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Neural correlates of bilingual language control during interlingual homograph processing in a logogram writing system

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ABSTRACT

Bilingual studies using alphabetic languages have shown parallel activation of two languages during word recognition. However, little is known about the brain mechanisms of language control during word comprehension with a logogram writing system. We manipulated the types of words (interlingual homographs (IH), cognates, and language-specific words) and the types of participants (Chinese (L1)-Japanese (L2) bilinguals vs. Japanese monolinguals). Greater activation was found in the bilateral inferior frontal gyri, supplementary motor area, caudate nucleus and left fusiform gyrus, when the bilinguals processed IH, as compared to cognates. These areas were also commonly activated when the bilinguals processed L2 control words during an L1 lexical decision task. The areas function as the task/decision system that plays a role in cognitive control for resolving response conflict. Furthermore, the anterior cingulate cortex, left thalamus, and left middle temporal gyrus were activated during IH processing, suggesting resolution of the semantic conflict at the stimulus level (i.e., one logographic word having different meanings in the two languages).

1. Introduction

Psycholinguistic studies of bilingual language processing generally agree that representations from different languages are simultaneously activated and compete with each other (Kroll, Dussias, Bice, & Perrotti, 2015; van Heuven & Dijkstra, 2010). If this is the case, bilingual individuals must resolve this linguistic conflict during comprehension, which likely requires a great deal of cognitive effort. However, most bilinguals seem to attend to appropriate target representations or language quickly and efficiently during language comprehension. Bilinguals are thought to be able to select a target language using highly efficient cognitive control; that is, they select or inhibit an activated mental lexicon based on certain contexts (Green, 1998; van Heuven & Dijkstra, 2010). However, two major issues must be considered. First, the exact brain mechanisms that underlie the ultimate selection of an appropriate language under interference during bilingual comprehension remain unclear. Second, there is debate as to whether this processing can be generalized to the logogram systems of the Japanese or Chinese languages because a majority of previous studies have used alphabetic languages, such as English and Spanish. Logogram systems are unique and quite different from alphabetic languages in that they share similar orthographic properties, which are invented on the basis of meanings, but the phonology of each language develops differently. Thus, the present study attempted to examine the precise neural mechanisms underlying the resolution of conflict during word recognition in Chinese-Japanese bilinguals using the unique characteristics of different word types (e.g., interlingual homographs (IHs), cognates, and control words).

So far, one type of evidence of parallel activation of the two languages in bilinguals has typically turned out to be cross-language interference or facilitation, when bilinguals process a particular type of word, such as interlingual homographs and cognates, because these kinds of words have unique cross-linguistic characteristics (Studnitz & Green, 2002; van Heuven & Dijkstra, 2010). Most studies investigating this issue have assessed the processing of single words out of context rather than when reading natural

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text. In the lexical decision test, IHs (e.g., boom in English means tree in Dutch), which have the same orthographic form but different representations in the two languages, produced longer reaction times than cognate words (e.g., hotel in both English and Dutch), which have identical shapes and representations (Dijkstra, Bruijn, Schriefers, & Brinke, 2000; Dijkstra, Grainger, & van Heuven, 1999). Because two different representations of IHs are activated simultaneously in the bilingual brain, cross-language interference occurs during the comprehension of these words. This parallel activation of two languages is also supported by neurolinguistic evidence. An event-related potential (ERP) study conducted by Kerkhofs, Dijkstra, Chwilla, and de Bruijn (2006) reported that the N400 amplitude is influenced by word frequency during the reading of IHs in both Dutch and English, which indicates the parallel activation of two languages. Neuroimaging studies have also observed greater activation in the left inferior frontal gyrus (IFG) during the reading of IHs than during the reading of control words (van Heuven, Schriefers, Dijkstra, & Hagoort, 2008).

Despite the increasing amount of neurolinguistic evidence supporting the activation level of each language during recognition, it is important to consider the extent to which this parallel cognitive processing is influenced by factors such as language context (single or dual language), task demand, sentence condition, and language proficiency (Bultena, Dijkstra, & Van Hell, 2013; Dijkstra et al., 2000; Wu & Thierry, 2010). For example, Dijkstra et al. (2000) reported greater interference effects of interlingual homographs when Dutch (L1)-English (L2) bilinguals performed an L2 (English) lexical decision task with intermixed L1 (English) and L2 (Dutch) stimuli than in a task with only L2 (English) stimuli. Furthermore, bilinguals exhibit a significant enhancement in language conflict during lexical decision tasks than during a perceptual identification task due to the different demands of lexical access between the tasks (Macizo, Bajo, & Martín, 2010; van Heuven et al., 2008). When bilinguals process their less dominant language (L2), their dominant language (L1) likely influences L2 and results in greater interference during L2 processing, which reflects sensitivity to language proficiency (Bultena et al., 2013; Van Hell & Tanner, 2012). Thus, non-linguistic factors such as task demands and context may also influence the degree of non-selective language activation and performance in bilinguals.

The Bilingual Interactive Activation (BIA) and BIA Plus (BIA+) models (Dijkstra & van Heuven, 1998, 2002) have been proposed to explain how bilinguals select appropriate target meanings or language during the parallel activation of two languages in the word recognition task. The BIA model (Dijkstra & van Heuven, 1998) explains language control during the parallel activation of two languages such that bilingual word recognition is accomplished in a non-selective manner across four levels: feature level, letter level, word level, and language node level. Once the features of the words in each position are analyzed, they activate lexical items in different languages that are integrated at the word level. At this level, the lexicons are mutually connected with each other and this connection makes the lexicons compete with each other either within or between languages (Dijkstra & van Heuven, 1998). Finally, once a representation of a word in a language is activated, language nodes can suppress the other language (Thomas & Van Heuven, 2005). Thus, in the BIA model, it is essential to use both bottom-up access and top-down inhibition from language nodes during bilingual word recognition.

The BIA+ model (Dijkstra & van Heuven, 2002) is the successor of the BIA model and consists of a word identification system and a task/decision system. According to this newer model, the word identification system is associated with bottom-up activation of lexical representation (e.g., orthographic, semantic, and phonological information) while the task/decision system is involved in response regulation and selection during word comprehension. Because the word identification system is independent of the task/decision system, neither the language nodes nor non-linguistic characteristics, such as task demands or types of response, can influence bilingual word recognition directly. According to the BIA+ model, the two languages of the IHs are activated non-selectively and these representations compete with each other in the word identification system. Executive control processes at the level of the decision system then guide appropriate lexical selection. Recent neuroimaging data are consistent with the BIA+ model, in that the executive control network is associated with the task/decision system and the lexical semantic network is related to the word identification system (van Heuven & Dijkstra, 2010; van Heuven et al., 2008).

Based on the BIA+ framework, a previous neuroimaging study (van Heuven et al., 2008) investigated brain mechanisms of language control underlying interlingual homograph processing with different task demands. In their study, two Dutch groups who learned English as their L2 performed a general lexical decision test (GLD) and an English (L2) lexical decision test (ELD). Both tests were composed of interlingual homographs, exclusively English control words, and pseudo-words (PW). In the GLD test, participants were instructed to press a button if the stimuli on screen were real words, but they only needed to respond to English words in the ELD test. As a result, the left IFG was associated with the processing of IHs in both the GLD and ELD tests due to the parallel activation of both readings of the homographs. These authors suggested that the activation in the IFG reflected stimulus conflict in the word identification system. Additionally, the pre-supplementary motor area (pre-SMA) and anterior cingulate cortex (ACC) were activated in the ELD test, which suggests that control of the response conflict is part of the task/decision system. Indeed, the SMA and ACC have frequently been implicated in brain circuits underlying bilingual cognitive control by many neuroimaging studies that used tasks such as language switching or picture naming (Abutalebi & Green, 2016; Luk, Green, Abutalebi, & Grady, 2011).

Although van Heuven et al. (2008) demonstrated that response conflict induced by task demands is implemented outside language-related systems, whether or not the top-down control system affects the lexical representation system during word recognition remains controversial (van Heuven & Dijkstra, 2010). Rodriguez-Fornells, Rotte, Heinze, Nösselt, and Münte (2002) reported that words from a non-target language are rejected at an early stage (i.e., prior to semantic analysis) in bilinguals. In that study, the brain responses of Spanish-Catalan bilingual and monolingual groups were examined using ERP and functional magnetic resonance imaging (fMRI) as the subjects performed go/no–go tasks. Spanish, Catalan, and PWs were presented randomly and the subjects were instructed to respond to the word in the target language according to whether the word began with a vowel or a consonant but to ignore words in the non-target language and PWs. The ERP data revealed that the non-target language did not show the N400 word-frequency effect that typically appears during the semantic access of words. However, this task required focusing on the sound of the first letter of a word, which may have influenced the manner in which the subjects accessed lexical representations. The fMRI data revealed involvement of the left prefrontal cortex, including the IFG, in response to both non-target and PWs that required no-go responses. These findings indicate that cognitive control induced by response conflict occurred because there was no difference between the non-target words and PWs in terms of brain activation patterns.

The findings of Rodriguez-Fornells et al. (2002) support the idea that the type of task influences the processing of words. Similarly, the results of a recent ERP study (Hoversten, Brothers, Swaab, & Traxler, 2015) showed that top-down access requires the use of language nodes to modulate language processing based on task demands. Hoversten et al. (2015) employed a go/no-go paradigm in language membership and semantic classification tasks and demonstrated that language membership identification precedes semantic access and that the non-target language was suppressed in the language membership task. These findings suggest that top-down access uses language nodes to modulate language processing according to task demands and support the BIA model rather than BIA+ model.

