EXPLORING THE COGNITIVE EFFECTS OF BILINGUALISM:

NEUROIMAGING INVESTIGATIONS OF LEXICAL PROCESSING, EXECUTIVE CONTROL, AND THE BILINGUAL ADVANTAGE

EMILY L. CODERRE, MSc.

Thesis submitted to the University of Nottingham
for the degree of Doctor of Philosophy

DECEMBER 2012

Abstract

Bilingualism has been shown to influence a variety of cognitive functions, most notably lexical processing and cognitive control. These effects are both detrimental and advantageous. On one hand, it has been proposed that bilinguals experience delayed lexical access compared to monolinguals, both in the less-proficient language and in the native language, due to the relatively reduced frequency of use. On the other hand, the constant need to juggle and control two languages enhances cognitive control abilities in bilinguals, such that they outperform monolinguals on tasks of executive processing and conflict resolution. This dissertation explores these cognitive changes associated with bilingualism, primarily through the use of a Stroop task. As it combines lexical processing with cognitive control, the Stroop task is a unique paradigm in which to investigate these abilities in bilinguals. Using behavioural measures, electroencephalography, and functional magnetic resonance imaging, the experiments presented here seek to deepen our understanding of lexical processing and cognitive control in bilingualism, in order to better understand how the now-common use of multiple languages affects the functional brain.

Declaration

I declare that this is my own work, conducted during my time as a PhD student at the University of Nottingham. Although some data presented here were collected during my Master's year and reported in my MSc thesis, it has all been significantly re-analyzed, or more data has been collected. Specifically, the monolingual and Chinese-English data of Chapter 3 was presented as part of my Master's thesis, but for this PhD thesis an additional group of bilinguals was tested which significantly changed the interpretation of the data. Furthermore, the monolingual data of Chapter 5 were also presented in my Master's thesis, but additional participants were tested and a complete reanalysis was performed for the thesis chapter.

Due to length restrictions of the PhD thesis and to present a more cohesive overall narrative, some data collected during these experiments are not reported. In addition to the behavioural data presented in Chapter 6, EEG data were also collected, but these are not reported due to space restrictions. The experiment presented in Chapter 7 also collected fMRI data on a flanker task, but as the main focus of this chapter is on SOA manipulation in the Stroop task, the flanker data are omitted. Finally, the paradigm of Chapter 8 also included an additional control condition to provide supplementary information on conflict management in monolinguals and bilinguals; in the interest of space and clarity, the results of this condition are also not reported.

Two of the chapters included here have been accepted for publication in peer-reviewed journals and three others are under review or in preparation. The data reported in Chapter 3 have recently been published in *Bilingualism: Language and Cognition* (Coderre, van Heuven, & Conklin, in press), although slight modifications were made to the text in the interest of clarity and length. The data of Chapter 4 have been submitted to *Frontiers in Language Sciences* (Coderre, van Heuven, & Conklin, submitted). The monolingual results from Chapter 5 have been published in *Brain Research* (Coderre, Conklin, & van Heuven, 2011); for this thesis the analyses were redone slightly, but the overall data patterns remained the same (see Footnote 15 in Chapter 5). The bilingual results of Chapter 5 are in preparation for submission (Coderre, Conklin & van Heuven, in preparation) and the data of Chapter 7 have been submitted to *Neuropsychologia* (Coderre & van Heuven, submitted).

Manuscripts submitted or accepted for publication, or in preparation

Coderre, E., Conklin, K., & van Heuven, W.J.B. (in preparation). Executive Control Abilities in Monolinguals and Bilinguals Using ERP.

Coderre, E., Conklin, K., & van Heuven, W.J.B. (submitted). The Effects of Bilingualism on the Timecourse of Early Word Recognition. *Frontiers in Language Sciences.*

Coderre, E., Conklin, K., & van Heuven, W.J.B. (2011). Time Course Analysis of Stroop Interference: An ERP Study. *Brain Research, 1413*, 51-59.

Coderre, E. & van Heuven, W.J.B. (submitted). Modulations of the Executive Control Network by Stimulus Onset Asynchrony in a Stroop Task. *Neuropsychologia.*

Coderre, E., van Heuven, W.J.B. & Conklin, K. (In Press). The Timing and Magnitude of Stroop Interference in Monolinguals and Bilinguals. *Bilingualism: Language and Cognition.*

Acknowledgements

In the four years it has taken me to produce the work presented here I have received support, both academically and personally, from many people to whom I am immensely thankful. First and foremost, none of this would be possible without Walter van Heuven: a huge thanks for taking me on and giving me this opportunity, for providing encouragement and advice, for answering even small questions with immeasurable patience, and for letting me find my own way in my research. Many thanks are also due to Kathy Conklin, for her enormous help with the work presented here and for backing me up when I let an Americanism slip.

I am immensely grateful to all of the teachers, mentors, and friends who have helped me acquire the knowledge I have gained throughout my studies. Specifically, thanks to Lucy Cragg, who not only gave me valuable advice as my internal examiner but who put up with many stupid questions and in doing so was instrumental in helping me learn EEG analysis. Thanks to Barry Horwitz at the NIH, who hosted me as a guest researcher in his lab and with whom I shared many interesting discussions. Thanks to Jason Smith, who threw me in the deep end but was invaluable in my understanding of fMRI design and analysis. And thanks to my fellow MSc coursemates, specifically Kate, Chris, and Molly, who over many long afternoons helped me learn EEG and have fun while doing it.

Thanks to the Bilingualism Research Group for their feedback and patient help with posters and presentations. Thanks also to the students, technicians and colleagues who helped with data collection and paradigm design, especially Lifang Wang, Kay Head, Ana Pellicier-Sánchez, Jose Cuenca, DJ Bolger, Jeanette Black, and Renee Hill. And a very special thanks to Andrew Kelly, my officemate and friend, who not only helped in collecting data but was always gracious in performing many favours, small and large, that I am truly grateful for.

I offer immense thanks for the many friends I have made in these four years, especially the residents and regulars of 48 Toston Drive, for making my time in Nottingham not just about getting a graduate degree but a true life experience. Thank you all for being bright spots on dark days and for reminding me of what is important when all I could see was work. Thanks in particular to Lauren, for helping with a small favour which meant a great deal; and a special thanks to Carolyn, for leading me through difficult times and for always being available for a hug and a laugh.

I have no words strong enough to offer thanks to my parents. Thank you for being my ‘thesis army’ and for being just as nerdily enthusiastic about editing and formatting as me: I truly am your daughter! Thank you for always supporting and never pressuring me, for always letting me make my own decisions, for keeping me constantly in awe of your selflessness and decency, and for, once again, being the model of love and understanding on which I try to mould myself.

Finally, special thanks to Julie for her constant mentoring and life guidance, who has unknowingly directed the course of my life for the better. Thanks, always, to Tim, for brightening my world and for being the epitome of unconditional love and patience: I told you I would come back. And, ultimately, thank you to Stephen, my thesis study buddy and a true friend, who I came to rely on more than I realized. May your graphs be ever symmetric.

Table of Contents

Chapter 7: Neural Effects of Stroop SOA Manipulation on Executive Control: an fMRI Study in Monolinguals 164

List of Figures

Chapter 1

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Chapter 6

Chapter 7

Chapter 8

Chapter 9

List of Tables

Chapter 1

Chapter 3

Chapter 4

Chapter 5

Chapter 6

Chapter 7

Chapter 8

Chapter 1: Introduction to Bilingualism

Language is a uniquely human capacity, arguably the greatest ability mankind has ever developed. Modern humans use language constantly and in many different contexts; it is so highly practised, in fact, that it becomes automatic and is often taken for granted. Yet language is vastly complicated, consisting of complex interacting processes like acoustic recognition of speech, production of fluent and meaningful speech, visual word recognition, and parsing complicated grammar. The majority of the world today speaks two or more languages, a trend reflected in the increasing interest in the neuropsychological effects of bilingualism. The maintenance and control of multiple languages place huge demands on the cognitive system and subsequently affect many aspects of development. Bilingualism research aims to understand not only how the brain deals with the presence and interaction of multiple languages, but also the cognitive and developmental effects of such experience.

This thesis explores the benefits and consequences of bilingualism, using behavioural and neuroimaging methods to gain insight into the cognitive effects of dual language use. This first introductory chapter provides an overview of these topics: Part 1 discusses the bilingual language system, including theories and models of bilingual language processing, and reviews evidence regarding the neural management of multiple languages. Part 2 reviews the detrimental impact of bilingualism on language processing and presents two hypotheses regarding lexical processing speed. Part 3 provides an introduction to executive control, a cognitive ability in which bilinguals are advantaged compared to monolinguals, as well as a general background of its behavioural and neural correlates. Finally, Part 4 examines the implications of bilingualism for executive control, providing an overview of the current evidence concerning bilinguals' superior abilities in cognitive processing and discussing two distinct hypotheses regarding these abilities. Following this general background on the cognitive effects of bilingualism, Chapter 2 then presents an introduction to the Stroop task, a linguistically-based cognitive control paradigm which is used throughout this thesis to investigate lexical processing speed and executive control abilities.

1. Part 1: The Bilingual Language System

Monolingual language processing is a complex endeavour requiring extensive cognitive resources; the acquisition and processing of a second language is justifiably much more arduous. Much of bilingualism research focuses on how the presence of two languages alters the structure and function of the language system. Of specific interest has been how multiple languages are integrated, especially when they contain disparate orthographic formats or grammatical structures (Abutalebi & Green, 2007; Kroll, Bobb, & Wodniecka, 2006; Kroll, Dussias, Bogulski, & Valdes Kroff, 2012). Is a second language assimilated into the structures and resources of the first, or does it start anew with completely separate representations? If the languages are integrated, do they interact with each other? How do bilinguals select one language over the other or prevent interference from the non-target language?

Before discussing the literature addressing these questions, a brief introduction to the terminology of bilingualism research is required. The term ‘bilingual’ itself can be controversial, as it comprises a multitude of dynamic linguistic and cognitive factors. Bilinguals, for the sake of this thesis, are individuals who have achieved a reasonable level of proficiency in two languages and who use both languages on a frequent or daily basis. Language ‘proficiency’, referred to here as fluency or language skill, can be assessed with subjective or objective measures like questionnaires or vocabulary tests. However, this is also a fluid concept, as proficiency can change over years, months, or weeks, depending on factors like immersion or immigration (Hansen, 2001; Linck, Kroll, & Sunderman, 2009; Tokowicz, Michael, & Kroll, 2004). For the purposes of this thesis, the language with the higher subjective proficiency is considered a bilingual’s ‘dominant’ language. The ‘first language’ (L1) is considered the native language, which was learned first; the ‘second language’ (L2) is the later-acquired, ‘non-native’ language. ‘Early’ bilinguals are referred to here as individuals who learned both languages from birth or early childhood, whereas ‘late’ bilinguals acquired their L2 after approximately age 7 (the precise cut-off between early and late bilinguals also differs among researchers). Finally, ‘balanced’ bilinguals are defined here as individuals who have learned two languages from birth and are equally proficient in both, whereas ‘unbalanced’ bilinguals are more dominant in one language than the other. These concepts can all become confounded with language experience: for example, bilinguals may become more proficient in their non-native language after immigration to a foreign country. Most of the bilinguals tested throughout this thesis are late bilinguals, with the L1 as the dominant language and the L2 the non-dominant; where there is a question of dominance, this is explicitly addressed.

