef	Cow	Beef	Swear
Bay (pear)	Fruit	Say	Rock	Peach	Fruit	Sure	Man
bee (rain)	Cloud	Weigh	Hot	Fog	Cloud	Hard	Skin
Pea (blood)	Skin	Bay	Rope	Burn	Skin	Lip	Field
Meat (bottom)	Under	Toe	Place	Low	Under	Hang	Kiss
Sum (island)	Ocean	Sum	Cow	Boat	Ocean	Vow	Bone
Toe (vomit)	Sick	Pea	Rose	Flu	Sick	Wave	Pole
Weigh (outer ear)	Lobe	Sun	Tissue	Ear	Lobe	Flu	Music
Yolk (curse)	Swear	Dole	Nerd	Vow	Swear	Ear	Stick
Hay (sun)	Beach	Yolk	Wash	Wave	Beach	Boat	Parent
Dole (stone)	Rock	Hay	New	Hard	Rock	Burn	Rock

control-related (92%), and control-unrelated (94%) in the NoGo condition. For all participants included in the final analysis, at least 25 trials remained per condition. Average ERPs were generated for each participant, electrode, and experimental condition. Averaged ERPs were filtered with a low pass filter of 30 Hz only for the purpose of figure plotting.

Mean ERP amplitudes in the semantic task were calculated in every 50 ms time window between stimulus onset and 1000 ms. Early effects (e.g., P1, N1 and P2) were analyzed by conducting ANOVAs with relatedness (2: related vs. unrelated) × response type (2: Go vs. NoGo) × electrode (28) as within-subjects factors and group (2: bilinguals vs. monolinguals) as a between-subjects factor in every 50 ms time window from stimulus onset to 350 ms. For the N400 effect and LPC effect, we selected 8 centroparietal electrodes (C3/4, CP1/2, P3/4, Cz, and Pz) for ROI analyses based on previous literature (Hoshino and Thierry, 2012; Kuipers and Thierry, 2010). ANOVAs with relatedness (2: related vs. unrelated), response type (2: Go vs. NoGo), and electrode (8) as within-subjects factors and group (2: bilinguals vs. monolinguals) as a between-subjects factor were performed every 50 ms starting from 350 ms to 1000 ms. For both early components and the N400 and LPC effects, ANOVAs were performed separately for homophones conditions and non-homophone controls conditions[2]. Further, considering the different cognitive demands in Go and NoGo conditions, we also performed ANOVAs separately in Go and NoGo conditions with relatedness (2: related vs. unrelated) and electrode (28) as within-subjects factors and group (2: bilinguals vs. monolinguals) as a between-subjects factor in all the time windows. Because the difference in language co-activation effects was observed between bilinguals and monolinguals in several previous ERP studies (Hoshino and Thierry, 2012; Thierry and Wu, 2007), planned comparisons within each group were conducted regardless of the significance of the interaction between relatedness and group[3].

4.4.2. The flanker task

Data from two bilinguals and one monolingual were excluded due to an insufficient number of trials ($n < 25$ per condition). An additional monolingual was discarded because of poor data quality. The data from 18 bilinguals (out of 20) and 17 monolinguals (out of 19) were included in the final flanker analysis. The efficiency of resolving interference was measured by the P300 effect, which was obtained by subtracting the mean amplitudes of the neutral condition from those of the incongruent condition in the ROI (8 electrodes: C3/4, CP1/2, P3/4, Cz, and Pz) during the time window of 500–750 ms (Wu and Thierry, 2013). In the time window of 500–750 ms, an ANOVA with group (2: bilinguals vs. monolinguals) as a between-subjects factor, and condition (3: congruent, incongruent, and neutral) and electrode (8) as within-subjects factors was also performed.

Acknowledgements

Appendix A

Appendix B. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.brainres.2017.03.023.

References

Balota, D.A., Yap, M.J., Cortese, M.J., Hutchison, K.A., Kessler, B., Loftis, B., Neely, J.H., Nelson, D.L., Simpson, G.B., Treiman, R., 2007. The English lexicon project. Behav. Res. Methods 39, 445–459.

Barr, D.J., Levy, R., Scheepers, C., Tily, H.J., 2013. Random effects structure for confirmatory hypothesis testing: Keep it maximal. J. Mem. Lang. 68 (3), 255–278.