Despite the publication of theoretical accounts and empirical studies investigating bilingual word processing, little is known about the brain mechanisms by which these control systems manage the activation of two languages such that interference from the non-target language can be avoided during word recognition. Additionally, the brain mechanisms that support selection of the appropriate meaning of IHs remain unclear. To date, neuroimaging studies investigating language control in bilinguals have frequently used switching or production tasks and reported activation in the left prefrontal cortex, ACC, SMA, and left caudate nucleus. These areas all play roles in executive, inhibitory, and monitoring control functions and are implemented in a top-down manner (Abutalebi & Green, 2016; Luk et al., 2011). In fact, contrary to language production processes, visual word recognition processes may be strongly driven by lexical input, as well as being influenced by top-down control depending on the type of task (Dehaene & Cohen, 2011). Furthermore, imaging studies evaluating the conflict resolution of visual stimuli have shown that general cognitive control mechanisms are carried out with top-down adjustments from the left prefrontal cortex and bottom-up input from the visual sensory cortex during conflict resolution with visual stimuli (Egner & Hirsch, 2005; Jahfari, Waldorp, Ridderinkhof, & Scholte, 2015). Because IHs are characterized by one orthographic form having two representations across two languages, the stimulus itself may induce conflict (van Heuven & Dijkstra, 2010; van Heuven et al., 2008). Thus, stimulus conflict may arise in the lexical representation system, including the visual word recognition system, which may cooperate with top-down control processes to resolve the conflict.

Furthermore, in the abovementioned van Heuven et al. (2008) study, two groups of Dutch speakers who had learned English as their L2 performed a language decision task in L2, which is their less-skilled language, and experienced the cross-language interference effect. This result is in line with those of a majority of previous bilingual studies, which demonstrated that the dominant language (L1) is likely to influence the less dominant language (L2; e.g., Dijkstra & van Heuven, 2002; Jeong et al., 2007; Kerkhofs et al., 2006; Van Hell & Tanner, 2012). Given the evidence for the automatic and unconscious activation of L1 during L2 word recognition (Thierry & Wu, 2007), interference from L1 during L2 processing cannot be avoided. Although a facilitation effect of cognates during L1 sentence processing has been reported previously (Van Assche, Duyck, Hartsuiker, & Diependaele, 2009), whether the later-learned intermediate level of L2 impacts L1 word recognition processing in the brain, especially in terms of the interference effect of IHs, remains to be clarified. To expand previous findings and further elucidate this issue, the present study required L2 learners who had achieved an intermediate level of L2 proficiency to perform an L1 lexical task.

A remaining issue is that most of the previous behavior and neuroimaging studies on IH processing among bilinguals (Kroll et al., 2015; van Heuven & Dijkstra, 2010) have been conducted using Indo-European languages in which the written representations involve alphabetic systems. Most European languages have strong alphabetical overlaps and similar grapheme-phoneme correspondence rules (Dijkstra et al., 1999; Schwartz, Kroll, & Diaz, 2007). In contrast, logogram systems, such as Chinese 'Hanzi' and Japanese 'Kanji', were originally invented based on meanings and retain morphographical functions even though phonological conversion rules have developed independently (Chen, Yamauchi, Tamaoka, & Vaid, 2007; Tamaoka, 1991). Because the Japanese language has adopted many Chinese characters, both Japanese and Chinese speakers can understand the majority of characters in both languages and directly decode the meaning without necessarily knowing the corresponding sounds. For example, cognates share identical orthographic forms and meanings in both Chinese and Japanese (e.g., 銀行 means "bank" in both languages) while IHs possess identical orthographic forms but different meanings in these two languages (e.g., the characters 汽車 mean "car" in Chinese but "train" in Japanese). In terms of phonological information, both IHs and cognates have different phonological representations in the two languages (e.g., 銀行: /yínháng/ in Chinese, /ginkou/ in Japanese). Xu (2014) quantitatively analyzed Japanese-Chinese homographs and reported that the population of cognates is much larger than that of IHs. This type of script similarity helps native Chinese speakers to learn Japanese Kanji as their L2 relatively easily (Tamaoka, Kiyama, & Chu, 2012). Thus, script similarity may enhance the learning of each language, but this similarity may also cause greater cross-language interference during the processing of interlingual homographs. Indeed, bilinguals whose two languages have a large degree of orthographic overlap tend to engage in greater executive control to manage their languages than bilinguals whose languages do not overlap (Coderre & van Heuven, 2014). Furthermore, properties of logographic characters such as semantic-orthographic conversion may facilitate greater activation in the left inferior temporal areas along with the left prefrontal cortex when semantic conflict increases (Coderre, Filippi, Newhouse, & Dumas, 2008; Nakamura et al., 2010). Thus, we hypothesized that, in terms of the interference effect, the present study using the logographic writing system would be consistent with previous studies using alphabetic languages but there would be some differences in the neural mechanisms and brain areas involved in word recognition.

Thus, the present study investigated language control in the bilingual brain from the perspectives of stimulus conflict and response conflict during word recognition and the manner in which bilinguals resolve instances of semantic conflict induced by the inherent characteristics of IHs. The present study also aimed to confirm whether previous findings of bilinguals using alphabetic languages could be generalizable to logogram systems, such as Japanese or Chinese. To do this, we recruited Taiwanese subjects who had learned Japanese as their L2 and asked them to perform an L1 lexical decision task because Chinese in Taiwan and Japanese share the same orthographic form; Japanese monolinguals were included as a control group.

Five types of words were selected based on the characteristics of the two languages by controlling the familiarity, frequency, and visual complexity of the words: IHs, cognates (CO), Chinese control words that exist only in Chinese (CC), Japanese control words that exist only in Japanese (JC), and PWs that do not exist in either language. During the L1 lexical decision task, bilinguals were required to respond with YES (i.e., acceptance) to IH, CO, and CC words but to respond with NO (i.e., rejection) to JC words and PWs; PWs do not have any lexical representation in either language. By manipulating the task requirements and types of words, four real word conditions (IH, CO, CC, and JC) that exhibited different characteristics in terms of response-level and stimulus-level conflicts during an L1 lexical decision task in bilinguals were created.

The present study primarily focused on the differences between IHs and COs to examine the brain mechanisms involved in the resolution of the semantic conflict of IHs. IHs and COs belong to both Japanese and Chinese and share the same orthographic form, but only IHs have different meanings in the two languages. It was assumed that the cognitive demands of the IH and CO words did not differ in terms of phonological representation because IHs and COs have different phonological representations in the two languages due to the independent phonological conversion rules of each language. Thus, IHs may produce semantic conflict due to the two meanings of one orthographic form. Furthermore, recognition of IHs in bilinguals may enhance semantic conflict as well as cause a response conflict because the non-target representation (L2) of IHs might also evoke a tendency to respond NO during the L1 lexical decision task (van Heuven & Dijkstra, 2010; van Heuven et al., 2008).

At the response level, JCs require a NO response for bilinguals in the L1 (Chinese) lexical decision task because bilinguals know JC words as L2 words and, thus, cognitive control processing induced by response conflict will likely increase. Furthermore, the intermixing of the JCs had two benefits. First, when Chinese (L1)-Japanese (L2) bilinguals process L2 (Japanese) control words in the L1 lexical decision task, the activation level of their L2 may be strengthened. This would enable us to see any increasing cross-language interference effect. Second, the processing L2 (Japanese) control words requires controlling and suppressing of competing responses when Chinese-Japanese bilinguals correctly reject L2 words in the L1 lexical decision tasks because the responses should be opposite to the requirements of the intended task (Green, 1998, for a review, see Abutalebi & Green, 2016). This processing is crucial because the language information of JCs is used by the task/decision system, which is outside the word identification according to the BIA+ model. Based on the work of van Heuven et al. (2008) and other neuroimaging studies of bilingual language control (Abutalebi & Green, 2016; Luk et al., 2011), task/decision system, including the left prefrontal cortex, ACC, SMA, and caudate nucleus may be involved in the processing of JCs during the L1 lexical task due to the response conflict.

It was first hypothesized that some of the cognitive control areas underlying the processing of IHs may be shared with those involved in the processing of JCs and would be found within the task/decision system. Second, specific brain areas associated with the resolution of the semantic conflict of IH processing may be observed due to the inherent characteristics of IHs relative to other types of real words (CO, CC, and JC). Thus, it was expected that the cognitive control system (i.e., the task decision system) and the word identification system would cooperate to achieve resolution of the semantic conflict of IHs. Additionally, to further investigate the effects of language membership demonstrated by Hoversten et al. (2015), brain activation to COs versus that to CCs was evaluated in bilinguals. While COs belong to both Japanese and Chinese, CCs exist only in the Chinese language and, thus, would not produce any conflict at either the response level or stimulus level for bilinguals during the L1 lexical decision task.

In contrast, it was hypothesized that the interference effect of IHs and the resolution of semantic conflict would not be observed among Japanese monolinguals. Furthermore, there would be no conflict at either the stimulus level or response level in the real word conditions (IH, CO, and JC) during the L1 (Japanese) lexical decision task because monolinguals do not understand Chinese. Although we did not directly compare our findings with those of studies using alphabetic languages, we assumed that native Chinese speakers might experience greater interference between the two languages during IH processing in wider brain areas associated with orthographic and semantic connections.