1.1. The bilingual lexicon: integration and access

One important issue in early bilingualism research concerned whether bilinguals’ two lexicons were separate, meaning that individual conceptual representations existed for each language, or integrated, meaning that both languages shared the same conceptual representations (Figure 1.1). For example, bilingual aphasics sometimes lose only one of their languages while the other is kept intact (see Lorenzen & Murray, 2008 for a review), which would suggest separate language representations. In the case of separate lexicons, the subsequent question of interest was how bilinguals switched from one language ‘mode’ to another; i.e. how a language was selected or how the non-target language was suppressed (‘selective’ access to a non-integrated lexicon). In the case of integrated lexicons, the question was how bilinguals controlled language activation and managed cross-linguistic influences (‘non-selective’ access to an integrated lexicon).

Figure 1.1: Schematic representations of language non-specific and language specific selection in Spanish-Catalan bilinguals (from Costa, Miozzo, & Caramazza, 1999).

Please refer to Figure 1; Costa, A., Miozzo, M., & Caramazza, A. (1999). Lexical selection in bilinguals: Do words in the bilingual's two lexicons compete for selection? ***Journal of Memory and Language, 397*****, 365–397.**

Language-selective models of bilingualism such as that of La Heij et al. (e.g. Bloem & La Heij, 2003; Bloem, van den Boogaard, & La Heij, 2004) propose that a language tag or feature serves as a conceptual specification, which allows for language-selective access based on task demands; therefore only a single concept becomes available for encoding. For example, Macnamara & Kushnir (1971) reported that switching between languages during reading caused processing difficulties (i.e. longer reaction times (RTs)), interpreted as reflecting the need to turn languages 'on' and 'off'. Further evidence for selective access comes from lexical decision tasks demonstrating a lack of influence of the non-target language on target language processing (Gerard & Scarborough, 1989; Scarborough, Gerard,

& Cortese, 1984). For example, Gerard & Scarborough (1989) performed a lexical decision task in Spanish-English bilinguals which manipulated lexical frequency between languages by using homographic noncognates (words that share the same orthographic form between languages but have different semantic meanings: e.g. ‘fin’ is a low-frequency word in English but a high-frequency word meaning ‘end’ in Spanish). They found no influence of non-target-language homographic noncognates on target language processing (either interference or facilitation) and concluded that, because the non-target language was not activated, bilinguals were essentially functioning as monolinguals.

In contrast, other paradigms have demonstrated significant L2 effects on L1 processing, supporting the theory of non-selective access (see reviews in Brysbaert & Duyck, 2010; Dijkstra & van Heuven, 2002; Kroll et al., 2006, 2012). Such paradigms often use cognates (words sharing both spelling and meaning across languages) or interlingual homographs (same spelling but different meaning and pronunciation) to assess cross-linguistic influences (e.g. Degani & Tokowicz, 2010; Kerkhofs, Dijkstra, Chwilla, & de Bruijn, 2006; van Hell & Dijkstra, 2002; van Heuven, Schriefers, Dijkstra, & Hagoort, 2008). For example, van Heuven et al. (2008), using functional magnetic resonance imaging (fMRI) with a lexical decision task, found that despite a monolingual task context, interlingual homographs elicited enhanced activation in areas of the executive control network (see Part 3), suggesting that the parallel activation of both languages causes cognitive conflict in the bilingual brain.

Other studies have demonstrated cross-linguistic effects in the absence of cognates or any other non-target-language cues (e.g. Colomé, 2001; Rodriguez-Fornells et al., 2005; Spalek, Hoshino, Damian, & Thierry, 2011; Thierry & Wu, 2004, 2007; Wu & Thierry, 2011), providing stronger support for non-selective access. For example, Spalek et al. (2011) performed a picture naming task while recording electroencephalography (EEG) in German-English bilinguals. Naming was performed in a monolingual context, but in some cases the name’s initial phoneme overlapped between the L1 and L2 translations. Spalek et al. reported a more positive EEG wave between 280-500 ms for the overlap conditions compared to non-overlap conditions. They interpreted this as evidence of non-target language effects on target language processing, despite the completely monolingual naming context. Rodriguez-Fornells et al. (2005) performed a picture-naming task in German-Spanish bilinguals with a phonological go/no-go component: in alternating language naming blocks, participants responded when the picture name in the target language began with a consonant and withheld a response when the name began with a vowel. In some conditions, both the bilinguals’ languages required the same response, whereas in others the responses conflicted between languages. Using a combination of behavioural, EEG, and fMRI measures, they observed that conflicting-response trials generated more errors, exhibited an increased negativity in the EEG data at approximately 200 ms, and activated the executive control network in the brain (see section 3.2.1); in sum, the cross-language interference created clear processing difficulties.

In light of additional accumulating evidence demonstrating cross-linguistic influences in bilinguals (e.g. Brysbaert & Duyck, 2010; Kroll et al., 2006, 2012; Midgley, Holcomb, van

Heuven, & Grainger, 2008; Poulisse & Bongaerts, 1994; Soares & Grosjean, 1984; Thierry & Wu, 2004; van Heuven, Dijkstra, & Grainger, 1998), the literature has reached the general consensus that bilingual lexical access is non-selective in nature: the non-target language can interfere with the target language during production or comprehension, even in completely monolingual contexts. Thus bilinguals cannot completely ‘turn off’ one language: both are activated in parallel and can interact with each other, to the detriment or advantage of the bilingual language processing system.

1.1.1. The specific locus of language control

Although completely-selective bilingual lexical access has been largely discounted, the discussion has shifted to the precise locus of lexical selection: even if both languages are activated, do lexical candidates in both languages become active and compete with each other, or is only the target language considered for lexical selection? One hypothesis proposes language-specific lexical selection, in which bilinguals can control the degree of activation of each language (e.g. Bialystok, Craik, Green, & Gollan, 2009; Costa, Miozzo, & Caramazza, 1999; Costa, Santesteban, & Ivanova, 2006; Rodriguez-Fornells, Rotte, Heinze, Nösselt, & Münte, 2002). For example, Rodriguez-Fornells et al. (2002) proposed that bilinguals can suppress the activation of the non-target language during word identification, before semantic analysis. Testing Spanish-Catalan bilinguals on a linguistic go/no-go task, in which subjects responded only for Spanish words, the authors found no effects of Catalan word frequency on electrophysiological responses. This suggests that words in the non-target language were ‘rejected’ before the level of semantic activation.

Bialystok et al. (2009) take a more global view, suggesting that although both languages may not always be *fully* active, they are always *potentially* active; the extent of activation depends on the likelihood of being the target language. For example, constraining the semantic context can reduce non-target language effects (e.g. Libben & Titone, 2009; Schwartz & Kroll, 2006; van Hell & de Groot, 2008; but see van Assche, Duyck, & Hartsuiker, 2012 for a lack of context effects). Other viewpoints differ more considerably: for example, Hoshino & Thierry (2011) find evidence of lexical alternatives activated to the level of phonology. Thus while non-selective lexical access is generally agreed upon, language selection can be restricted via numerous cognitive mechanisms and at various loci of linguistic processing (see Kroll et al., 2006 for a review) which have yet to be defined.

1.2. Language representations in the brain

Another major theme of bilingualism research considers how languages are managed and represented in the brain. For instance, does linguistic processing proceed along the same timecourse in bilinguals as in monolinguals, or are certain stages slowed? Do bilinguals use the same brain areas as monolinguals for language processing, or do they recruit different areas to manage the increased cognitive demands? Behavioural studies provide limited information about the organization of the bilingual lexicon, but with advancing neuroimaging technology the understanding of bilingual language processing has expanded considerably.

1.2.1. EEG indices of language processing

Monolingual language studies using EEG have identified a series of event-related potentials (ERPs) reflecting specific steps along the timecourse of linguistic processing (Figure 1.2; Sereno, Rayner, & Posner, 1998). Word recognition, for example, first elicits a positive peak at approximately 100 ms known as the P1, which is believed to reflect perceptual and attentional processes (e.g. Luck, Heinze, Mangun, & Hillyard, 1990; Mangun, Buonocore, Girelli, & Jha, 1998), although some have reported linguistic influences at the P1 component (Segalowitz & Zheng, 2009; Sereno et al., 1998). Following the P1 is a negative peak at approximately 170 ms, known as the N1 or N170. This component distinguishes between words and symbol strings and is therefore thought to index orthographic processing (Appelbaum, Liotti, Perez, Fox, & Woldorff, 2009; Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999; Grossi, Savill, Thomas, & Thierry, 2010; Maurer, Brem, Bucher, & Brandeis, 2005; Ruz & Nobre, 2008; see Chapter 4 for further discussion). Higher-level linguistic processes such as semantic retrieval and integration are indexed by the N400, which is elicited approximately 300-600 ms after the presentation of a semantically incongruous word in a sentence (Kutas & Hillyard, 1980; see Lau, Phillips, & Poeppel, 2008 for a review). Finally, a later P600 (a positive wave from approximately 600-1000 ms) is elicited by syntactic anomalies and thus indexes grammatical processing (e.g. Friederici & Meyer, 2004). The literature and experiments presented here mainly focus on the N170 and N400 components, therefore other language-related ERP components are not discussed in detail.

Most studies investigating bilingual language processing with EEG have focused on the later ERP components reflecting higher-level linguistic processes (see Moreno, Rodríguez-Fornells, & Laine, 2008 for a review). For example, the N400 is significantly delayed in the bilingual L2 compared to the L1 (Ardal, Donald, Meuter, Muldrew, & Luce, 1990; Hahne, 2001; Moreno & Kutas, 2005; Moreno et al., 2008), indicating that semantic integration processes operate differently in a native versus a non-native language. Bilinguals also show differences at the P600 in the L2, indicating syntactic processing difficulties (e.g. Hahne, 2001; Hahne & Friederici, 2001; Proverbio, Čok, & Zani, 2002). Research has also addressed the roles of L2 proficiency and age of acquisition (AoA) in bilingual language processing. For example, some have reported that the N400 latency is delayed for late compared to early learners (e.g. Weber-Fox & Neville, 1996), or in non-natives compared to natives, but is not affected by proficiency (e.g. Ardal et al., 1990; Newman, Tremblay, Nichols, Neville, & Ullman, 2012), suggesting a stronger influence of AoA on N400 delays. In contrast, others report later latencies or enhanced amplitudes of semantic and syntactic processing components in low-proficiency bilinguals (e.g. Moreno & Kutas, 2005; Weber-Fox & Neville, 2001), suggesting a primary role of proficiency. Finally, some evidence suggests that proficiency and AoA interact in bilingual language processing (Proverbio, Adorni, & Zani, 2009). In sum, processing difficulties, especially in the L2, have been documented across a range of language-related ERP components and may be modulated by individual differences (see section 2).

Figure 1.2: Timeline of visual word recognition (from Sereno et al., 1998).

Please refer to Figure 4; Sereno, S. C., Rayner, K., & Posner, M. I. (1998). Establishing a time-line of word recognition: Evidence from eye movements and event-related potentials. *Neuroreport, 9*(10), 2195–2200.

1.2.2. fMRI studies of language processing

While EEG studies primarily concern the timing of linguistic processes, fMRI is employed to address the spatial representations of language in the brain. In monolinguals, the various facets of language activate a widespread left-lateralized[1] fronto-temporal network of brain areas (e.g. Binder et al., 1997; Ferstl, Neumann, Bogler, & Von Cramon, 2008; Gitelman, Nobre, Sonty, Parrish, & Mesulam, 2005; Richardson, Seghier, Leff, Thomas, & Price, 2011). Some brain areas are involved in certain linguistic processes, such as the left angular gyrus in orthography and the left temporal lobe in semantics. However, there is extensive overlap: in a conjunction analysis, Gitelman et al. (2005) identified a neural network commonly involved in orthographic, phonological, and semantic processing which included the left inferior frontal gyrus (LIFG), middle frontal gyrus (MFG), insula, precentral sulcus, and supplementary motor area (SMA; Figure 1.3).