Bates, D., Mächler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using lme4. J. Stat. Softw. 67 (1), 1–48. http://dx.doi.org/10.18637/jss.v067.i01.

Bialystok, E., 2006. Effect of bilingualism and computer video game experience on the Simon task. Can. J. Exp. Psychol./Revue canadienne de psychologie expérimentale 60 (1), 68.

Bialystok, E., DePape, A.M., 2009. Musical expertise, bilingualism, and executive functioning. J. Exp. Psychol. Hum. Percept. Perform. 35 (2), 565.

Blumenfeld, H.K., Marian, V., 2013. Parallel language activation and cognitive control during spoken word recognition in bilinguals. J. Cognit. Psychol. 25 (5), 547–567. http://dx.doi.org/10.1080/20445911.2013.812093.

Boersma, P., Weenink, D., 2004. Praat Version 4.2. 09. In Institute of Phonetic Sciences: Amsterdam.

Brainard, D.H., 1997. The psychophysics toolbox. Spat. Vis. 10, 433–436.

Chen, P., Marian, V., 2016. Bilingual spoken word recognition. In: Gaskell, M.G., Mirković, J. (Eds.), Speech Perception and Spoken Word Recognition. Psychology Press.

Clayson, P.E., Larson, M.J., 2011. Conflict adaptation and sequential trial effects: Support for the conflict monitoring theory. Neuropsychologia 49 (7), 1953–1961.

Colomé, À., Miozzo, M., 2010. Which words are activated during bilingual word production? J. Exp. Psychol. Learn. Mem. Cogn. 36 (1), 96.

Costa, A., Hernández, M., Sebastián-Gallés, N., 2008. Bilingualism aids conflict resolution: Evidence from the ANT task. Cognition 106 (1), 59–86.

De Groot, A.M., Delmaar, P., Lupker, S.J., 2000. The processing of interlexical homographs in translation recognition and lexical decision: Support for non-selective access to bilingual memory. Q. J. Exp. Psychol.: Section A 53 (2), 397–428.

Delorme, A., Makeig, S., 2004. EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. J. Neurosci. Methods 134 (1), 9–21.

Dijkstra, T., Timmermans, M., Schriefers, H., 2000. On being blinded by your other language: Effects of task demands on interlingual homograph recognition. J. Mem. Lang. 42 (4), 445–464.

Dijkstra, T., Van Heuven, W.J.B., 1998. The BIA model and bilingual word recognition. In: Grainger, J., Jacobs, A.M. (Eds.), Localist Connectionist Approaches to Human Cognition. Lawrence Erlbaum Associates, Mahwah, NJ, pp. 189–225.

Dijkstra, T., Van Heuven, W.J.B., 2002. The architecture of the bilingual word recognition system: From identification to decision. Bilingualism: Language and Cognition 5 (3), 175–197. http://dx.doi.org/10.1017/S1366728902003012.

Dijkstra, T., Van Jaarsveld, H., Ten Brinke, S., 1998. Interlingual homograph recognition: effects of task demands and language intermixing. Bilingualism: Language and Cognition 1, 51–66.

Durlik, J., Szewczyk, J., Muszyński, M., Wodniecka, Z., 2016. Interference and inhibition in bilingual language comprehension: evidence from polish-english interlingual homographs. PLoS ONE 11 (3), e0151430.

Elston-Güttler, K.E., Gunter, T.C., Kotz, S.A., 2005. Zooming into L2: Global language context and adjustment affect processing of interlingual homographs in sentences. Cognitive Brain Res. 25 (1), 57–70. http://dx.doi.org/10.1016/j.cogbrainres.2005.04.007.

FitzPatrick, I., Indefrey, P., 2014. Head start for target language in bilingual listening. Brain Res. 1542, 111–130. http://dx.doi.org/10.1016/j.brainres.2013.10.014.

Gabriel, K.R., 1969. Simultaneous test procedures–some theory of multiple comparisons. Ann. Math. Stat., 224–250

Green, D.W., 1998. Mental control of the bilingual lexico-semantic system. Bilingualism: Language and cognition 1 (02), 67–81.

Groom, M.J., Cragg, L., 2015. Differential modulation of the N2 and P3 event-related potentials by response conflict and inhibition. Brain Cogn. 97, 1–9.