2. Materials and methods

2.1. Subjects

In this study, the Chinese learners of Japanese were considered the bilingual group, and the native speaker of Japanese, the monolingual group. The bilingual group included 28 right-handed Taiwanese (13 males, 15 females) who were native speakers of Chinese and had learned Japanese as L2. At the time of the experiment, all of the bilinguals were undergraduates, graduate students, or postdoctoral researchers, and their mean (±SD) age was 24.64 ± 3.47 years old. They had started learning Japanese at the mean (±SD) age of 20.72 ± 3.56 years. The bilingual groups' mean period of living in Japan was 12.07 months (range, 1 month to 3 years). All of the bilinguals were required to take the Japanese Language Proficiency Test N2 (JLPT N2, the Japan Foundation and Japan Educational Exchanges and Services) before the fMRI experiment to demonstrate sufficient proficiency in Japanese to perform the experimental tasks. The monolingual group consisted of 26 right-handed native speakers of Japanese (19 males, 7 females) who did not understand Chinese at all at the time of the experiment. All of the monolinguals were undergraduate or graduate students; their mean (±SD) age was 21.81 ± 1.36 years old. Participants in both groups were required to take the Raven test to ensure that their intelligence quotient (IQ) was normal. All participants were right-handed, with normal hearing, and either normal or corrected-to-normal vision, with either Chinese or Japanese as their first language, and with no neurological or psychiatric history. This study was conducted with the approval of the institutional review board of the Graduate School of Medicine, Tohoku University in Sendai, Japan. Written informed consent was obtained from each participant before scanning took place.

2.2. Stimuli

We created five types of two-character words for the experiment: interlingual homographs (IH) with identical orthographic forms but different semantic and phonological representations between Chinese and Japanese, cognates (CO) with identical forms and semantic representations but different phonological representations in Chinese and Japanese, control words for each language that exist only in Chinese (CC) or Japanese (JC), and pseudowords (PW) that do not exist in either language but follow the orthographic rules of both languages. As far as language membership is concerned, representations of IH and CO belong to both languages. The following pilot tests were conducted to control familiarity in both languages: real words (IH, CO, CC, and JC) were first collected from the corpora (ChineseTaiwanWac and JpWac) on Sketch Engine (http://www.sketchengine.co.uk). The native speakers of each language (Chinese: 20, Japanese: 20) who did not participate in the experiment were invited to take a seven-point scale-rating test (7 = most familiar to 1 = not familiar), and the words with mean scores above 4 in the rating test were selected as the candidates of experimental stimuli. The objective frequency was controlled across conditions in Chinese (mean: IH = 43.74; CO = 57.99; & CC = 36.59 per million, $F[2,217] = 1.129$, $P = 0.325$) and Japanese (mean: IH = 30.62; CO = 39.92; & JC = 31.33 per million, $F[2,217] = 0.500$, $P = 0.608$), and these frequencies matched across these two languages ($P = 0.263$). In order not to result in bias from the visual complexity of the stimuli, the number of strokes across conditions was also controlled (mean: IH = 18.46; CO = 18.92; CC = 18.78; JC = 18.15). No difference was observed from both Chinese ($F(2,217) = 0.115$, $p = 0.892$) and Japanese stimuli ($F(2,217) = 0.384$, $p = 0.681$). However, Garlock, Walley, and Metsala (2001) suggested that objective counting might result in underestimating low-frequency words, further restricting range effects. In order to ensure that our participants were really familiar with the stimuli, all of them were required to do rating tests after the fMRI experiments. One-way ANOVA was conducted to analyze both the Chinese-Japanese bilinguals and the Japanese monolinguals' seven-point scale rating tests for real words in their L1 (bilinguals: IH, CO, CC; monolinguals: IH, CO, JC). No significant difference was found among real words in Chinese (mean: IH = 6.47; CO = 6.55; CC = 6.66, $F(2,63) = 0.639$, $P = 0.531$) or Japanese (mean: IH = 6.32; CO = 6.30; JC = 6.49, $F(2,63) = 0.669$, $P = 0.516$). This suggests that the participants' familiarity with the stimuli did not differ and their judgments were not influenced by familiarity with the words.

The phonological similarities are low between Chinese and Japanese, even though both languages belong to the tonal language (Kuo, 2015). The phonological structure in Japanese is simpler than Chinese. For instance, Chinese native speakers can use the glides [i], [ɥ], and [w] to construct phonological structures. The phonological structures (C)V and (C)GV are both acceptable in Chinese, such as /ʂā/ "kill" (CV) and /ʂwā/ "wash" (CGV). In contrast, (C)V is the only acceptable phonological structure in Japanese, e.g., /momó/ "thigh" (CVCV). Moreover, Kuo (2015) indicates that the Chinese tone and Japanese accent are different from each other. Chinese tone can influence representations in monosyllables, such as /mā/ "mother," /má/ "hemp," /mǎ/ "horse," and /mà/ "blame." However, the Japanese accent can affect at least disyllables. For instance, /mómo/ represents "peach," but /momó/ represents "thigh." From the aforementioned examples, we suggest that the Chinese phonological structure is distinct from the Japanese, unlike the phonological overlap in Indo-European languages.

The logograms in Chinese characters and Japanese Kanjis can be combined into different characters such as compound ideographs and phono-semantic compound characters. We followed the orthographic rules of these two writing systems to create pseudowords. For instance, both Chinese and Japanese native speakers are able to recognize the logograms 多 "many," 辶 "walk," 口 "mouth," and 平 "flat." However, the combination of the logograms 迻 and 呯 cannot be represented in either Chinese characters or Japanese Kanjis, and the pseudo-word 迻呯 does not exist in either writing system. Finally, 340 stimuli were collected for the experiment (IH: 60 words, CO: 100 words, CC: 60 words, JC: 60 words, and PW: 60 words). Stimuli were divided into two sets (170 stimuli, IH: 30 words, CO: 50 words, CC: 30 words, JC: 30 words, and PW: 30 words) and each set was used for the current study and for a different purpose of the experiment with the same participants. Two sets were counterbalanced between the experiments.

2.3. Tasks

In the fMRI experiment, both bilinguals and monolinguals performed a lexical decision test, which asked them to determine whether the stimuli belonged to their L1 or not; that is, bilinguals needed to focus on Chinese, but monolinguals had to focus on Japanese in the fMRI experiment, using the four types of real words (IH, CO, JC, CC) and PW. Both written and oral instructions for the experiment were given to the participants in their L1. Participants were not informed about the differences between types of words in the L1 decision task. The participants were required to press the "Yes" button with the index finger of their right hand if the stimulus belonged to their L1; in contrast, they used the "No" button with their left hand to reject it. Thus, bilinguals accepted IH, CO, and CC because these three types of words are real words in Chinese; in contrast, monolinguals should accept IH, CO, and JC because these types of words exist in Japanese. Under these conditions, IHs, which have different representations in the two languages, would require both response conflict and stimulus conflict for the bilingual group to match the task requirement, but this would not be the case for the monolingual group. However, while bilinguals should make "No" response to JCs, monolinguals should make a "No" response to CCs because the subjects were required to perform the L1 lexical decision task. Finally, under PW as a control condition, both groups were asked to make a "No" response because the characters were meaningless in both Chinese and Japanese. In the PW condition, we did not assume that there was a different cognitive demand between the two groups. Table 1 shows these required responses for each type of word by bilinguals and monolinguals.

An event-related design was used in this experiment, and each trial began with the presentation of a white fixation point (+) on a black background, randomly, for 2–5 s, and then each word was presented for 2 s. Each stimulus was presented in random order in the lexical decision test and participants were required to make decisions within 2 s. The total experiment time was 900 s (Fig. 1). Before the fMRI experiment, instructions were provided to participants to minimize head movement during fMRI scanning, and participants performed 10 practice trials inside the MRI scanners to become familiar with the experimental procedure and learn how to keep their heads stable. Head movement was also limited using a foam rubber pad and a head-restraining belt. The timing of this experiment (word presentation, response time, and button press) was recorded digitally using E-Prime 2.0 (Psychology Software Tools, Inc.). After the fMRI experiment, the participants were required to fill in a seven-point scale-rating test for the experimental stimuli to ensure that their familiarity across the stimuli did not differ (see stimuli section).

2.4. Data acquisition and preprocessing

Scanning was performed using a 3.0-T Philips Achieva system (Eindhoven, the Netherlands). Functional images were acquired with the following parameters: echo time = 30 ms, flip angle = 90°, slice thickness = 3.75 mm, field of view = 240 mm, and a 64×64 matrix. In total, 34 slices from scanning the entire brain were obtained every 2 s, and 437 volumes were acquired for each participant after stabilization of the T1 saturation effect. T1-weighted anatomical images (thickness = 1 mm, field of view = 256 mm, 192×224 matrix, repetition time = 1900 ms, echo time = 3.93 ms) were obtained from each participant to serve as a reference for anatomical correlates. The following preprocessing procedures were conducted using Statistical Parametric Mapping software (SPM12, Wellcome Department of Imaging Neuroscience, London, UK) and Matlab (Mathworks, Natick, MA, USA). Functional volumes were spatially realigned to the first EPI volume. The anatomical T1 image was co-registered to the mean EPI image, which had been

Table 1
Mean reaction time (RT) and accuracy in each condition.