It may be a natural assumption that bilingualism alters the organization of the language network, especially when two languages are integrated in the brain from birth. A wealth of research has investigated how bilingual language representation differs from that of monolinguals and how the L1 and L2 are differentially represented (see reviews in Abutalebi, 2008; Abutalebi & Green, 2007; Indefrey, 2006; Stowe & Sabourin, 2005; van Heuven & Dijkstra, 2010). Language processing generally elicits more extensive neural activation in bilinguals than in monolinguals (Kovelman, Baker, & Petitto, 2008; Kovelman, Shalinsky, Berens, & Petitto, 2008; Parker Jones et al., 2011). For example, Parker Jones et al. (2011) reported that during naming and reading tasks, bilinguals demonstrated extensive activation for both the L1 and L2 in regions of the left frontal and temporoparietal cortex (e.g. pars opercularis and pars triangularis); in monolinguals, these regions are associated with native language processing and/or control of interference. Using a grammaticality judgment task,

---

[1] Although note that the left-lateralization is specific to alphabetic languages; neural representations differ with writing systems, with Chinese for example activating a more bilateral neural network due to its heavier reliance on spatial processing (see Bolger, Perfetti, & Schneider, 2005 and Tan, Laird, Li, & Fox, 2005 for meta-analyses).

Kovelman, Baker, et al. (2008) observed that although both monolinguals and bilinguals activated the LIFG, activation in this area was stronger and more extensive for bilinguals when performing in the L2. Using the same task, Kovelman, Shalinsky, et al. (2008) reported that bilinguals recruited additional working memory and attention areas (Brodmann areas (BA) 47/11 and 46/9) more bilaterally than monolinguals. This work illustrates that language processing is more cognitively demanding in bilingualism, especially in an L2.

An ongoing debate in the field of neurobilingualism concerns whether the L1 and L2 have common or distinct neural representations. On one hand, some research has reported common spatial activation for both languages (e.g. Briellmann et al., 2004; Consonni et al., 2012; Hasegawa, Carpenter, & Just, 2002; Hernandez, Dapretto, Mazziotta, & Bookheimer, 2001; Hernandez, Martinez, & Kohnert, 2000; Illes et al., 1999; Mahendra, Plante, Magloire, Milman, & Trouard, 2003; Rüschemeyer, Zysset, & Friederici, 2006; Vingerhoets et al., 2003). For example, an extensive review by Abutalebi & Green (2007) concluded that the representations of a second language largely converge with those of the native language. Common representations have been reported for both early and late bilinguals (e.g. Consonni et al., 2012; Hernandez et al., 2000; Illes et al., 1999), suggesting a subordinate role of AoA in determining neural language representations. Alternatively, Mahendra et al. (2003) reported that similar regions of activation were elicited for both early and late bilinguals, but the extent of activation was greater for late bilinguals, suggesting a contributing role of AoA.

Figure 1.3: From Gitelman et al. (2005). Top: brain areas activated by various linguistic processes, including regions sensitive to orthography (ANA), phonology (HOM), and semantics (SYN). Bottom: conjunction of all three.

Please refer to Figures 2 and 3; Gitelman, D. R., Nobre, A. C., Sonty, S., Parrish, T. B., & Mesulam, M.-M. (2005). Language network specializations: An analysis with parallel task designs and functional magnetic resonance imaging. *NeuroImage, 26*(4), 975–985.

On the other hand, others have found that the extent of second language activation differs considerably from that of the native language (e.g. Chee, Hon, Lee, & Soon, 2001; Dehaene et al., 1997; Ding et al., 2003; Kim, Relkin, Lee, & Hirsch, 1997; Marian, Spivey, & Hirsch, 2003; Newman, Bavelier, Corina, Jezzard, & Neville, 2002; Perani et al., 1998, 2003; Wartenburger et al., 2003). Furthermore, the extent of differential activation may be sensitive to proficiency (e.g. Briellmann et al., 2004; Chee et al., 2001; De Bleser et al., 2003; Meschyan & Hernandez, 2006; Perani et al., 1998; Wartenburger et al., 2003) and AoA (e.g. Mahendra et al., 2003; Perani et al., 1996). For example, Kim et al. (1997) reported that the LIFG was sensitive to AoA, with L1 and L2 being spatially separated in late bilinguals but largely overlapping in early bilinguals. These two factors may also interact: Perani et al. (2003) assessed the roles of AoA and proficiency using a verbal fluency task and reported that earlier AoA and higher proficiency led to less extensive activation in the LIFG. The relative influences of proficiency and AoA may also be modulated by the specific linguistic process: for example, Wartenburger et al. (2003) concluded that activation for semantic judgments was more significantly affected by proficiency level, whereas grammaticality processing was more affected by AoA.

Regardless of the amount of neural overlap between the L1 and L2, the L2 generally activates a more extensive region of areas, reflecting the more effortful processing as a consequence of reduced proficiency (e.g. Briellmann et al., 2004; Chee et al., 2001; Ding et al., 2003; Hasegawa et al., 2002; Hernandez & Meschyan, 2006; Marian et al., 2003; Meschyan & Hernandez, 2006; Perani et al., 2003; Rüschemeyer et al., 2006; Vingerhoets et al., 2003; Wartenburger et al., 2003). For example, Briellmann et al. (2004) reported that the extent of activation during a noun generation task correlated with language proficiency. Hernandez & Meschyan (2006) reported more extensive activation for L2 in areas of the executive control network (see Part 3) during picture naming, suggesting that naming in an L2 requires more cognitive control. The L2 often activates the LIFG to a greater extent (De Bleser et al., 2003; Kim et al., 1997; Marian et al., 2003; Perani et al., 2003), suggesting that the weaker language places increased cognitive demands on the language processing system and requires more extensive neural resources.

In sum, fMRI research suggests that although bilinguals activate similar language processing areas as monolinguals, the amount and sometimes the regions of activation are more extensive in bilinguals, specifically in brain areas related to interference processing (Parker Jones et al., 2011). The need to control multiple languages places substantial cognitive demands not just on the language processing system, as this research demonstrates, but also on the executive processing system, leading to substantial cognitive changes that will be discussed in Part 4.

1.3. Models of bilingual language processing

Numerous language processing models have arisen from bilingualism research in attempts to explain how bilinguals control and select languages (see review in van Heuven & Dijkstra, 2010). Reflecting the general consensus of the literature, the more recent models all incorporate non-selective access. The three that are most relevant to the current discussions are reviewed.

1.3.1. The BIA+ model

The Bilingual Interactive Activation (BIA) + Model (Dijkstra & van Heuven, 2002; amended from the original BIA model: van Heuven et al., 1998) is a model of bilingual word recognition which proposes an integrated bilingual lexicon, in which the words in a target language are selected by means of a higher-level control system. This model distinguishes between a word identification system and a task/decision system (Figure 1.4). Within the word identification system, orthographic inputs activate associated phonological and semantic representations, as well as associated language nodes which act as tags specifying a word's language membership. These language nodes are connected directly to lexical form representations, so the activation of language nodes depends on the activation of other linguistic representations. As representations from different languages are activated, the word identification system collects the relative activation and passes this information to the task/decision system, which achieves response selection by weighing the relative activation of language node information from the word identification system and making a decision based on the specific task goal.[2] Thus the BIA+ model achieves language selection by accumulating evidence from bottom-up word identification processes. This model generalizes across a variety of tasks and modalities and can account for much of the emerging neuroimaging evidence on bilingual comprehension (e.g. van Heuven & Dijkstra, 2010), making it one of the primary models of bilingual language processing.

---

[2] Distinctively, the BIA+ model proposes that linguistic and non-linguistic contexts affect these systems differently. Syntactic and semantic context (and cross-linguistic similarity) can influence the word identification system, while non-linguistic context modulates the task/decision system.

Figure 1.4: The BIA+ model of bilingual word recognition (Dijkstra & van Heuven, 2002), taken from van Heuven & Dijkstra (2010).

Please refer to Figure 1; van Heuven, W., & Dijkstra, T. (2010). Language comprehension in the bilingual brain: fMRI and ERP support for psycholinguistic models. *Brain Research Reviews, 64*(1), 104–122.

1.3.2. Bilingual translation: word association, concept mediation, and the Revised Hierarchical Model

Of interest in bilingualism research is not only how lexical selection is achieved but how bilinguals move between languages, i.e. translating between L1 and L2. The theories of word association and concept mediation (e.g. Potter, So, von Eckardt, & Feldman, 1984; Figure 1.5a) consider how the L1 and L2 are linked to semantic representations. Word association proposes that L1 words have a direct link to concepts but L2 words do not, resulting in an intermediate step in L2 conceptual processing such that meaning is accessed via the L1. In contrast, concept mediation proposes that both L1 and L2 words have direct links to conceptual representations.

The Revised Hierarchical Model (RHM) of Kroll & Stewart (1994) adopted the word association and conceptual mediation theories to explain how proficiency affects bilingual language production (Figure 1.5b). The RHM proposes that early in L2 acquisition, when proficiency is low, L2 semantic access occurs via word association: L2 words are first translated into the L1, which then accesses the concept. With increasing proficiency, the links between the L2 and concepts become stronger, such that semantic access proceeds via concept mediation. The RHM's biggest strength is its ability to explain the phenomenon of 'translation asymmetry': in unbalanced bilinguals, translation from L1 to L2 is slower than translation from L2 back to L1 (Meuter & Allport, 1999). If language production in low-proficiency bilinguals proceeds through word association, L1-L2 translation requires that words must first be accessed conceptually, then be translated into the L2. In contrast, L2-L1 translation proceeds automatically through the L1 to access concepts and is therefore faster.

Balanced or highly-proficient bilinguals do not show such an asymmetry: translation in both directions occurs at the same rate because, according to the RHM, conceptual access in both languages proceeds via conceptual mediation.

Figure 1.5: From Kroll & Stewart (1994): a) Schematics of word association and concept mediation; b) The RHM.

Please refer to Figures 1 and 3; Kroll, J. F., & Stewart, E. (1994). Category interference in translation and picture naming: Evidence for asymmetric connections between bilingual memory representations. *Journal of Memory and Language, 33*, 149–174.

Although still a popular model, the RHM has been recently criticized for its assumptions, some of which are not supported by empirical evidence: for example, the RHM proposes separate lexicons and language-selective access which, as discussed above, have been largely discounted. (As the RHM is not extensively discussed in this thesis its flaws are not reviewed in detail, but see Brysbaert & Duyck, 2010; Brysbaert, Verreyt, & Duyck, 2010; and Kroll, van Hell, Tokowicz, & Green, 2010 for the full discussion, as well as section 1.4.) However, the two central predictions of the RHM – that of translation asymmetries between the languages and the importance of L2 proficiency in development – remain unique to this model.