---

[2] The reason why we performed separate analyses for homophone vs. non-homophone word pairs was that the experimental design was not balanced between homophone word pairs and non-homophone word pairs; all the word pairs in the homophone condition required "No" responses, while half of the non-homophone condition required "Yes" and the other half required "No" responses. Significant main effects of word type (homophone vs. non-homophone control) do not reflect the language co-activation effect of homophones, but rather the overall semantic relatedness difference.

[3] Significant pairwise comparisons can be masked because of the failure to reject the null hypothesis on an F test, which is referred to as nonconsonance (Gabriel, 1969; Hancock and Klockars, 1996).

Guo, T., Liu, H., Misra, M., Kroll, J.F., 2011. Local and global inhibition in bilingual word production: fMRI evidence from Chinese-English bilinguals. NeuroImage 56 (4), 2300–2309. http://dx.doi.org/10.1016/j.neuroimage.2011.03.049.

Hancock, G.R., Klockars, A.J., 1996. The quest for alpha: developments in multiple comparison procedures in the quarter century since Games (1971). Rev. Educ. Res. 66 (3), 269–306. http://dx.doi.org/10.3102/00346543066003269.

Hoshino, N., Kroll, J.F., 2008. Cognate effects in picture naming: does cross-language activation survive a change of script? Cognition 106 (1), 501–511.

Hoshino, N., Thierry, G., 2012. Do Spanish-English bilinguals have their fingers in two pies—or is it their toes? An electrophysiological investigation of semantic access in bilinguals. Front. Psychol. 3, 52–57.

Ju, M., Luce, P.A., 2004. Falling on sensitive ears: constraints on bilingual lexical activation. Psychol. Sci. 15 (5), 314–318.

Kang, K.H., Guion, S.G., 2006. Phonological systems in bilinguals: age of learning effects on the stop consonant systems of Korean-English bilingualsa). J. Acoust. Soc. Am. 119 (3), 1672–1683.

Kuipers, J.R., Thierry, G., 2010. Event-related brain potentials reveal the time-course of language change detection in early bilinguals. Neuroimage 50 (4), 1633–1638.

Kroll, J.F., 2008. Juggling two languages in one mind. Psychol. Sci. Agenda, APA 22 (1).

Kroll, J.F., Bialystok, E., 2013. Understanding the consequences of bilingualism for language processing and cognition. J. Cognitive Psychol. 25 (5), 497–514. http://dx.doi.org/10.1080/20445911.2013.799170.

Lagrou, E., Hartsuiker, R.J., Duyck, W., 2011. Knowledge of a second language influences auditory word recognition in the native language. J. Exp. Psychol. Learn. Mem. Cogn. 37 (4), 952.

Lopez-Calderon, J., Luck, S.J., 2014. ERPLAB: an open-source toolbox for the analysis of event-related potentials. Front. Hum. Neurosci. 8 (4), 1–14.

Luk, G., Anderson, J.A., Craik, F.I., Grady, C., Bialystok, E., 2010. Distinct neural correlates for two types of inhibition in bilinguals: response inhibition versus interference suppression. Brain Cogn. 74 (3), 347–357.

Luk, G., Bialystok, E., 2013. Bilingualism is not a categorical variable: Interaction between language proficiency and usage. J. Cognitive Psychol. 25 (5), 605–621.

Macizo, P., Bajo, T., Martín, M.C., 2010. Inhibitory processes in bilingual language comprehension: evidence from Spanish-English interlexical homographs. J. Mem. Lang. 63 (2), 232–244.

Marian, V., Blumenfeld, H.K., Kaushanskaya, M., 2007. The Language Experience and Proficiency Questionnaire (LEAP-Q): assessing language profiles in bilinguals and multilinguals. J. Speech Language Hearing Res. 50 (4), 940.

Marian, V., Spivey, M., 2003. Competing activation in bilingual language processing: within-and between-language competition. Bilingualism: Language and Cognition 6 (02), 97–115.

Martín, M.C., Macizo, P., Bajo, T., 2010. Time course of inhibitory processes in bilingual language processing. Br. J. Psychol. 101 (4), 679–693.

McLaughlin, J., Osterhout, L., Kim, A., 2004. Neural correlates of second-language word learning: minimal instruction produces rapid change. Nat. Neurosci. 7 (7), 703–704.