Required response in L1 task	Bilinguals			Monolinguals		
	Type of word	RT (ms)	Accuracy (%)	Type of word	RT (ms)	Accuracy (%)
"YES" response	IH	986.9 (±129.3)	90 (±6.66)	IH	903.5 (±147.6)	98 (±2.43)
	CO	853.1 (±93.3)	99 (±2.31)	CO	884.8 (±140.8)	97 (±2.27)
	CC	865.4 (±108.4)	99 (±0.86)	JC	866.5 (±162.1)	98 (±2.64)
"NO" response	JC	1134.1 (±139.3)	94 (±4.44)	CC	1303.2 (±226.8)	76 (±12.82)
	PW	953.1 (±211.6)	98 (±6.47)	PW	1006.9 (±200.2)	98 (±2.58)

IH: interlingual homographs, CO: cognates, CC: Chinese control words, JC: Japanese control words, PW: pseudo-words.

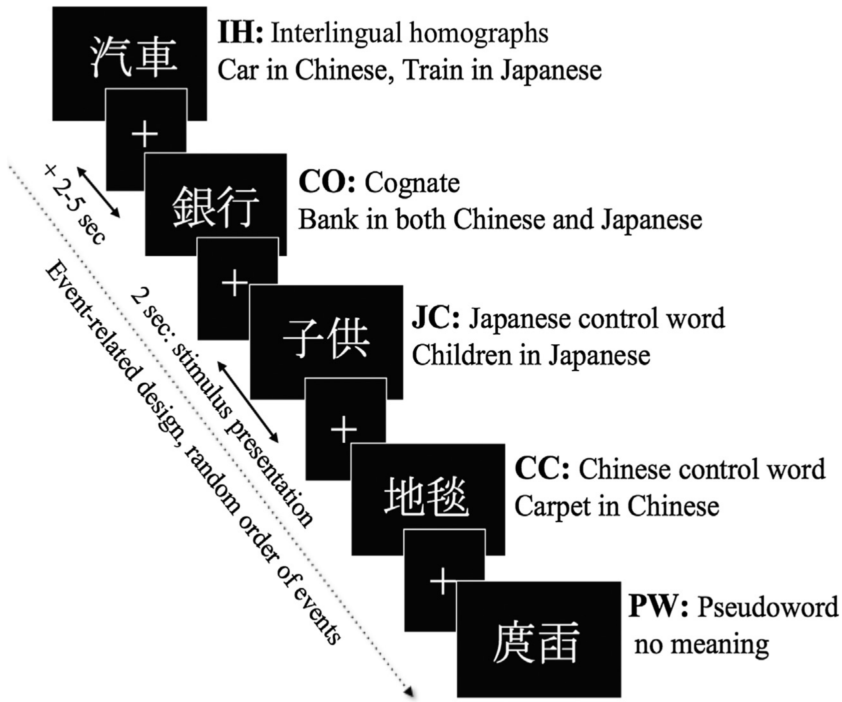

Fig. 1. Experimental design: event sequence used for the fMRI task.

generated during the realignment step and then normalized spatially to the Montreal Neurological Institute (MNI) space. To spatially normalize all EPI scans to the MNI space, we applied the deformation field parameters that were obtained during the normalization of the anatomical T1 image. The original resolution of the different images was maintained during normalization ($3 \times 3 \times 3$ mm^3 for EPI images). After the normalization procedure, EPI images were smoothed spatially with an 8-mm full-width-at-half-maximum isotropic Gaussian kernel. Imaging data for 22 of the 28 bilinguals and 22 of the 26 monolinguals were included in the final analysis, based on their L2 proficiency, head movement, and accuracy rate in the fMRI task. Four bilinguals were excluded because they did not reach JLPT level 2, which was used as a Japanese proficiency test. We also excluded two participants from each group due to excessive head movement during fMRI scanning (>3 mm). Finally, two participants from the monolingual group were excluded because they showed less than a chance level (<50%) of accuracy under any condition among the five types of words.

2.5. fMRI analysis

We used SPM12 to conduct a conventional two-level analysis for event-related fMRI data. In the first-level analysis, the functional imaging data from each subject were analyzed through a general linear model to analyze hemodynamic responses and the timing of the response to the stimulus was set as the onset time of a trial because time is essential for participants to generalize meanings and make decisions. Incorrect answers might have resulted from unawareness of the differences between Chinese and Japanese, further leading to wrong interpretations of meanings from the stimuli; thus, only correct responses from each subject were accepted in this analysis. Five regressors from each condition (IH, CO, CC, JC, and PW) were created to model hemodynamic responses, where incorrect trials across conditions were modeled as errors separately. Six movement parameters (three translations, three rotations) were also included as regressors of no interest. A high-pass filter with a cut-off period of 128 s was used to eliminate an artifactual low-frequency trend. First, contrast images of each real word condition (IH, CO, CC, and JC) were prepared for the second-level analysis to examine the effects of IHs in each group. Second, to compare the IH effects between groups, contrast images ([IH vs. CO] and [IH vs. language control condition]; which included CCs for bilinguals and JCs for monolinguals) were created. Finally, contrast images between each condition versus PWs were created as a baseline to illustrate the activation patterns in each condition. Because it was assumed that there would be no difference in the cognitive demand for PWs between groups, PW could act as a stable baseline.

2.6. Effect of word type in the bilingual group

To investigate the effect of IHs in each group, a repeated measure one-way analysis of variance (ANOVA; subtraction and conjunction analyses [conjunction null]) was performed with the four real word conditions (IH, CO, CC, and JC) in the bilingual group for the second-level random-effects analysis. Several statistical contrasts were tested: First, the different activation patterns among the YES response conditions (IH, CO, and CC) were evaluated because these three word types have different characteristics between Chinese and Japanese in bilinguals, in terms of lexical representation. The contrasts [IH > CO] and [IH > CC] were tested to examine the effect of IHs in both stimulus conflict and response conflict. The contrast [CO > CC] was tested to determine the brain areas associated with language membership.

Second, to evaluate whether the brain areas involved in the [IH > CO] contrast were shared with those of the JC condition involved in response conflict, we conducted conjunction analysis (conjunction-null) using the statistical maps [IH > CO] (logical) and [JC > CO]. While the *t*-contrast analysis displays the mean of a linear combination of the regressors and can potentially show only significant activations in one condition, the conjunction null hypothesis method identifies voxels that are deemed to be statistically significant in all components (Nichols, Brett, Andersson, Wager, & Poline, 2005). Thus, this analysis enabled the identification of common brain areas associated with cognitive control induced by response conflict in both contrasts.

Third, to identify brain areas showing significantly higher activation under the IH condition than with the other three types of words (CO, CC, and JC), we estimated the contrast [IH > CO] with two inclusive masks: [IH > JC] and [IH > CC]. This enabled the identification of brain areas involved in resolution of semantic conflict induced by IHs. A masking procedure was applied to limit the analysis of the main contrast to the areas showing significant activation in the mask contrast at a liberal statistical threshold (height threshold $p < 0.05$, uncorrected).

Although there was no assumption that the monolingual subjects showed different activation among the YES response conditions (IH, CO, and JC), comparisons between these conditions were tested to confirm the absence of an effect.

2.7. Group comparisons between bilingual and monolingual subjects

To examine the effect of IHs between groups, the contrast [IH > CO] was compared between groups, and the contrast [IH > CC] in bilinguals and the contrast [IH > JC] in monolinguals were compared with independent two-sample *t*-tests. Based on the whole-brain analysis, a region of interest (ROI) analysis was conducted on observed brain areas to compare the activation pattern across conditions. We extracted the parametric estimates of the activation peak of the observed brain area under each condition versus PW and tested the significance at a region-level threshold ($P < 0.05$, without correction for multiple comparisons) using SPSS software (ver. 23.0; SPSS Inc., Chicago, IL).

The statistical parameter map of the *t*-values was set at a voxel-level threshold of $P < 0.05$ FDR (Genovese, Lazar, & Nichols, 2002). The resulting activation maps were superimposed on the standard T1-weighted MR image. Activation coordinates (MNI) were provided by SPM, with anatomical labeling obtained using automatic anatomical labeling software (Tzourio-Mazoyer, Landeau, & Papathanassiou, 2002).

3. Results

3.1. Lexical decision task

In the reaction time (RT) analysis, incorrect responses were excluded because it may have influenced the experimental results. Table 1 shows RT and accuracy rates in each condition for both groups, along with required responses during the L1 lexical decision task. To evaluate the differences in RT across conditions in the bilinguals, a one-way ANOVA was conducted. A significant difference in RT was observed ($F(3,63) = 17.32$, $p < 0.001$). *Post hoc* pair-wise comparison showed significantly longer reaction times for IHs than (COs ($t = 6.00$, $P < 0.001$), exclusively Chinese control words ($t = 5.50$, $p < 0.001$) and exclusively Japanese control words than CO ($t = 4.30$, $P < 0.001$) and CC ($t = 5.72$, $p < 0.001$), but there was no significant difference between CO and CC ($t = 0.54$, $p = 0.59$) or IH and JC ($t = 0.36$, $p = 0.72$). That is, although bilingual subjects were required to respond with the YES button in IH, CO and CC, they took longer to process IH than other conditions, but IH showed similar reaction times to the JC condition that required a NO response. In contrast, in the Japanese monolingual group, this tendency was not observed between IH and CO ($t = 1.73$, $p = 0.09$). The only difference was found between CC and other conditions. CC, which required monolinguals to respond with the NO, showed longer reaction times than the YES response conditions (IH, $t = 10.33$, CO, $t = 9.64$, and JC, $t = 11.20$; all $p < 0.001$).