1.3.3. The Inhibitory Control model

One drawback of the RHM is its omission of a control mechanism to explain how bilinguals restrain from naming the word that is intended for translation. The Inhibitory Control (IC) model (Green, 1998) is a production model explicitly addressing bilingual language control. This model considers languages as task schemas which compete with each other to control the output from the lexico-semantic system. Inhibitory links within and between the language task schemas ensure that the task goals of a higher-level ‘supervisory attentional system’ (SAS) are met. Word selection in each language is performed via ‘language tags’ at the lemma level (lemmas are conceptual representations which are associated with specific word forms and specify various syntactic properties): during language selection, lemmas in both languages are activated and all lemmas that do not possess the target language tag are inhibited. To illustrate, when a bilingual intends to speak in an L2, the SAS conceptualizes this goal and then modulates the activation of the language task schemas of the L1 and L2 (Figure 1.6). As the L2 is the goal, both language task schemas inhibit lemmas with an L1 language tag. Language control in the IC model is thus cross-linguistically inhibitory (i.e. is exerted by the target L2 task schema over the non-target L1 task schema) and self-inhibitory (i.e. within the L1 language task schema).

Importantly, the SAS is a *reactive* system, responding proportionally to the amount of activation of the lemmas in each language: if the non-target language is activated strongly, the SAS will respond accordingly by implementing strong inhibition. Illustrating this, the IC model predicts that speaking in an L2 requires stronger inhibitory control because the L1, the non-target language, is the stronger language. This is supported by language switching paradigms, which require participants to switch between languages while naming pictures. Switching from the L2 into the L1 elicits larger switch costs (longer RTs) than switching from the L1 to the L2. According to the IC model, L2-to-L1 switching requires overcoming the stronger inhibition that the SAS exerts over the more dominant language. In sum, this model proposes that language control over non-selective lexical access is obtained by reactive inhibition at the lemma level.

Figure 1.6: Schematic from the IC model (from Green, 1998) depicting how regulatory processing occurs in a lexical decision task (LDT) involving language switching.

Please refer to Figure 3; Green, D. W. (1998). Mental control of the bilingual lexico-semantic system. *Bilingualism: Language and Cognition, 1,* 67–81.

1.4. Production versus comprehension

One important issue in bilingualism research is the distinction between language production (e.g. speaking, picture naming) and language comprehension (e.g. reading or listening to language, lexical decision tasks). Historically this has been a significant divide in language research, as although they reach a common goal of communication and involve seemingly similar processes, production and comprehension can be two very different sides of the same coin (see review in Gollan et al., 2011). Comprehension requires translation of an input signal (e.g. a word or spoken phrase), sometimes noisy or incomplete, into a semantic representation. In contrast, production works in reverse, beginning with a semantic concept, selecting the appropriate word(s), and resulting in motor production and articulation. In short, comprehension works from lexical forms to semantics, while production works from semantics to lexical forms.

This distinction is especially important when discussing bilingual language processing models, as most extant models are specific to either production or comprehension and may not be applicable to the alternative modality. For instance, one recent criticism of the RHM is its assumption of excitatory lexical connections between words in L1 and L2. Computationally, this would create additional cross-linguistic activation and impede processing of the perceptual input (therefore most computational language models include inhibitory connections; Brysbaert & Duyck, 2010). In response, Kroll et al. (2010) argue that although excitatory connections are problematic for comprehension models like the BIA+ (because they create more interference between word-form neighbours), production models like the RHM are supported by empirical evidence suggesting top-down activation of semantically-related concepts. As the RHM proposes that an L2 word activates its L1 translation equivalent via top-down excitatory connections, Kroll et al. (2010) argue that it is therefore not at odds with the literature. In short, bilingual language processing models are generally only applicable to the modality they are designed to explain.

To demonstrate this distinction, recall that the IC model argues for language control via active inhibition of the non-target language during production. In contrast, the BIA+ model proposes a more passive language control mechanism during comprehension, namely via selection of language membership from among activated lexical representations. These models thus place the locus of language control on different mechanisms. However, these are not mutually exclusive: although production and comprehension may each be comprised of both inhibition and selection, inhibition may feature more prominently when selecting a language for speech whereas selection may be the foremost mechanism of comprehension. All of the experiments presented in this thesis will test comprehension in the context of automatic, covert (silent) reading (a Stroop task). Nevertheless, the distinction between production and comprehension is an important issue which is considered throughout these discussions.

1.5. Summary of the bilingual language system

To summarize Part 1, research suggests that the bilingual language system is fundamentally different from that of monolinguals. Bilingual lexical access is now believed to be largely non-selective: both languages are activated in parallel and can interact, although some degree of language-specific lexical control may be possible (Costa et al., 1999, 2006). Bilingual non-selective lexical access creates cross-linguistic conflict, even in a monolingual context, which requires additional cognitive control resources during language processing. Computational models of bilingual language processing such as the BIA+ model and the IC model have embraced this theory of non-selective access by incorporating mechanisms of language selection and control. Neuroimaging evidence suggests that although bilinguals activate similar areas as monolinguals for language processing, the amount of activation is usually stronger and more extensive, especially for the L2 or non-dominant language. As a result of this altered structure of the language system, bilingualism creates cognitive changes that can be both detrimental and beneficial in nature. The next section (Part 2) will investigate the detrimental aspects of bilingualism: that of delayed language processing.

2. Part 2: The Bilingual Disadvantage in Lexical Processing

Part 1 has demonstrated how the bilingual language system is altered by the presence of two (or more) languages. As might be expected, having multiple languages to choose from consequently impedes (or, in some cases, facilitates) language processing. Accordingly, it is commonly reported that throughout the lifespan, bilinguals are slower in lexical processing see e.g. Bialystok et al., 2009 and Bialystok, 2009 for reviews). For instance, Bialystok et al. (2008) tested monolinguals and bilinguals on a range of working memory, lexical retrieval, and cognitive control tasks. Bilinguals performed worse on all tasks of verbal ability: they were slower to name pictures, produced fewer exemplars in category fluency, and scored lower on vocabulary measures.

Figure 1.7: Vocabulary measures across the lifespan (from Bialystok et al., 2009).

Please refer to Figure 1; Bialystok, E., Craik, F. I. M., Green, D. W., & Gollan, T. H. (2009). Bilingual Minds. *Psychological Science in the Public Interest, 10*(3), 89–129.

Although the phenomenon of a 'bilingual disadvantage' on language and vocabulary measures is commonly reported, this conclusion is often derived from research that does not clearly delineate between L1 and L2 (e.g. Bialystok et al., 2008; Bialystok & Feng, 2009; Gollan & Acenas, 2004). For example, the bilingual group in Bialystok et al. (2008) consisted of individuals from a range of language backgrounds; furthermore, some participants were native English speakers and some were not, meaning that some bilinguals were tested in their L1 and some in their L2. This makes it difficult to discern whether the bilingual disadvantage results from the weaker language system in the L2 or whether bilingualism creates widespread disadvantages that are also observable in the L1. To avoid such ambiguity, this thesis strives to distinguish between delays in the L1 and L2 by collecting evidence on each individually. As an introduction to the literature documenting the bilingual disadvantage, the evidence regarding lexical access speed in the L2 is reviewed first, followed by the L1.

2.1. The bilingual L2 lexical disadvantage

The majority of bilingualism research has focused on processing difficulties in the L2, as this is often the weaker, less-dominant language. Reduced proficiency can affect the performance of the language system in a number of ways. One variable that is particularly susceptible to language proficiency is lexical processing speed. This is best understood from a computational point of view. For example, some computational models of cognitive processing (specifically regarding the Stroop task; see Chapter 2, section 2.1.1) propose that the strength of connections between words and concepts are modulated by experience and practice (Cohen, Dunbar, & McClelland, 1990; Logan, 1980; Lovett, 2002; MacLeod & Dunbar, 1988). Reduced proficiency in an L2 generally stems from fewer lifetime encounters of L2 words. Therefore bilinguals have less experience with the L2, resulting in weaker connection strengths, or ‘weights’, in the L2 language system. Within word or concept nodes in a language system, activation accumulates as a function of connection weights until the system reaches a critical threshold. Weaker weights between nodes in the L2 language system will therefore accumulate activation more slowly, taking longer to reach this threshold and resulting in ‘slower’ language processing. Ergo, strength equals speed.

Notably, the BIA+ model implements the L2 processing delay not as weaker connection strengths but as a lower resting-level activation of L2 semantic representations. Resting-level, like connection strength, is determined by subjective frequency, i.e. how often the word is encountered. Reduced experience with the less-proficient language creates a lower resting-level activation of L2 words, requiring more accumulated evidence and therefore more processing time before the critical threshold is achieved and, consequently, producing delayed semantic activation in the L2 compared to the L1. This hypothesis is incorporated in the BIA+ model as the *temporal delay assumption* (Dijkstra & van Heuven, 2002; see also van Heuven & Dijkstra, 2010).

Regardless of the specific mechanism of the processing delay (i.e. weaker weights or lower resting-level activation), the theory that bilinguals have delayed lexical access in their L2 due to reduced proficiency compared to both the L1 and to monolinguals is referred to hereafter as the ‘*bilingual L2 lexical disadvantage hypothesis’*. Evidence for this conjecture comes from a range of tasks demonstrating that bilinguals experience difficulties and delays in lexical processing in their L2 (see Table 1.1 for quantifications of the delay; see Moreno et al., 2008; Runnqvist, Strijkers, Sadat, & Costa, 2011; van Heuven & Dijkstra, 2010 for reviews). For example, in category fluency, Gollan, Montoya, & Werner (2002) reported that bilinguals produced fewer words in their L2 than monolinguals. Bilinguals also experience more tip-of-the-tongue (ToT) states than monolinguals when naming pictures in their L2, demonstrating word-finding difficulties (Gollan, Montoya, & Bonanni, 2005; Gollan & Silverberg, 2001; Pyers, Gollan, & Emmorey, 2009). In production tasks such as picture naming, bilinguals name pictures in their L2 or less-dominant language more slowly than monolinguals (Gollan, Montoya, Cera, & Sandoval, 2008; Ivanova & Costa, 2008; Kohnert, Hernandez, & Bates, 1998). L2 delays have also been documented in comprehension tasks such as lexical decision, in which bilinguals perform more slowly in their L2 compared to monolinguals (Portin & Laine, 2001; Ransdell & Fischler, 1987).

More compelling support for the L2 processing delay comes from studies using EEG, which provides fine-grained temporal resolution of cognitive processes. As mentioned earlier (section 1.2.1), the L2 experiences delays in higher-level semantic and syntactic ERP components such as the N400 and P600 (Ardal et al., 1990; Hahne, 2001; Hahne & Friederici, 2001; Moreno & Kutas, 2005; Proverbio et al., 2002; see review in Moreno et al., 2008). Importantly, EEG studies have also reported L2 delays at very early stages of linguistic processing. Differences between native and non-native languages are observable as early as 150 ms after word presentation, indicating delays in low-level lexical processes such as visual letter decoding or orthographic word recognition (Liu & Perfetti, 2003; Proverbio et al., 2009). For example, Liu & Perfetti (2003) observed later peaks of the N150 (thought to index graphical form) and the N250 (thought to index phonological processing and articulatory preparation) in the L2 than the L1. Proverbio et al. (2009), testing trilinguals on a letter detection task, observed different time windows of lexical effects for each language. Word-vs.-pseudoword differences occurred in an L1 between 160-180 ms (N1 component); in an L2 between 260-320 ms (N2 component); and in an L3 between 320-380 ms (N3 window), demonstrating non-native delays at very early stages of linguistic processing.

Therefore the L2 delay in lexical processing is robust and well-documented, both in behavioural and neuroimaging studies and across production and comprehension modalities. However, bilinguals do not always show disadvantages in picture naming. For example, cognate facilitation effects have been documented (e.g. Hoshino & Kroll, 2008) and Gollan, Montoya, & Bonanni (2005) reported no bilingual delays when naming proper nouns. Specifically, the fact that bilinguals do not experience delays when naming cognates – which theoretically should be used across both languages with a frequency equal to that of monolinguals – highlights that the bilingual disadvantage arises from reduced frequency of language use.