Mercier, J., Pivneva, I., Titone, D., 2014. Individual differences in inhibitory control relate to bilingual spoken word processing. Bilingualism: Language and Cognition 17 (1), 89–117. http://dx.doi.org/10.1017/S1366728913000084.

Mishra, R.K., Singh, N., 2014. Language non-selective activation of orthography during spoken word processing in Hindi-English sequential bilinguals: an eye tracking visual world study. Read. Writ. 27 (1), 129–151.

Misra, M., Guo, T., Bobb, S.C., Kroll, J.F., 2012. When bilinguals choose a single word to speak: electrophysiological evidence for inhibition of the native language. J. Mem. Lang. 67 (1), 224–237.

Nelson, D.L., McEvoy, C.L., & Schreiber, T.A., 1998. The University of South Florida word association, rhyme, and word fragment norms. http://www. usf. edu. FreeAssociation.[PubMed].

Oldfield, R.C., 1971. The assessment and analysis of handedness: the Edinburgh inventory. Neuropsychologia 9 (1), 97–113.

Orgs, G., Lange, K., Dombrowski, J.H., Heil, M., 2008. N400-effects to task-irrelevant environmental sounds: further evidence for obligatory conceptual processing. Neurosci. Lett. 436 (2), 133–137.

Osterhout, L., Holcomb, P.J., 1993. Event-related potentials and syntactic anomaly: evidence of anomaly detection during the perception of continuous speech. Language Cognitive Process. 8 (4), 413–437.

Paap, K.R., Johnson, H.A., Sawi, O., 2015. Bilingual advantages in executive functioning either do not exist or are restricted to very specific and undetermined circumstances. Cortex 69, 265–278.

Paller, K.A., Kutas, M., McIsaac, H.K., 1995. Monitoring conscious recollection via the electrical activity of the brain. Psychol. Sci. 6 (2), 107–111.

Pivik, R., Broughton, R., Coppola, R., Davidson, R., Fox, N., Nuwer, M., 1993. Guidelines for the recording and quantitative analysis of electroencephalographic activity in research contexts. Psychophysiology 30 (6), 547–558.

Polich, J., 2007. Updating P300: an integrative theory of P3a and P3b. Clin. Neurophysiol. 118 (10), 2128–2148.

Pratt, N., Willoughby, A., Swick, D., 2011. Effects of working memory load on visual selective attention: behavioral and electrophysiological evidence. Front. Hum. Neurosci. 5, 57.

Core Team, R., 2015. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Rossi, E., Newman, S., Diaz, M., Guo, T., & Kroll, J. F. (in preparation). There are no mental firewalls: fMRI evidence for global inhibition of the native language in bilingual speech.

Rugg, M.D., Furda, J., Lorist, M., 1988. The effects of task on the modulation of event-related potentials by word repetition. Psychophysiology 25 (1), 55–63.

Schroeder, S.R., Marian, V., Shook, A., Bartolotti, J., 2016. Bilingualism and musicianship enhance cognitive control. Neural Plasticity 2016.

Schwartz, A.I., Kroll, J.F., 2006. Bilingual lexical activation in sentence context. J. Mem. Lang. 55 (2), 197–212.

Shook, A., Marian, V., 2013. The bilingual language interaction network for comprehension of speech. Bilingualism: Language and Cognition 16 (2), 304–324. http://dx.doi.org/10.1017/S1366728912000466.

Thierry, G., Wu, Y.J., 2007. Brain potentials reveal unconscious translation during foreign-language comprehension. Proc. Natl. Acad. Sci. 104 (30), 12530–12535.

Van Hell, J.G., Dijkstra, T., 2002. Foreign language knowledge can influence native language performance in exclusively native contexts. Psychon. Bull. Rev. 9 (4), 780–789.

Van Hell, J.G., Tanner, D., 2012. Second language proficiency and cross language lexical activation. Language Learning 62 (s2), 148–171.

Veivo, O., Järvikivi, J., 2013. Proficiency modulates early orthographic and phonological processing in L2 spoken word recognition. Bilingualism: Language and Cognition 16 (04), 864–883.

Wu, Y.J., Thierry, G., 2013. Fast modulation of executive function by language context in bilinguals. J. Neurosci. 33 (33), 13533–13537.