Regarding the accuracy rate, Chinese-Japanese bilinguals showed an average accuracy >90% in all conditions, but statistically significant differences were found among the conditions ($F(3,64) = 22.58$, $p < 0.001$). *Post hoc* pair-wise comparisons showed a significantly lower accuracy rate in IH than CO ($t = 6.14$, $p < 0.001$) and CC ($t = 6.53$, $p < 0.001$). There was no difference between IH and JC ($t = -1.81$, $p = 0.84$) or CO and CC ($t = 2.07$, $p = 0.06$). For the Japanese monolinguals, the CC condition, which required a NO response, showed a lower accuracy rate than the IH, CO, and JC conditions ($F(3,64) = 57.44$, $p < 0.001$). There were no differences among the YES response conditions (IH, CO and JC) in the Japanese monolinguals.

3.2. Imaging results

3.2.1. Effect of word type in Chinese-Japanese bilinguals

First, the comparisons among the YES response conditions (IH, CO, and CC) in the bilingual group showed greater activation during IH word processing than during the processing of CO and CC in a wide range of brain areas: the bilateral IFG, ACC, bilateral superior medial gyri, left fusiform and inferior temporal gyri, bilateral thalamus and caudate nucleus, and right cerebellum (Table 2, Fig. 2). The [CO > CC] contrast analysis conducted to determine the brain areas associated with language membership did not reveal any significant activation under the threshold ($p < 0.05$, FDR correction). However, under a height threshold of $p < 0.001$ without multiple corrections, activation in the SMA was greater for COs than CCs (total of 42 voxels in a cluster, peak voxel, x, y,

Table 2
Comparison between YES response conditions (IH, CO and CC) in bilinguals.

Structure	*x, y, z*	*T*-value	Cluster size
[IH > CO]			
Left triangular part of IFG	−51, 17, 16	5.29	1447
Left opercular part of IFG	−48, 14, 1	5.13	
Left orbital part of IFG	−39, 20, −8	5.17	
Right IFG	54, 20, 16	4.85	912
Anterior cingulate cortex	12, 26, 19	4.42	929
	−9, 23, 19	3.99	
Superior medial gyrus	−6, 41, 31	4.56	
Supplementary motor area	6, 2, 64		
Left fusiform gyrus	−42, −58, −14	4.16	328
Left inferior temporal gyrus	−54, −49, 1	4.12	
Left inferior parietal lobule	−18, −64, 43	4.07	140
	−42, −46, 22	3.37	
Thalamus/caudate	−12, −13, 7	4.75	628
	9, −10, 7	4.59	
Right cerebellum	33, −64, −29	4.20	100
[IH > CC]			
Left triangular part of IFG	−51, 17, 16	6.33	3583#
Left opercular part of IFG	−48, 8, 22	6.52	
Left orbital part of IFG	−42, 23, −2	6.29	
Right IFG	54, 20, 19	5.80	894
Anterior cingulate cortex	−6, 29, 31	5.01	#
	9, 32, 37	4.60	
Supplementary motor area	−3, 17, 58	6.77	#
Left fusiform gyrus	−42, −58, −17	4.36	250
Left inferior temporal gyrus	−42, −40, 1	4.10	
Left inferior parietal lobule	−48, −43, 46	4.28	495
Thalamus/caudate	−9, −10, 7	5.23	716
	15, 14, 7	5.35	
Right cerebellum	33, −67, −29	4.94	250
*[CO > CC]**			
Supplementary motor area	0, 20, 58	4.35	42

For each area, the coordinates (*x*, *y*, *z*) of the activation peak in MNI space, peak *T*-value, and size of the activated cluster (in voxels) are shown for Chinese-Japanese bilinguals ($n = 22$) and monolinguals ($n = 22$). The threshold was set at a voxel-level correction of $p < 0.05$ FDR. *[CO > CC] was threshold at $p < 0.001$, uncorrected.

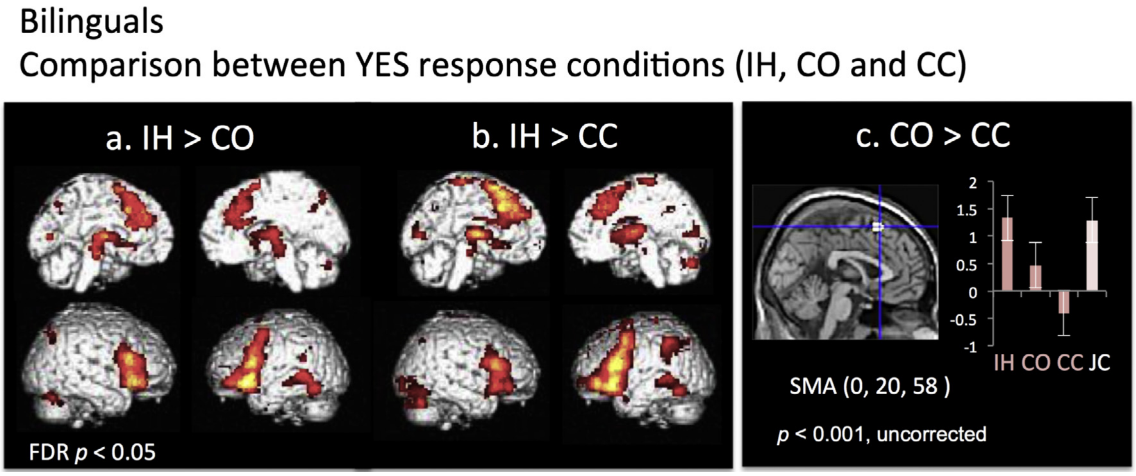

Fig. 2. Brain areas showing significant activation for the contrasts [IH > CO] (a) and [IH > CC] (b) at a threshold of $p < 0.05$, FDR correction. The supplementary motor area (SMA) was identified by the contrast [CO > CC] at a threshold of $p < 0.001$, uncorrected (c). The average parametric estimates at the peak voxel in each condition versus PW for bilinguals were plotted on the vertical axis.

Table 3
Brain activity involved in cognitive control induced by response conflict in bilinguals.

Structure	*x*, *y*, *z*	*T*-value	Cluster size
Conjunction [IH > CO] ∧ [JC > CO]			
Left triangular part of IFG	−51, 17, 16	5.29	982
Left opercular part of IFG	−48, 35, 1	5.13	
Left orbital part of IFG	−48, 32, −14	5.16	
Right inferior frontal gyrus	51, 20, 19	4.73	477
	42, 23, 19	4.65	
Left supplementary motor area	−6, 17, 40	4.25	252
Left fusiform gyrus	−42, −58, −14	3.95	151
Left inferior temporal gyrus	−54, −49, 1	3.93	
Right thalamus/caudate	12, −13, 7	4.46	131
	15, −1, 10	3.63	
Left thalamus/caudate	−12, −7, 7	3.22	78
	−9, 5, −5		

For each area, the coordinates (*x*, *y*, *z*) of the activation peak in MNI space, peak *T*-value, and size of the activated cluster (in voxels) are shown for Chinese-Japanese bilinguals ($n = 22$) and monolinguals ($n = 22$). The threshold was set at a voxel-level correction of $p < 0.05$ FDR.

and z: 0, 20, and 58, respectively). The peak activation of this contrast was very similar to the peak activation of the contrast between IHs and COs. To confirm the activation pattern in this area, the parametric estimates of each condition across subjects in this peak are illustrated in Fig. 2c. Although the degree of involvement exhibited by this area differed for IHs and COs, higher activation was observed to COs than to CCs under a liberal threshold ($p < 0.001$, uncorrected). In the monolingual group, the activations among the YES response conditions (IH, CO, and JC) did not differ.

Second, because common brain areas involved in cognitive control are induced by response conflict, a conjunction null analysis of IH > CO and JC > CO showed significant activation in the bilateral IFG, left SMA, left fusiform gyrus, bilateral thalamus and caudate nucleus (Table 3, Fig. 3).

Finally, in terms of the resolution of the semantic conflict for IHs, significant activations under IHs versus the three other conditions (CO, CC, and JC) were found in the ACC, left thalamus, and left middle temporal gyrus (Table 4, Fig. 4). To illustrate the patterns of activation across conditions, the mean effect sizes for each condition relative to the PWs as a baseline were plotted using the parametric estimates of the activation peaks of each brain area.