Table 1.1: Summary of behavioural and EEG studies quantifying bilingual lexical processing delays by directly testing monolinguals vs. bilinguals or bilinguals' L1 vs. L2. Where multiple task conditions were included, RTs are collapsed over all trial types for each language group. Studies that do not quantify a delay, or that report differences based on an absence of effects in bilinguals (e.g. Hahne & Friederici, 2001), are omitted.

Study	Participants	Modality	Task	Magnitude of Delay		
				Monolinguals vs. L1	**Monolinguals vs. L2**	**L1 vs. L2**
Ardal et al., 1990	- English monolinguals - French-English bilinguals (mixed L1 English and L1 French)	- Comprehension - EEG (N400 component)	- Reading semantically anomalous sentences in English and French	**22 ms** (monolinguals 377 ms; L1 399 ms)	**43 ms** (monolinguals 377 ms; L2 420 ms)	**21 ms** (L1 399 ms; L2 420 ms)
Elston-Güttler & Friederici, 2005	- English natives - German-English bilinguals	- Comprehension - Behavioural - EEG (N400)	- English lexical decision			**107 ms** in behavioural data (English natives 656; non-natives 763) **50 ms** in N400
Gollan, Montoya, Fennema-Notestine & Morris, 2005 (Exp. 1)	- English monolinguals - English-Spanish bilinguals (English-dominant)	- Production - Comprehension - Behavioural	- Picture naming in English - Picture classification	**90 ms** (approx.) for naming (Monolingual 900 ms; L1 approx. 990 ms) No difference in classification		
Gollan et al., 2008 (Exp. 1)	- English monolinguals - English-Spanish bilinguals (English dominant)	- Production - Behavioural	- Picture naming in English and Spanish	**125 ms** (Monolinguals approx. 900 ms; L1 approx. 1025 ms)	**500 ms** (Monolinguals approx. 900 ms; L2 approx. 1400 ms)	**375 ms** (L1 approx. 1025 ms; L2 approx. 1400)

Gollan et al., 2011	- English monolinguals - Spanish-English bilinguals - Dutch-English bilinguals	- Production - Comprehension - Behavioural	- English picture naming (Exp. 1) - English lexical decision (Exp. 2)		**Naming:** **140 ms** for Spanish-English; **275 ms** for Dutch-English (Monolinguals approx. 850 ms; Spanish-English approx. 990 ms; Dutch-English approx. 1125 ms) **Lexical Decision:** **70 ms** for Spanish-English; **80 ms** for Dutch-English (Monolinguals approx. 650; Spanish-English approx. 720 ms; Dutch-English approx. 730 ms)	
Hahne, 2001	- German monolinguals - Russian-German bilinguals	- Comprehension - EEG (N400 and later syntactic positivity)	- Auditory comprehension of German semantic violations		**110 ms** in N400 (monolinguals 340 ms; L2 450 ms) **150 ms** in later syntactic positivity (monolinguals 800 ms; L2 950 ms)	
Ivanova & Costa, 2008	- Spanish monolinguals - Spanish-Catalan bilinguals (mixed L1 Spanish and L1 Catalan)	- Production - Behavioural	- Spanish picture naming	**33 ms** (monolinguals 573 ms; L1 606 ms)	**77 ms** (monolinguals 573 ms; L2 650 ms)	**44 ms** (L1 606 ms; L2 650 ms)

Lehtonen & Laine, 2003	- Finnish monolinguals - Finnish-Swedish bilinguals	- Comprehension - Behavioural	- Finnish lexical decision	**127 ms** (monolinguals 614 ms; L1 741 ms)		
Lehtonen et al., 2012	- Finnish monolinguals - Finnish-Swedish bilinguals	- Comprehension - Behavioural - EEG (N400)	- Finnish lexical decision	**116 ms** in behavioural data (monolinguals 668 ms; L1 784 ms) No latency differences in N400		
Liu & Perfetti, 2003	- Chinese-English bilinguals	- Production - EEG (N150 and N250)	- Delayed naming task in English and Chinese			**100 ms** (L1 150 ms; L2 250 ms)
Moreno & Kutas, 2005	- Spanish-English bilinguals (Mixed English-dominant and Spanish-dominant)	- Comprehension - EEG (N400)	- Reading semantically anomalous English sentences			**27 ms** (English-dominant 390 ms; English non-dominant 417 ms)
Newman et al., 2012	- Native English speakers - Spanish-English bilinguals	- Comprehension - EEG (N400)	- Reading English semantic violations			**28 ms** (L1 English 311 ms; L2 English 339 ms)
Phillips et al., 2004	- English-French bilinguals	- Comprehension - Behavioural - EEG	- Semantic categorization in English and French			**96 ms** in behavioural RTs (L1 626 ms; L2 722) **50 ms** in N400 latency (for high-proficiency subjects)
Phillips et al., 2006	- English-French bilinguals	- Comprehension - EEG (N400)	- Auditory comprehension in English and French			**100 ms** (200-250 in L1; 300-350 in L2)

Proverbio et al., 2009	- Italian-English-German trilinguals	- Comprehension - EEG (N1, N2, N3)	- Silent letter detection with Italian, English, and German words			**100 ms** (L1 160-180 ms; L2 260-320 ms; L3 320-380 ms)
Ransdell & Fischler, 1987	- English monolinguals - Native English bilinguals (range of L2s)	- Comprehension - Behavioural	- English lexical decision	**129 ms** (monolinguals 731 ms; L1 860 ms)		

2.2. The bilingual L1 lexical disadvantage

Given that the L2 is often the less-dominant, later-learned language, processing difficulties might be expected. However, it has also been proposed that the bilingual L1 is delayed compared to monolinguals (Gollan, Montoya, Fennema-Notestine, & Morris, 2005). This theory, known as the *weaker links hypothesis* (Gollan, Montoya, Fennema-Notestine, et al., 2005) or the *reduced frequency account* (Pyers et al., 2009), proposes that compared to monolinguals, bilinguals use each of their languages less often, including their first language. As discussed earlier, reduced frequency of use leads to weaker ties between words and concepts and consequently delayed lexical access. Therefore splitting communication between two languages predicts delays not only in the L2 but also in the L1 compared to monolinguals (Gollan & Acenas, 2004; Gollan et al., 2008; Gollan, Montoya, Fennema-Notestine, et al., 2005)[3]. In other words, bilingual lexical access is slower than that of monolinguals even when both groups are performing in their native language. This theory is referred to here as the '*bilingual L1 lexical disadvantage hypothesis'*.

Mirroring the L2 disadvantage patterns, evidence shows that bilinguals are slower at picture naming in their L1 or more dominant language compared to monolinguals (Table 1.1; Gollan, Montoya, Fennema-Notestine, et al., 2005; Ivanova & Costa, 2008). For example, Ivanova & Costa (2008) reported faster picture naming responses for monolinguals than bilinguals, even when bilinguals were naming in their first and most-dominant language. L1 delays have also been reported in comprehension, such that bilinguals demonstrate slower RTs in lexical decision and list recognition tasks (e.g. Lehtonen & Laine, 2003; Ransdell & Fischler, 1987). Only two previous studies have used EEG to investigate processing delays in bilinguals' L1 (Ardal et al., 1990; Proverbio et al., 2002). Proverbio et al. (2002) found that bilinguals were slower to make grammaticality judgments on sentences in their native language than monolinguals were, indicating bilingual difficulties with higher-level syntactic processing in the L1. Ardal et al. (1990) reported a small but significant delay (approximately 22 ms) in the N400 response to semantically-anomalous sentences for bilinguals when performing in their L1 compared to monolinguals. Therefore EEG evidence also exists for L1 lexical processing delays; however, these previous studies tested higher-level semantic and syntactic processing rather than earlier lexical access, so it remains unclear how early L1 processing delays occur. This question will be explicitly addressed in Chapter 4.

2.3. Production versus comprehension in bilingual delays

As mentioned earlier (section 1.4), the issue of production versus comprehension is an important factor to consider in bilingualism, especially when discussing the bilingual lexical

---

[3] Note that the temporal delay assumption and the weaker links hypothesis place the locus of the delay at different points. The temporal delay assumption proposes that differences in the resting-level activations of words, which are based on subjective word frequency, create delays in the L2. In contrast, the weaker links/reduced frequency hypothesis places the delay in the weaker connection strengths between words and concepts.

disadvantage hypotheses. Specifically, the reduced frequency hypothesis was developed to explain bilingual disadvantages in *production*, while the temporal delay assumption primarily explains delays in *comprehension*. Presumably a delay in one modality would translate to another; however, recent evidence has demonstrated that processing delays are more robust in production tasks than comprehension. According to the 'frequency lag hypothesis', this occurs because production requires more exposures, or more lifetime practice, to reach high levels of proficiency (Gollan et al., 2011). Nevertheless, although the magnitude of the bilingual processing delay may be affected by modality, delays have been documented in both production and comprehension, as would be expected if the bilingual delay is a fundamental part of the language system.

2.4. Summary of the bilingual lexical disadvantage

In summary, one cognitive consequence of bilingualism is a processing delay across a range of linguistic levels, including word recognition, language production, and semantic integration. This delay is especially prominent in the L2. Evidence for delays in the L1, particularly at early stages of linguistic processing, is less robust. These theories, collectively referred to as the *bilingual lexical disadvantage hypotheses*, will be evaluated throughout this thesis.

In contrast to this cognitive disadvantage of bilingualism, the presence of multiple languages in the brain also confers cognitive benefits in executive control abilities, which will be discussed next. Part 3 will first provide an overview of the field of executive control and Part 4 will discuss how and why these abilities are enhanced in bilinguals.

3. Part 3: Introduction to Executive Control

A key feature of the human cognitive system is the implementation of executive control, which refers to a variety of cognitive situations in which distracting information must be ignored, a habitual response must be overcome, or one must switch between varying mental sets. (The terms 'executive control', 'cognitive control', and 'executive processing' are used synonymously throughout this thesis, although further distinction is made when discussing bilingual abilities: see sections 4.4 and 4.5). These processes require a number of cognitive functions including working memory, decision making, task maintenance, response selection and/or suppression, conflict detection/resolution, and inhibitory control. For the purposes of the current discussions, this review focuses mainly on conflict processing and monitoring, as these abilities are thought to be primarily enhanced in bilingualism.

3.1. Measuring executive control

Numerous cognitive paradigms exist for assessing executive control abilities. Typical conflict resolution paradigms, such as the Stroop (Stroop, 1935), Simon (Simon, 1969), or flanker (Eriksen & Eriksen, 1974) tasks, require responding to one stimulus dimension while suppressing or ignoring another (see Lu & Proctor, 1994 and MacLeod, 1991 for reviews). For example, in the flanker task participants must judge the directionality of an arrow (e.g. left or right) while ignoring distracting information from other flanking arrows (e.g. Fan, Fossella, Sommer, Wu, & Posner, 2003; Figure 1.8a). Incongruent conditions occur when the two dimensions do not match (e.g. a rightward-pointing arrow flanked by leftward-pointing arrows), whereas congruent conditions consist of converging stimulus information (e.g. a rightward-pointing arrow flanked by other rightward-pointing arrows). 'Neutral' or 'control' trials generally contain no conflicting or facilitating information (e.g. an arrow flanked by lines or squares). Another common conflict paradigm, particularly in bilingualism research, is the Simon task, in which a coloured square is presented peripherally on the screen and participants indicate its colour using one of two hands (e.g. left hand for blue, right hand for red; Figure 1.8b). In incongruent conditions, the hand required for response differs from the laterality of stimulus presentation (e.g. a red square, requiring a right-hand response, presented on the left side of the screen). Congruent conditions consist of converging spatial and response information, whereas neutral conditions contain no conflicting or converging information.