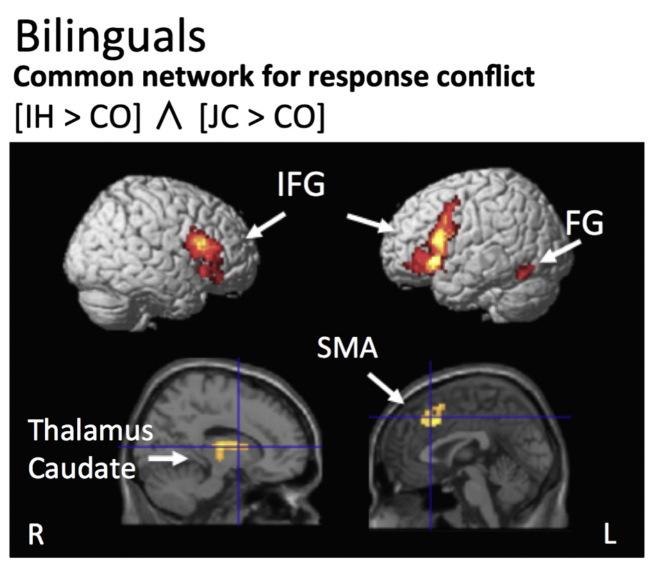

Fig. 3. Brain areas commonly activated for both comparisons of interlingual homographs (IH) with cognate words (CO) and between Japanese control words (JC) with CO in the L1 lexical decision task for Chinese (L1)-Japanese (L2) bilinguals. IFG: inferior frontal gyrus, SMA: supplementary motor area, FG: fusiform gyrus. $p < 0.05$ FDR correction.

Table 4
Brain activity showing higher activation for IHs than other types of words in bilinguals.

Structure	*x*, *y*, *z*	*T*-value	Cluster size
Higher activation for IH			
[IH > CO] with inclusive masks [IH > CC] and [IH > JC]			
Anterior cingulate cortex	−9, 47, 28	4.50	153
	−9, 23, 19	4.20	
Left middle temporal gyrus	−48, −28, −8	4.12	18
Left thalamus	−12, −19, 4	3.93	37

For each area, the coordinates (*x*, *y*, *z*) of the activation peak in MNI space, peak *T*-value, and size of the activated cluster (in voxels) are shown for a voxel-level correction of $p < 0.05$ FDR.

3.2.2. Comparison between bilinguals and monolinguals

The two-sample *t*-test showed greater activations in the left IFG, SMA and ACC in IH > CO contrast among the bilinguals than

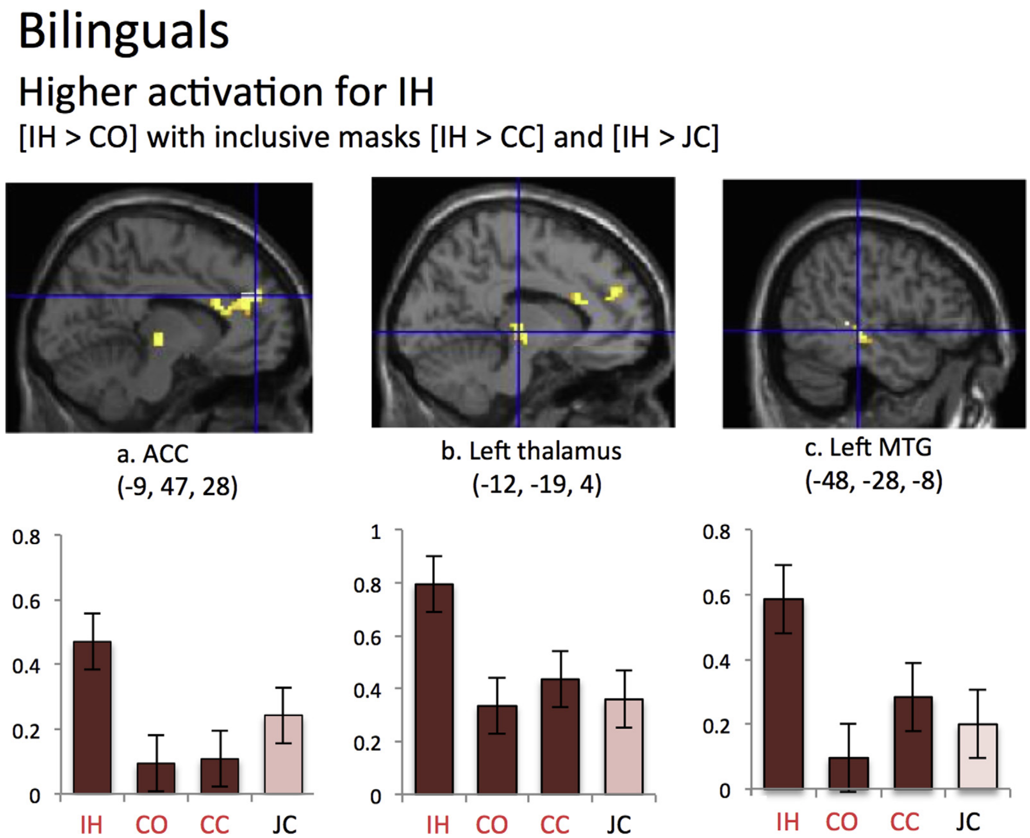

Fig. 4. Brain areas showing significant activation for IH versus other types of words: cognates (CO), Chinese control words (CC), and Japanese control words (JC). ACC, anterior cingulate cortex. MTG, middle temporal gyrus. The average of the parametric estimates at the peak area under each condition versus PW as baseline were plotted on the vertical axis. IH, CO and CC written in red were the conditions that required a YES response and JC in black was the conditions that required a NO response in the task for bilinguals. $p < 0.05$ FDR correction.

Table 5
Comparisons between bilinguals and monolinguals.

Structure	*x, y, z*	*T*-value	Cluster size
Bilinguals [IH > CO] > monolinguals [IH > CO]			
Left orbital part of IFG	−48, 32, −14	5.74	76
Left triangular part of IFG	−51, 17, 16	5.15	143
Left opercular part of IFG	−42, 11, 40	4.83	
Supplementary motor area	−6, 20, 49	5.13	53
Anterior cingulate cortex	−9, 47, 28	4.55	33
Bilinguals [IH > CC] > monolinguals [IH > JC]			
Left orbital part of IFG	−45, 35, −14	5.74	69
Left triangular part of IFG	−48, 23, 10	5.15	163
Left opercular part of IFG	−42, 11, 37	4.83	
Supplementary motor area	−6, 23, 49	5.13	140
Anterior cingulate cortex	−9, 38, 34	3.88	

For each area, the coordinates (*x, y, z*) of the activation peak in MNI space, peak *T*-value, and size of the activated cluster (in voxels) are shown for a voxel-level correction of $p < 0.05$ FDR.

in the monolinguals (Table 5, Fig. 5). The comparison of the contrast [IH > language control condition] with CCs for bilinguals and JCs for monolinguals also showed greater activation in the same brain areas; namely, the left IFG, SMA, and ACC. Activation profiles in the left IFG and SMA were extracted and analyzed with a one-way repeated ANOVA to evaluate the differences across all conditions of IFG activation ($F(3,63) = 17.3$, $p < 0.001$) and SMA activation ($F(3,63) = 25.34$, $p < 0.001$). *Post hoc* pair-wise comparison revealed significant IFG activation under the IH, as compared to CO ($t = 6.09$) and CC ($t = 5.50$), and under JC (NO response condition), as compared to CO ($t = 4.30$) and CC ($t = 5.72$) (all, $p < 0.001$), but there was no difference between the IHs and JCs ($t = -0.36$, $P = 0.73$). Activation in the SMA was found to manifest the same activation pattern as that in the IFG. The IH condition showed greater activation in SMA than did CO ($t = 5.48$, $p < 0.001$) and CC ($t = 7.05$, $P < 0.001$), but there was no difference between the IH and JC conditions ($t = -1.66$, $p = 0.11$) among Chinese-Japanese bilinguals.

In contrast, differential activation between the IH and CO conditions was not observed among the Japanese monolinguals. For the IFG activation, a significant difference was not found across four conditions ($F(3,63) = 0.71$, $P = 0.54$). Significant differences across four conditions ($F(3,63) = 7.51$, $p < 0.001$) were observed in the SMA. Pair-wise comparison revealed that the CC condition, in which monolinguals were asked to respond using the "NO" button, showed greater activation in SMA than IH ($t = 3.13$, $p < 0.05$), CO ($t = 2.76$, $p < 0.05$), and JC ($t = 3.28$, $p < 0.05$). There was no difference among the YES response conditions (IH, CO, and JC) in monolinguals, as expected.

4. Discussion

In this study, we investigated the neural correlates of language control when late Chinese-Japanese bilinguals dealt with language interference from L2 during the processing of L1 as well as the manner in which bilinguals resolve the semantic conflict of IHs using fMRI. To do this, we manipulated the type of words (IHs, cognates, and language-specific control words) and the type of participants (bilinguals vs. monolinguals). Participants performed an L1 lexical decision task with different types of words that were designed to enhance the various cognitive demands required in

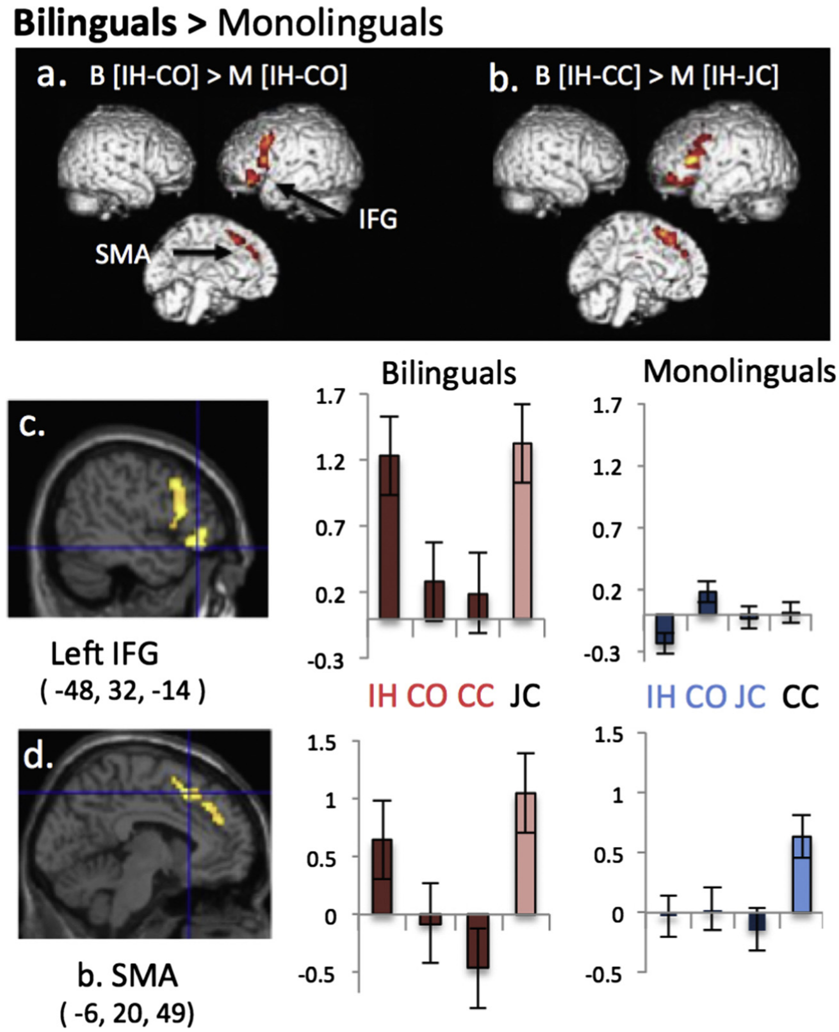

Fig. 5. Brain areas showing significant differential activation in the [IH vs. CO] contrast in bilinguals versus monolinguals (a) and in the contrasts [IH vs. CC] in bilinguals compared to [IH vs. JC] in monolinguals (b). Brain activations projected on the MNI brain template (left side). c. Left inferior frontal gyrus, d. supplementary motor area. The average parametric estimates at the peak area in each condition versus PW for bilinguals and monolinguals were plotted on the vertical axis. IH, CO, and CC in red were the conditions that required a YES response for bilinguals. IH, CO, and JC in blue were the conditions that required a YES response for monolinguals. JC and CC were the NO response conditions for bilinguals and monolinguals, respectively. $p < 0.05$ FDR correction.

terms of stimulus conflict and response conflict in bilinguals but not monolinguals. Consistent with the stated hypotheses, the Chinese-Japanese bilinguals were found to show a cross-language interference effect while accessing the meaning of IHs versus cognates during the L1 lexical decision task. The processing of IHs activated broad brain areas related to executive and inhibitory control. Within this circuit, the bilateral IFG, SMA, caudate nucleus, and left fusiform gyrus showed similar activation when the subjects processed Japanese (L2) control words that required top-down control induced by response-conflict in the L1 lexical decision task. On the other hand, the ACC, left thalamus, and left middle temporal gyrus were specifically involved in the processing of IHs. This result indicates that the semantic conflict caused by the lexical representation level may be resolved by interplay with conflict monitoring in the ACC. Taken together, the present results confirm the effect of interference from the intermediate level of L2 during L1 recognition in a logographic writing system and also contribute to a better understanding of the brain mechanisms supporting language control induced by response conflict and stimulus conflict during IH processing. The following sections will discuss these findings in detail.

4.1. Behavioral data: parallel activation of L1 and L2

This study presented five different types of words (IH, CO, CC, JC, and PW) to Chinese-Japanese bilinguals and Japanese monolinguals to determine whether the stimuli belonged to their L1 or were not in the mixed language context. Consistent with previous findings (Dijkstra & van Heuven, 2002; Dijkstra et al., 2000; van Heuven et al., 2008), the present behavioral results support that the representations of both L1 and L2 are activated simultaneously during bilingual language comprehension with logographic writing systems in the mixed language context. IHs have identical orthographic forms but different representations in (traditional) Chinese and Japanese. We found that the reaction times for IHs were significantly slower than those for COs and CCs when the Chinese (L1)-Japanese (L2) bilinguals accessed the meanings of real words. However, no significant differences were observed among the RTs of Japanese monolinguals for IHs, COs, or JCs. According to both the BIA and BIA+ models (Dijkstra & van Heuven, 1998, 2002; Thomas & Van Heuven, 2005), all nodes between languages are interconnected at the word level and mutually inhibit each other. The present behavioral data support this viewpoint because the slower RTs for IHs indicate that bilinguals experience competition of representations from their two languages during the processing of IH. This explanation is also supported by the accuracy rate: semantic conflict induced by an inherent characteristic of the homographs resulted in less accurate performances for IHs than cognate words (Macizo et al., 2010; van Heuven et al., 2008). The present study thus confirms that non-selective access is likely to be universal to bilinguals, regardless of writing systems.

However, there was no difference between COs and CCs in terms of either RT or accuracy rate in the bilingual participants. This result is inconsistent with previous behavioral studies showing the cognate facilitation effect (Dijkstra, Miwa, Brummelhuis, Sappelli, & Baayen, 2010) because COs share identical form and meaning in both languages. There are at least two possible reasons that can explain this inconsistency. First, the mixed language context in the present experiment may have reduced the facilitation effect because the participants were aware of the language memberships for both sets of words. Second, the size of the overlap across the lexical information may have weakened the effect because Chinese and Japanese cognates overlap in form and representation but not in terms of phonological information due to the unique characteristics of the logogram system. Further investigation using other tasks and contexts will be necessary to generalize the present results.

An unexpected finding was that the Japanese monolinguals in this study showed a poorer accuracy rate in the CC condition. This result may have been caused by the neighborhood effect of the word stimuli. Although the CCs do not exist in Japanese, the participants were able to recognize individual Chinese characters as a unit of representation with an inherent representation in Japanese. Thus, this characteristic may have caused the interference effect when the Japanese monolinguals processed Chinese control words.

4.2. Cognitive control induced by response conflict in bilingual word comprehension

When the Chinese (L1)-Japanese (L2) bilinguals performed the L1 lexical decision tasks, the effect of interlingual homographs versus cognates was found in broad brain areas. Surprisingly, within these areas, the bilateral IFG, SMA, left fusiform gyrus and caudate nucleus were commonly activated when the bilingual participants made a NO response to their L2 control words during the L1 lexical decision task. Both the IHs and L2 control words enhanced cognitive control to select an appropriate response for an intended task by suppressing the irrelevant one. While processing IHs, the bilinguals should control their response to the L2 semantic representation of the IH, which is activated simultaneously, to select a correct response to L1. In a similar way, when the L2 control words were presented, the bilingual participants may have mapped these items to the NO response in the L1 lexical decision task.

Consistent with previous neuroimaging studies on bilingual language comprehension and production (Abutalebi & Green, 2016; Luk et al., 2011; van Heuven et al., 2008), our results confirm that executive and inhibitory control in the task/decision system is necessary to resolve response conflict of IHs in bilingual language comprehension. The left ventral lateral prefrontal cortex is considered a putative locus of cognitive control, regardless of domains (Thompson-Schill, Bedny, & Goldberg, 2005). The functions of the left IFG are related to top-down control (Costumero, Pujadas, Claramonte, & Ávila, 2015) and suppression of inappropriate response (Abutalebi & Green, 2016, for a review). Pathological studies also indicate that the left IFG is related to inhibitory control, to reduce interference of other languages (Fabbro, Skrap, & Aglioti, 2000). The right IFG and SMA are considered to be involved in inhibition because activation in these areas is sensitive to inhibition cost during language switching tasks (De Bruin, Roelofs, Dijkstra, & FitzPatrick, 2014; Hampshire, Chamberlain, Monti, Duncan, & Owen, 2010; Jahfari et al., 2011). In particular, activation in the right IFG and SMA increases when bilinguals switch from a strong language to a weaker language, such as L2 and L3 (De Bruin et al., 2014; Garbin, Costa, Sanjuan, & Forn, 2011). The basal ganglia including the caudate are associated with cognitive sequence motor planning (Graybiel, 2000) and control of language use (Abutalebi & Green, 2016; Crinion et al., 2006).

The cognitive control induced by response conflict observed in the present study may have occurred within the task/decision system outside of the word identification system, as assumed by the BIA+ model (van Heuven & Dijkstra, 2010). Because the response conflict could also be prevented by improved task decision criteria in terms of mapping activation patterns across representations to the responses, the level of involvement of the task/decision system would have been sensitive to task demand. This interpretation of the present results can be supported by the findings of van Heuven et al. (2008). These authors reported greater activation in the left IFG, SMA, and left caudate nucleus during IH processing than during the processing of English control words when Dutch (L1)-English (L2) bilinguals performed an English lexical decision task that generated response conflict due to the non-target representation (Dutch) of IHs. However, when the bilinguals performed a general lexical decision task that required the participants to accept both Dutch and English words, activation in the SMA and left caudate disappeared and activation in the left IFG weakened. Furthermore, the present study observed activation in broader areas, such as the bilateral IFG and bilateral caudate nucleus, which are cognitive control areas (Crinion et al., 2006; Garbin et al., 2011). Because the present study included Japanese (L2) control words in the L1 lexical decision task, control demand during rejection response to L2 words likely increased. Intermixing L2 words in the L1 lexical decision task may have increased the interference effect of IHs at the response level due to the non-target representation (L2) of IHs.