Most of the studies presented in this thesis employ the Stroop task, a common linguistically-based conflict paradigm (see Chapter 2 for a detailed discussion). In a traditional Stroop task, participants are presented with colour words printed in coloured ink and must overcome the highly-practised reading process in order to name the colour of the ink (Figure 1.9; MacLeod, 1991; Stroop, 1935). Incongruent conditions consist of conflicting word and colour information (e.g. 'red' printed in blue ink, correct response 'blue'), whereas congruent conditions consist of matching information (e.g. 'red' printed in red ink). Control conditions generally consist of non-word symbol strings in coloured ink (e.g. 'xxxx' or '%%%%' in red) or colour patches.

Figure 1.8: a) Example of the flanker task (taken from Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002), in which participants respond to the directionality of the central arrow. b) Example of the Simon task, in which participants use two hands to indicate the colour of a square presented peripherally (in incongruent and congruent conditions) or centrally (in control conditions) on the screen.

a)

Please refer to Figure 1; Bunge, S. A., Dudukovic, N. M., Thomason, M. E., Vaidya, C. J., & Gabrieli, J. D. E. (2002). Immature frontal lobe contributions to cognitive control in children: Evidence from fMRI. *Neuron*, *33*(2), 301–311.

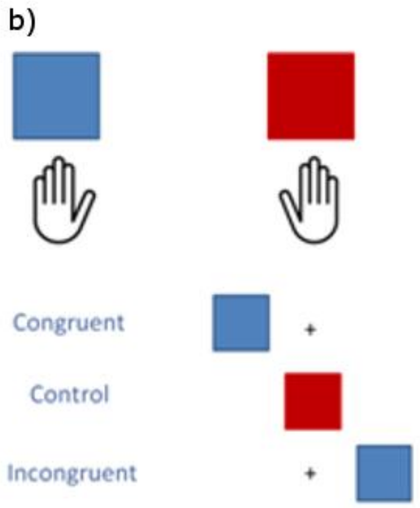
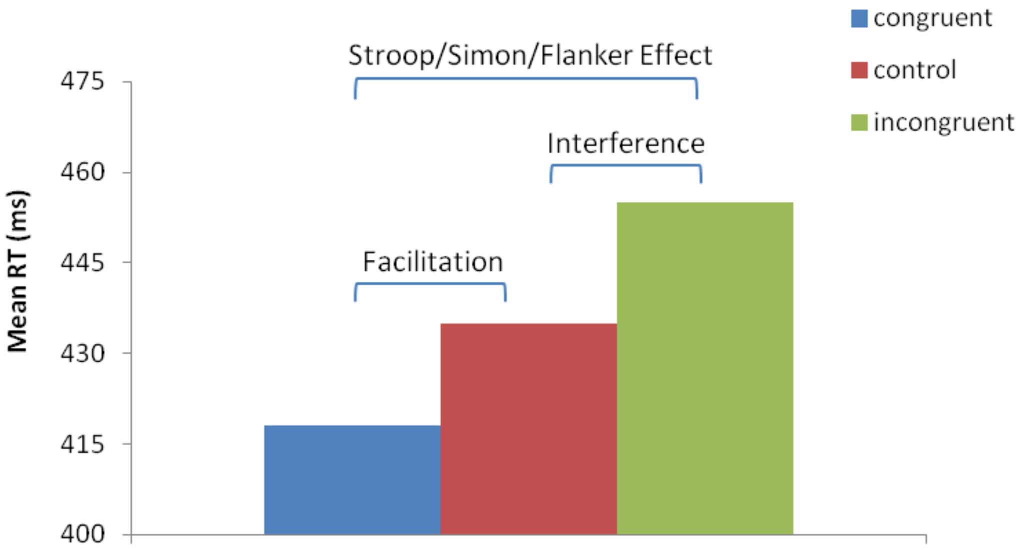


Figure 1.9: Example of congruent, control, and incongruent stimuli, respectively, in the Stroop task.

In all executive control tasks, including the Stroop, incongruent conditions generally elicit slower RTs due to the need to overcome the conflicting information, whereas the converging information in congruent conditions generates faster RTs. RTs for the control condition, which does not generate any interference or facilitation, generally fall between the incongruent and congruent conditions (Figure 1.10). The ‘interference effect’ is typically calculated as the difference between incongruent and control RTs and the ‘facilitation effect’ as the difference between control and congruent RTs. The difference between the incongruent and congruent conditions, termed the ‘Stroop effect’ (or Simon/Flanker effect, depending on the task), is also often reported. (The term ‘conflict effects’ is used here to refer to either Stroop or interference effects, i.e. the presence of incongruent trials.) Stroop effects are comprised of both interference and facilitation and may confound conflict effects; therefore including an appropriate control condition is important. Specifically, the magnitude of interference can be modulated by the semantic salience of the word (Brown, 2011). For example, words with semantic colour associates such as ‘blood’ or ‘grass’ generate more interference than colour-neutral words like ‘chair’ (Dalrymple-Alford, 1972; MacLeod, 1991). Most researchers use a control condition of symbol or letter strings (‘%%%%’ or ‘xxxx’), colour patches, or colour words printed in black ink (MacLeod, 1991; Stroop, 1935). Letter and symbol strings (i.e. either ‘xxxx’ or ‘%%%%’) are used throughout this thesis.

Figure 1.10: Typical distribution of RTs in conflict tasks (based on data from Aisenberg & Henik, 2012), with incongruent RTs being longest, followed by control and congruent conditions, respectively. Stroop/Simon/Flanker effects (depending on the task) refer to the difference between incongruent and congruent trials; interference effects to incongruent minus control; and facilitation effects to control minus congruent.



The magnitude of the interference effect in conflict tasks provides a measure of cognitive control abilities: individuals with poorer cognitive control exhibit larger interference effects. For example, compared to young adults at the peak of their cognitive abilities, children and older adults demonstrate increased interference effects due to their respectively underdeveloped and declining cognitive abilities (e.g. Bunge, Dudukovic, et al., 2002; Davidson, Amso, Anderson, & Diamond, 2006; Milham et al., 2002). Other factors such as working memory ability and fluid intelligence are also associated with cognitive control (Gray, Chabris, & Braver, 2003; Unsworth & Engle, 2007), although the directionality of these relationships is unclear. As will be discussed in Part 4, one other individual difference that affects cognitive control is bilingualism.

3.2. Neuroimaging studies of executive control

Neuroimaging techniques have been immeasurably valuable in understanding the neural mechanisms involved in executive control. A full review of executive control tasks is beyond the scope of this thesis, so the current discussions focus on studies of conflict processing using EEG and fMRI.

3.2.1. Cognitive control as measured by fMRI

Studies using fMRI have identified an extensive network of brain areas involved in executive control, mainly localized to the prefrontal and parietal cortices. This network is reliably activated for a range of executive functions, including working memory, vigilance or sustained attention, inhibition of prepotent behaviours, and the detection and resolution of cognitive conflict (Niendam et al., 2012). Most commonly implicated is the anterior cingulate cortex (ACC; e.g. Melcher & Gruber, 2009; Peterson et al., 1999, 2002) which, according to the *conflict monitoring hypothesis*, monitors for incoming conflict, then signals other areas of the prefrontal cortex such as the dorsolateral prefrontal cortex (DLPFC) to resolve the conflict (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Botvinick, Cohen, & Carter, 2004; van Veen & Carter, 2002). The conflict monitoring hypothesis is a popular theory in the literature; however, the ACC is active in many aspects of cognition and other theories exist regarding conflict processing in the prefrontal cortex (e.g. Roelofs, van Turennout, & Coles, 2006; Swick & Turken, 2002; see Chapter 5, section 3.1.3).

Besides the ACC, the executive control network consists of numerous prefrontal and parietal structures. For example, a specific area of the medial frontal cortex termed the ‘rostral cingulate zone’ (RCZ), which includes the ACC, is involved in performance monitoring and response conflict (Figure 1.11; Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004). The left inferior frontal gyrus (LIFG), which comprises Broca’s area and is often implicated in language processing (e.g. Costafreda et al., 2006; Montant, Schön, Anton, & Ziegler, 2011), is active in both linguistic and non-linguistic conflict tasks and may execute suppression of irrelevant semantic information (Novick, Kan, Trueswell, & Thompson-Schill, 2009; Novick, Trueswell, & Thompson-Schill, 2005; Ye & Zhou, 2009). The left angular gyrus, also usually implicated in language processes (e.g. Binder et al., 1997; Horwitz, Rumsey, & Donohue, 1998; Penniello et al., 1995; Pugh et al., 2000), has been reported for conflict tasks and may be involved in keeping multiple responses in mind during response selection (Bunge, Hazeltine, Scanlon, Rosen, & Gabrieli, 2002; Fan, Flombaum, McCandliss, Thomas, & Posner, 2003; Schroeder et al., 2002; Ye & Zhou, 2009). The right angular gyrus and the right inferior and superior parietal lobes have been associated with visuospatial attention, particularly top-down control of attention towards the task-relevant target (Corbetta, Miezin, Shulman, & Petersen, 1993; Culham & Kanwisher, 2001; Milham, Banich, & Barad, 2003; Rushworth, Ellison, & Walsh, 2001). Finally, subcortical structures like the basal ganglia and caudate are also involved in cognitive control (Abutalebi & Green, 2007; Lehtonen et al., 2005; Niendam et al., 2012). Although debates still exist about the contributions of these structures to executive control and conflicting evidence exists regarding the function of almost all of them, their reliable activation across tasks highlights their involvement in the control network in a general and non-specific way.

The executive control network is activated during general executive functioning such as shifting and updating, initiation and planning of actions, and cognitive flexibility (Figure 1.12; see Nee, Wager, & Jonides, 2007; Niendam et al., 2012 for meta-analyses). In conflict control tasks, activation in areas such as the ACC, DLPFC, and left parietal lobe are typically enhanced for incongruent relative to congruent or control trials (e.g. Barch et al., 2001; Bunge, Hazeltine, et al., 2002; Fan, Flombaum, et al., 2003; Frühholz, Godde, Finke, & Herrmann, 2011; Kim, Chung, & Kim, 2010; King, Korb, & Egner, 2012; Liu, Banich, Jacobson, & Tanabe, 2004; Peterson et al., 1999, 2002). The recruitment of this network is largely similar across conflict tasks. For example, comparing a flanker, Stroop, and spatial conflict task, Fan, Flombaum, et al. (2003) found that although the precise areas of activation differed with the specific task, a conjunction of all three types of conflict activated a largely similar network including the ACC, left inferior parietal lobe, and right inferior frontal gyrus. Thus an extensive, domain-general executive control network is activated for conflict processing as well as for general monitoring and maintenance faculties.

Figure 1.11: From a meta-analysis of cognitive control, a specific area in the medial frontal cortex termed the ‘rostral cingulate zone’ (RCZ) is reliably involved in various aspects of cognitive control (from Ridderinkhof, Ullsperger et al., 2004).

Please refer to Figure 1; Ridderinkhof, K. R., Ullsperger, M., Crone, E. A., & Nieuwenhuis, S. (2004). The role of the medial frontal cortex in cognitive control. *Science, 306*(5695), 443–447.

Figure 1.12: Primary regions of the executive control network and their functions (from Abutalebi & Green, 2007).