Furthermore, in contrast to previous findings on bilingual word comprehension with alphabetic writing systems (van Heuven & Dijkstra, 2010; van Heuven et al., 2008), activation in the left fusiform gyrus spread to the ventral part of the temporal area (also known as the visual word form areas) and increased due to response conflict during word recognition. This area has been primarily associated with the identification of words and letters from lower-level shape images prior to association with phonology or semantics (Dehaene & Cohen, 2011). However, the activation level in this region is modulated by top-down signals from the higher-order linguistic properties of a word. That is, when participants are asked to perform semantic decision or rhyming judgment tasks, the left fusiform areas showed increased activation compared with passive reading (Chen, Davis, Pulvermüller, & Hauk, 2013; Dehaene & Cohen, 2011; Twomey, Kawabata Duncan, Price, & Devlin, 2011). Because we controlled for the number of strokes in a character, frequency, and IH familiarity across types of words, these visual properties probably did not influence brain activity. When cross-language interference or response conflict increased during word comprehension, orthographic processing may have been upregulated by reinforcement of top-down attention to visual word form.

4.3. Resolution of semantic conflict for IHs

Greater activation in the ACC, left thalamus, and left middle temporal gyrus was found in the processing of IHs as compared to other types of words (even Japanese control words). Contrary to the cognates, IH words have two meanings for one visual form across the Chinese and Japanese languages. Therefore, high levels of competition in terms of accessing the two meanings could have occurred at the lexical level, but only one of these meanings could have been selected based on the task requirements.

Significant activation in the ACC and left middle temporal gyrus may have reflected demand for conflict monitoring of lexical information and selection of target semantic information of IHs during the L1 task. In previous neuroimaging studies, the ACC has been considered to play a role in monitoring or detecting conflict rather than participating in inhibitory control (Abutalebi et al., 2008; Botvinick, Cohen, & Carter, 2004; Branzi, Rosa, Canini, & Costa, 2016; Egner & Hirsch, 2005). The left middle temporal gyrus is associated with post-lexical processing for mapping a word form onto a meaning (Campanella, Mondani, Skrap, & Shallice, 2009; Vandenbulcke, Peeters, & Dupont, 2007). The same area is also sensitive to semantic priming in within- and cross-language conditions among Japanese and English bilinguals, reflecting automatic bottom-up processing of lexical representations (Nakamura et al., 2010).

The present study observed activation in the ACC, which is consistent with the findings of van Heuven et al. (2008) who demonstrated the involvement this region in solving response conflicts. These authors observed a strong activation in this area and the SMA when comparing IHs and English control words in English lexical decision tasks but not in general lexical decision tasks. The present study also controlled for response conflict induced by the task in which Japanese (L2) control words were used in the L1 lexical decision tasks. Thus, the present data provided evidence showing how bilinguals resolve the inherent lexical conflict of IHs. Our finding suggests that conflict monitoring, which is mediated in the ACC, and the processing of target lexical information, which is performed in the left middle temporal areas, may be associated with the resolution of semantic conflict induced by the inherent characteristics of IHs.

The present results are also comparable with previous imaging data showing that general cognitive control mechanisms are carried out with top-down adjustments from the left prefrontal cortex and bottom-up input from visual stimuli during conflict resolution (Egner & Hirsch, 2005; Jahfari et al., 2015). Egner and Hirsch (2005) investigated cognitive control mechanisms under a high conflict condition and found that there was enhanced performance due to the transient amplification of cortical responses to task-relevant information rather than the inhibition of responses to task-irrelevant information. Thus, bilinguals might attempt to resolve semantic conflict by intensifying activation of relevant target information in the left middle temporal area via conflict monitoring in the ACC. However, the precise mechanisms underlying selection of relevant information by bilinguals should be clarified in future studies.

The involvement of the thalamus has been reported in the selection of relevant lexical and semantic representations (Abutalebi & Green, 2016). The thalamus may be involved in the transition of information between the prefrontal and visual cortex and the regulation of this information flow during inhibition, selection, and attention tasks (Jahfari et al., 2015). For example, Jahfari et al. (2015) examined how the quality of visual information affected the front-basal ganglia routes, including the thalamus, which are associated with response selection and inhibition while subjects performed stop/go trials with face stimuli. They found that the thalamus is involved in the direct pathway of information flow between the prefrontal and sensory cortices and is central to a successful response. Accordingly, the thalamus activation in the present experiment might have been involved in controlling the information flow for the resolution of semantic conflict along with monitoring in the ACC and the bottom-up lexical-semantic processing in the left middle temporal gyrus.

The present results also support the BIA+ model (Dijkstra & van Heuven, 2002) in that the task/decision system was in charge of controlling non-linguistic demands, such as task or response demands, while the word identification system mainly processed lexical information. The IH processing results indicate that these two systems likely interface during word recognition depending on the task demands and stimulus properties. Additionally, in the present experiment, when the bilingual participants were performing the L1 lexical decision task, the SMA, which is one of the domain-general inhibitory control systems, exhibited different levels of activation according to the task requirements and word properties. This area was associated with both the IH and JC conditions, which required controlling response conflict, and was sensitive to language membership in the CO condition. The latter finding is in line with those of a previous ERP study (Hoversten et al., 2015), which demonstrated that language nodes directly modulate language processing according to task demands. However, in the present experiment, it was difficult to determine whether the language nodes suppressed irrelevant information or if increased in response conflict. Future studies will be necessary to examine both the time course and the brain areas that are important during bilingual word comprehension by combining different methodologies such as ERP and magnetoencephalography (MEG). Nevertheless, the present results suggest that task demands influence the brain mechanisms via which bilinguals process different word types, especially IHs and cognates.

4.4. Comparisons between monolinguals and bilinguals

A direct comparison between the bilingual and monolingual groups also confirmed greater activation in the IFG, SMA, and ACC among the bilingual group than among the monolinguals. Because both the bilinguals and monolinguals performed their L1 task, differential activation can be explained by cognitive control for conflict resolution during word recognition rather than by different language proficiency levels between the two groups. This comparison may have also been influenced by differences in task demands between the groups. Because both Japanese and Chinese control words were used in the L1 lexical decision task, a particular list of words would be a mixed language context for the bilingual group but only a single language for the monolingual group. This mixed language condition may have increased response conflict in the task/decision system at a greater rate in the bilingual participants than the monolingual participants.

Regarding brain activation patterns in the Japanese monolinguals, greater activation in the SMA was found during the processing of the Chinese control words than in the other conditions. This unexpected result was also consistent with their behavior results, which showed longer reaction times and lower accuracy in the Chinese control words condition than in the other conditions in monolinguals. As mentioned above, the SMA seems to be involved in a mechanism related to domain-general inhibition (De Bruin et al., 2014; Jahfari et al., 2011). Consistent with the present interpretation of the behavioral data mentioned above, increased activation in the SMA may have been involved in inhibitory control of the response conflict caused by the neighborhood effect of characters. Although the combination of characters (Chinese control word) does not exist in Japanese, each character exists in Japanese. Thus, Japanese monolinguals might have accessed the Japanese words containing each character and mapped the characters to the YES response.

The Chinese subjects' L2 influenced their L1 processing, even at an intermediate proficiency level of their L2. Many previous studies have reported asymmetric language interference effects between L1 and L2. In particular, the dominant language (L1) causes greater interference effects on L2 processing (see Van Hell & Tanner, 2012). However, in the current study, although the participants were late learners and had intermediate proficiency levels in L2, L2 strongly influenced their L1 processing during the L1 decision task. These results may be explained by two factors. First, intermixing L1 and L2 words in the L1 lexical decision task may have increased L2 interference (Dijkstra et al., 2000). This is because the participants had to focus on the L2 words to correctly reject them when they were presented. Second, Chinese and Japanese share most of the orthographic forms that were invented in a meaning-based way. This unique property of the writing system may have enhanced the conflict effect, even in late learners among the Chinese subjects. Indeed, the Chinese learners of Japanese could have accessed the meaning even when they did not know how to pronounce the word (Tamaoka et al., 2012). This explanation is supported by the present results demonstrating similar activation patterns between the contrasts [IH versus CO] and [IH versus CC], although both IHs and COs have two phonological representations in both languages. Our interpretation is also consistent with a previous study, which showed that a higher script similarity between two languages of bilinguals required more cognitive control than less similar scripts (Coderre & van Heuven, 2014).

5. Conclusions

Our results confirmed previous findings on alphabetic writing systems that showed parallel activation in L1 and L2 during word comprehension, and this parallel activation is apparently also true for the completely different logogram writing system. Our study is also consistent with the BIA+ model (Dijkstra & van Heuven, 2002) in that the lexical representation system provides information for the task/decision system during a particular task. Furthermore, the present study provides empirical evidence that two precise brain mechanisms underlie the ultimate selection of the appropriate language during interference in bilingual comprehension. First, bilinguals must recruit the task/decision system, which is implemented in the bilateral IFG, SMA, and caudate, to control the competing responses between languages. Second, conflict monitoring mediated in the ACC and selection of target lexical information in the left middle temporal areas may be associated with resolution of semantic conflict induced by the inherent characteristics of IH.

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