Please refer to Figure 1; Abutalebi, J., & Green, D. W. (2007). Bilingual language production: The neurocognition of language representation and control. ***Journal of Neurolinguistics, 20,*** **242–275.**

3.2.2. Cognitive control as measured by EEG

Cognitive control tasks typically elicit two conflict-related ERP components: an early negativity in the incongruent condition, referred to here as an ‘N_{inc}’ (i.e. a negativity associated with the incongruent condition), followed by a later positivity in the incongruent condition, referred to as an ‘LPC’ (late positive component). These components are commonly identified in Stroop, Simon, and flanker tasks, although they generally occur later in the Stroop task due to the slower process of word reading and earlier in the Simon and flanker task, which require lower-level perceptual processing.

3.2.2.1. The N_{inc}

The N_{inc}, sometimes called an N450, is identified as a more negative wave in the incongruent condition compared to either the congruent or control conditions, generally appearing from approximately 300-550 ms post-stimulus (Figure 1.13; Appelbaum, Meyerhoff, & Woldorff, 2009; Caldas, Machado-Pinheiro, Souza, Motta-Ribeiro, & David, 2012; Larson, Kaufman, & Perlstein, 2009; Liotti, Woldorff, Perez, & Mayberg, 2000; Markela-Lerenc et al., 2004; West, 2003). Source localization techniques have traced this component to the prefrontal cortex, specifically the ACC (Badzakova-Trajkov, Barnett, Waldie, & Kirk, 2009; Hanslmayr et al., 2008; Liotti et al., 2000; Markela-Lerenc et al., 2004). Although some have specifically suggested that the N_{inc} reflects conflict detection in the ACC (Hanslmayr et al., 2008; West, 2003), the majority of the literature implicates this component indistinctly in general conflict detection and resolution processes, which are more active in the incongruent condition (e.g. Badzakova-Trajkov et al., 2009; see Chapter 5). The N_{inc} amplitude is modulated by the degree of conflict present (West & Alain, 2000) and may be indicative of cognitive efficiency: for example, West & Alain (2000) reported an attenuated N_{inc} component in older adults with poorer cognitive control abilities.

Figure 1.13: Illustration of the N_{inc} (grey shading), in which the incongruent condition is more negative than the congruent condition; and the LPC (yellow shading), in which the incongruent condition is more positive. Adapted from Caldas et al. (2012); negativity is plotted upwards.

Please refer to Figure 4; Caldas, A. L., Machado-Pinheiro, W., Souza, L. B., Motta-Ribeiro, G. C., & David, I. A. (2012). The Stroop matching task presents conflict at both the response and nonresponse levels: An event-related potential and electromyography study. *Psychophysiology, 49*(9), 1215–1224.

3.2.2.2. The LPC

The second conflict-related ERP is a late positive component (LPC), sometimes called a slow positivity (SP: Chen & Melara, 2009) or a conflict slow potential (conflict SP: Larson et al., 2009; West, 2003). The LPC is identified as a positivity in the incongruent condition compared to the congruent or control conditions, occurring from approximately 600-900 ms post-stimulus (Figure 1.13; Appelbaum, Meyerhoff, et al., 2009; Larson et al., 2009; Liotti et al., 2000; West & Alain, 1999). The cognitive processes generating this component are still unclear (see Chapter 5). One study traced the LPC to the inferior frontal gyrus and left extrastriate region (West, 2003), suggesting that this component indexes conflict resolution processes. In contrast, the amplitude of the LPC has been correlated with RT and accuracy, suggesting the LPC instead reflects response selection (West, Jakubek, Wymbs, Perry, & Moore, 2005). As the LPC has also been localized to Wernicke’s area (Snyder, Abdullaev, Posner, & Raichle, 1995), some have proposed that it reflects semantic processing (Appelbaum, Meyerhoff, et al., 2009; Liotti et al., 2000); specifically, it may be associated with semantic re-activation of the word following conflict resolution (Liotti et al., 2000). Despite the ambiguous underlying function of this component, the LPC is nevertheless reliably activated during conflict processing.

3.3. Summary of executive control

Executive control is a large and active field of research in cognitive psychology. Conflict tasks assess cognitive control abilities via interference magnitude, which reflects the efficiency of conflict detection and resolution. Neuroimaging methods such as fMRI and EEG have identified neural and electrophysiological correlates of these processes, namely the prefrontal ‘executive control network’ and the N_{inc} and LPC ERP components. Throughout this thesis, cognitive control in monolinguals and bilinguals will be assessed via behavioural interference magnitude, N_{inc}/LPC amplitude and latency, and the extent of activation in the executive control network. Although many individual factors affect executive processing, the cognitive demands of bilingual language processing are thought to confer an enhancement of executive control abilities. Part 4 will examine the empirical phenomenon that bilinguals outperform monolinguals on cognitive control tasks: the so-called ‘bilingual advantage’.

4. Part 4: Implications of Bilingualism for Executive Control

As discussed in Part 1, non-selective access to an integrated bilingual lexicon suggests that both languages are activated in parallel during language processing. Consequently, bilinguals must constantly exert control over their languages, either by inhibiting the non-target language (as proposed by the IC model) or engaging advanced selection mechanisms (as proposed by the BIA+ model). This places extraordinary demands on cognitive resources and is accordingly thought to enhance executive processing abilities in bilinguals. This section first reviews evidence demonstrating cognitive control recruitment during bilingual language processing, then discusses the ‘bilingual advantage’, i.e. the phenomenon that bilinguals outperform monolinguals on cognitive control tasks. Behavioural and neuroimaging evidence for the bilingual advantage is reviewed, as are two theories of bilingual cognitive control which will be evaluated throughout this thesis.

4.1. Cognitive control during bilingual language processing

As previously discussed in section 1.1, cross-linguistic effects occur during bilingual language processing even in monolingual contexts (Degani & Tokowicz, 2010; Midgley et al., 2008; Poulisse & Bongaerts, 1994; Rodriguez-Fornells et al., 2005, 2002; Soares & Grosjean, 1984; Spalek et al., 2011; Thierry & Wu, 2007; Wu & Thierry, 2011; van Hell & Dijkstra, 2002; van Heuven et al., 2008). Furthermore, neuroimaging research demonstrates that bilinguals activate the executive control network during language comprehension and production (e.g. Hernandez & Meschyan, 2006; Rodriguez-Fornells et al., 2005; van Heuven et al., 2008). Therefore substantial evidence demonstrates that even during basic language processing, bilinguals recruit executive control mechanisms to manage the cross-linguistic activation resulting from non-selective access.

Many studies attempt to understand bilingual language control by investigating explicit language switching (Christoffels, Firk, & Schiller, 2007; Crinion et al., 2006; Hernandez, 2009; Hernandez et al., 2001, 2000; Kuipers & Thierry, 2010; Magezi, Khateb, Mouthon, Spierer, & Annoni, 2012; Price, Green, & von Studnitz, 1999; Wang, Kuhl, Chen, & Dong, 2009; see Hervais-Adelman, Moser-Mercer, & Golestani, 2011; Luk, Green, Abutalebi, & Grady, 2011; Rodriguez-Fornells, De Diego Balaguer, & Münte, 2006 for reviews). Language switching paradigms typically require bilinguals to name pictures in alternating languages, with the target language indicated by an external cue. Switch trials require naming in the alternative language from the previous trial, whereas non-switch trials maintain the same language across consecutive trials. The ‘switch cost’ is the RT difference between switch and non-switch trials. For unbalanced bilinguals, switching into the L1 generates larger switch costs than switching into the L2, whereas balanced bilinguals generally show similar switching costs for each language (Costa et al., 2006; Meuter & Allport, 1999; although see also Calabria, Hernández, Branzi, & Costa, 2012). This asymmetry in unbalanced bilinguals is attributed to the need to overcome the stronger inhibition exerted over the L1 (see the IC model, Green, 1998; section 1.3.3).

Neurally, bilinguals recruit areas of the executive control network during language switching, including the ACC, middle frontal gyri, LIFG, left parietal lobe, basal ganglia, and head of caudate (Figure 1.14; Abutalebi et al., 2007; Abutalebi & Green, 2008; Bialystok et al., 2009; Crinion et al., 2006; Guo, Liu, Misra, & Kroll, 2011; Hernandez, 2009; Hernandez et al., 2001; Luk et al., 2011; Price et al., 1999; Rodriguez-Fornells et al., 2006; Wang et al., 2009). For example, Crinion et al. (2006) found that the left caudate was sensitive to language switches during comprehension, suggesting its involvement in monitoring and language control. Abutalebi et al. (2007) reported ACC and left caudate activation during picture naming in bilinguals, suggesting that these areas are involved in active maintenance of both languages during production. Activation in these executive control areas is generally enhanced when switching into the weaker language (Abutalebi et al., 2007, 2008; Wang, Xue, Chen, Xue, & Dong, 2007), mirroring the pattern in asymmetric switch costs and suggesting that bilinguals inhibit their L1 to speak the L2.

Figure 1.14: Results of the meta-analysis by Luk et al. (2011) showing brain areas commonly activated during bilingual language switching tasks.

Please refer to Table 3 and Figure 1; Luk, G., Green, D. W., Abutalebi, J., & Grady, C. (2011). Cognitive control for language switching in bilinguals: A quantitative meta-analysis of functional neuroimaging studies. *Language and Cognitive Processes*, 1–10. doi: 10.1080/01690965.2011.613209.

Importantly, this neuroimaging evidence demonstrates that the areas recruited by bilinguals to deal with cross-linguistic interference and language switching are also involved more generally in the executive control network found in monolinguals. Therefore bilinguals use language-non-specific mechanisms of executive control to manage their languages. Because bilinguals use domain-general cognitive control during everyday language processing, their executive control abilities become enhanced, leading to a ‘bilingual advantage’ on cognitive control tasks.

4.2. The bilingual advantage in executive control tasks

The interdependence of cognitive control and language processing in bilingualism is believed to enhance cognitive processing abilities beyond those of monolinguals, who do not need to resolve language conflict on a daily basis. This is supported by extensive empirical evidence demonstrating that bilinguals outperform their monolingual counterparts across a range of executive control domains (see Bialystok, 2009, 2011; Bialystok et al., 2009; Hilchey & Klein, 2011; Tao, Marzecová, Taft, Asanowicz, & Wodniecka, 2011 for reviews). The hypothesis that bilinguals experience superior cognitive abilities due to the entwined functions of executive control and language processing is referred to here as the *bilingual cognitive advantage hypothesis*.

The bilingual cognitive advantage has been documented across a spectrum of executive control tasks. For instance, bilinguals show smaller conflict effects than monolinguals on the Simon and Stroop tasks, an advantage that is maintained across the lifespan (see Figure 1.15; Bialystok, 2006; Bialystok, Craik, Klein, & Viswanathan, 2004; Bialystok et al., 2008; Bialystok & Depape, 2009; Bialystok, Martin, & Viswanathan, 2005; Martin-Rhee & Bialystok, 2008). The attentional network task (ANT; Fan, McCandliss, Sommer, Raz, & Posner, 2002) is an executive control paradigm assessing three dimensions of executive processing: control (via a flanker task), alerting (response to cueing), and orienting (response to valid cueing). Bilinguals demonstrate not only smaller flanker effects (Costa, Hernández, Costa-Faidella, & Sebastián-Gallés, 2009; Costa, Hernández, & Sebastián-Gallés, 2008) but also more efficient use of alerting cues (Costa et al., 2008; although see Hernández, Costa, Fuentes, Vivas, & Sebastián-Gallés, 2010, who find no difference in orienting between monolinguals and bilinguals).

Similar to language switching, task- and goal-switching paradigms assess cognitive control by calculating switch costs (which index the ability to overcome the previous task goal). Bilinguals show smaller switch costs than monolinguals due to their experience with language switching (e.g. Garbin et al., 2010; Prior & Macwhinney, 2010). Tasks of cognitive flexibility also require goal-switching: for example, in a dimensional card-sort task, participants may be asked to first sort cards based on an object’s shape, then by its colour. Changing rules requires overcoming the previous rule set and focusing on the new target dimension. Again bilinguals show smaller costs for switching rules than monolinguals, both in cohorts of children (Bialystok & Martin, 2004) and across adulthood (Bialystok, Craik, & Ruocco, 2006). Bialystok & Shapero (2005) have also reported that bilingual children performed better on a reversible figures task, in which one figure may be seen in multiple different ways, demonstrating greater cognitive flexibility with bilingualism.

As well as inhibitory control and task switching, bilingual advantages have been documented in attentional control (Carlson & Meltzoff, 2008; Costa et al., 2009); theory of mind (Bialystok & Senman, 2004; Goetz, 2003); inhibiting pre-potent responses, as in anti-saccade and go/no-go tasks (Bialystok & Viswanathan, 2009; although see Luk, Anderson, Craik, Grady, & Bialystok, 2010, who find no advantage on the no-go); and even in learning new words (Bartolotti, Marian, Schroeder, & Shook, 2011). Therefore bilinguals demonstrate superior executive processing abilities across a wide range of tasks, not just in inhibitory control but in cognitive flexibility and monitoring as well.

Figure 1.15: Stroop effects for younger and older monolinguals and bilinguals (from Bialystok, 2011, adapted from Bialystok et al., 2008). In both groups, bilinguals show smaller Stroop effects than monolinguals.

Please refer to Figure 3; Bialystok, E. (2011). Reshaping the mind: The benefits of bilingualism. *Canadian Journal of Experimental Psychology*, *65*(4), 229–235.

4.2.1. Neuroimaging evidence for the bilingual advantage

Although the bilingual advantage is behaviourally well-established, there is a paucity of research examining this phenomenon using neuroimaging methods (see Bialystok et al., 2009; Hervais-Adelman et al., 2011; Hilchey & Klein, 2011; Moreno et al., 2008; Rodriguez-Fornells et al., 2006 for reviews). As will be reviewed next, while EEG evidence is scant and inconclusive, more robust bilingual differences in the structural and functional recruitment of the executive control network are observed with fMRI.

4.2.1.1. EEG studies

Only two EEG studies have investigated the electrophysiological indices of the bilingual cognitive advantage (Heidlmayr, Moutier, Hemforth, & Isel, 2012; Kousaie & Phillips, 2012). Kousaie & Phillips (2012) compared bilingual and monolingual performance on Stroop, Simon, and flanker tasks. As well as the typical N_{inc} conflict component (referred to as an N2), the P3 (reflecting resource allocation and schema updating) and the error-related negativity (ERN, reflecting error detection or post-response conflict) components were evaluated. Contrary to the majority of research, Kousaie & Phillips (2012) found no bilingual advantage in behavioural interference effects, although differences arose in the ERP data. The groups differed in indices of conflict monitoring (bilinguals showed a smaller N2 in the Stroop task), error-related processing (bilinguals showed smaller ERNs in the Stroop task but larger ERNs in the flanker task), resource allocation (bilinguals had smaller P3 amplitudes in the Simon task), and stimulus categorization (monolinguals had a later P3 component in the flanker task). In general, the amplitude of conflict components was reduced for bilinguals; however, these effects were not consistent across the three paradigms, suggesting that the particular task modulates how bilinguals and monolinguals respond to conflict.

Unpublished data by Heidlmayr et al. (2012) also tested monolinguals and bilinguals on a Stroop task with EEG. The authors observed no behavioural evidence of a bilingual advantage in inhibitory control; however, in the EEG data monolinguals demonstrated significant conflict effects at an N200, the N_{inc} (called an N400), and the LPC. The bilinguals, in contrast, showed only a significant N_{inc} effect, the amplitude of which was reduced relative to monolinguals. The results of Heidlmayr et al. (2012) thus converge with those of Kousaie & Phillips (2012), suggesting that the bilingual advantage may be manifest as a reduction in conflict-related ERP amplitude, reflecting more efficient conflict processing (e.g. Swick & Turken, 2002). However, a positive relationship has also been documented between ERP amplitude and cognitive abilities, such that poorer cognitive control is associated with a smaller N_{inc} (Holmes & Pizzagalli, 2008; West & Alain, 2000). The electrophysiological patterns of bilingual conflict processing will be further evaluated in Chapter 5.

4.2.1.2. fMRI/MEG studies

On a neural basis, fMRI and magnetoencephalography (MEG) evidence indicates differences in how the cognitive control network is recruited in bilingualism (Abutalebi et al., 2012; Bialystok, Craik, et al., 2005; Garbin et al., 2010; Luk et al., 2010). For example, Luk et al. (2010) observed that during interference suppression in a flanker task, monolinguals activated the left temporal pole and left superior parietal lobe whereas bilinguals activated a more extensive network including bilateral frontal, temporal and subcortical regions. Bialystok, Craik et al. (2005) reported MEG data demonstrated that better performance (faster RTs) on a Simon task was correlated with greater cingulate and superior/inferior frontal activity for bilinguals, but with left middle frontal regions in monolinguals, suggesting different underlying executive control mechanisms. Using a task-switching and flanker task, Abutalebi et al. (2012) also reported functional differences between monolinguals and bilinguals: although both groups activated the dorsal ACC for both tasks, bilinguals used this structure more efficiently than monolinguals, showing reduced activation which correlated with better behavioural performance. Finally, in a non-verbal task-switching paradigm, Garbin et al. (2010) found that monolinguals recruited the right IFG, ACC, and left inferior parietal lobe, whereas bilinguals recruited only the LIFG. This evidence therefore suggests that bilinguals use different functional networks than monolinguals for executive control tasks (see Chapter 8 for further discussions).

4.3. The elusiveness and sensitivity of the bilingual cognitive advantage

Although prevalent in the literature, the bilingual cognitive advantage is sensitive to a number of individual and experimental factors. For example, although advantages have been documented across the lifespan (Bialystok, 1999, 2010; Bialystok et al., 2004; Bialystok, Craik, & Ryan, 2006; Bialystok et al., 2008; Costa et al., 2008), the magnitude of the advantage is affected by development. As cognitive control follows an inverted-U distribution over the lifespan (Craik & Bialystok, 2006), larger bilingual advantages occur in children and older adults, since there is more room for improvement; in young adults who are at the peak of their cognitive abilities, the bilingual advantage may only be observed in cognitively-demanding situations (Costa et al., 2009; Martin-Rhee & Bialystok, 2008). The bilingual cognitive advantage is also sensitive to the type of executive control being tested. For instance, bilinguals typically show advantages on conflict tasks requiring management of conflicting attentional demands or interference suppression (e.g. ignoring the conflicting stimulus in a flanker task), but not on impulse control or response inhibition (e.g. withholding a button press in a no-go paradigm; Bialystok & Viswanathan, 2009; Carlson & Meltzoff, 2008; Luk et al., 2010; Martin-Rhee & Bialystok, 2008). Martin-Rhee & Bialystok (2008) proposed that interference suppression is similar to the type of conflict bilinguals experience during language processing, whereas response inhibition paradigms, which index the ability to stop an initiated action, do not mirror the bilingual experience and therefore demonstrate no advantage.

In some cases, a bilingual advantage is not found unless controlling for other variables. For example, Bialystok & Feng (2009), using a linguistic executive control task (proactive interference), observed a bilingual advantage only when controlling for vocabulary knowledge. Similarly, using a battery of executive function tasks in children, Carlson & Meltzoff (2008) found a bilingual advantage only when controlling for verbal ability, age, and socio-economical status (SES). Morton & Harper (2007) also identified SES as a critical factor, reporting identical performance for monolingual and bilingual children but larger cognitive advantages for children from high-SES families. Furthermore, the bilingual advantage is sensitive to individual differences such as proficiency level (e.g. superior cognitive control with higher L2 proficiency: Bialystok, Craik, & Ruocco, 2006) and the similarity of the bilingual's two languages (e.g. larger bilingual advantages for speakers of two orthographically-similar languages: Linck, Hoshino, & Kroll, 2008; see Chapter 6 for a more detailed discussion). The subjective frequency of language switching also plays a role: for example, Soveri et al. (2011) found that bilinguals who reported frequent language switching in daily conversations performed better on a task switching paradigm than bilinguals who rarely switched. In contrast, Festman et al. (2010) reported that frequent language switchers performed worse on tasks of inhibition, self-monitoring, problem-solving, and generative fluency, suggesting that frequent switching may be indicative of weaker language control. Individual differences can therefore significantly influence the magnitude of the bilingual cognitive advantage and, subsequently, are important factors to consider.

In sum, although the bilingual cognitive advantage is well-documented, in actuality it is an elusive phenomenon and is sensitive to a number of factors. In a recent review, Hilchey & Klein (2011) provided a critical and thorough quantification of the bilingual advantage, concluding that the bilingual 'interference advantage' on conflict tasks (i.e. smaller conflict effects when comparing incongruent and congruent trials) is a weak effect that is often not found at all. Far more common is the finding of a 'global reaction time' advantage, such that bilinguals are faster than monolinguals on *all* trials, both incongruent and congruent (e.g. Bialystok et al., 2004; Bialystok, Craik et al., 2005; Costa et al., 2009; Martin-Rhee & Bialystok, 2008; although see Bialystok et al., 2008). To distinguish these different effects, Hilchey & Klein outlined two hypotheses regarding bilingual executive processing, which will be contrasted throughout this thesis: the 'bilingual inhibitory control advantage', or BICA hypothesis; and the 'bilingual executive processing advantage', or BEPA hypothesis.

4.4. The Bilingual Inhibitory Control Advantage (BICA)

The *BICA hypothesis* refers specifically to the finding of smaller interference effects on inhibitory control tasks for bilinguals than monolinguals. It proposes that this occurs because bilinguals engage inhibitory control mechanisms to control cross-linguistic influences during language processing:

> “Frequent use of the inhibitory processes involved in language selection in bilinguals will result in more efficient inhibitory processes, which will confer general advantages on non-linguistic interference tasks – that is, those requiring conflict resolution. These advantages will be reflected in reduced interference effects in bilinguals as compared to monolinguals. In other words, bilinguals should show an advantage over monolinguals on trials with response conflict” (pg. 628).

Because this hypothesis places the locus of the bilingual advantage on inhibitory control mechanisms, it draws a parallel to the IC model (section 1.3.3), which proposes that the bilingual lexical system controls languages during production via reactive inhibition of lemmas (Green, 1998; although note that the IC model places the locus of inhibition specifically within the language system, whereas the BICA hypothesis does not specify where inhibition takes place). Crucially, this hypothesis predicts that bilinguals exhibit advantages only in the presence of conflict. Because most conflict tasks assess cognitive control by quantifying and comparing interference effects (incongruent vs. control) or Stroop/Simon/Flanker effects (incongruent vs. congruent), which assess conflict processing, this ‘interference advantage’ (i.e. smaller interference effects for bilinguals) has become the most common conception of the bilingual advantage. However, the BICA hypothesis predicts no difference between groups in the absence of conflict, such as on control or congruent trials (Figure 1.16a). It therefore cannot explain why bilinguals more often demonstrate faster RTs on all trial types, i.e. the global RT advantage.

4.5. The Bilingual Executive Processing Advantage (BEPA)

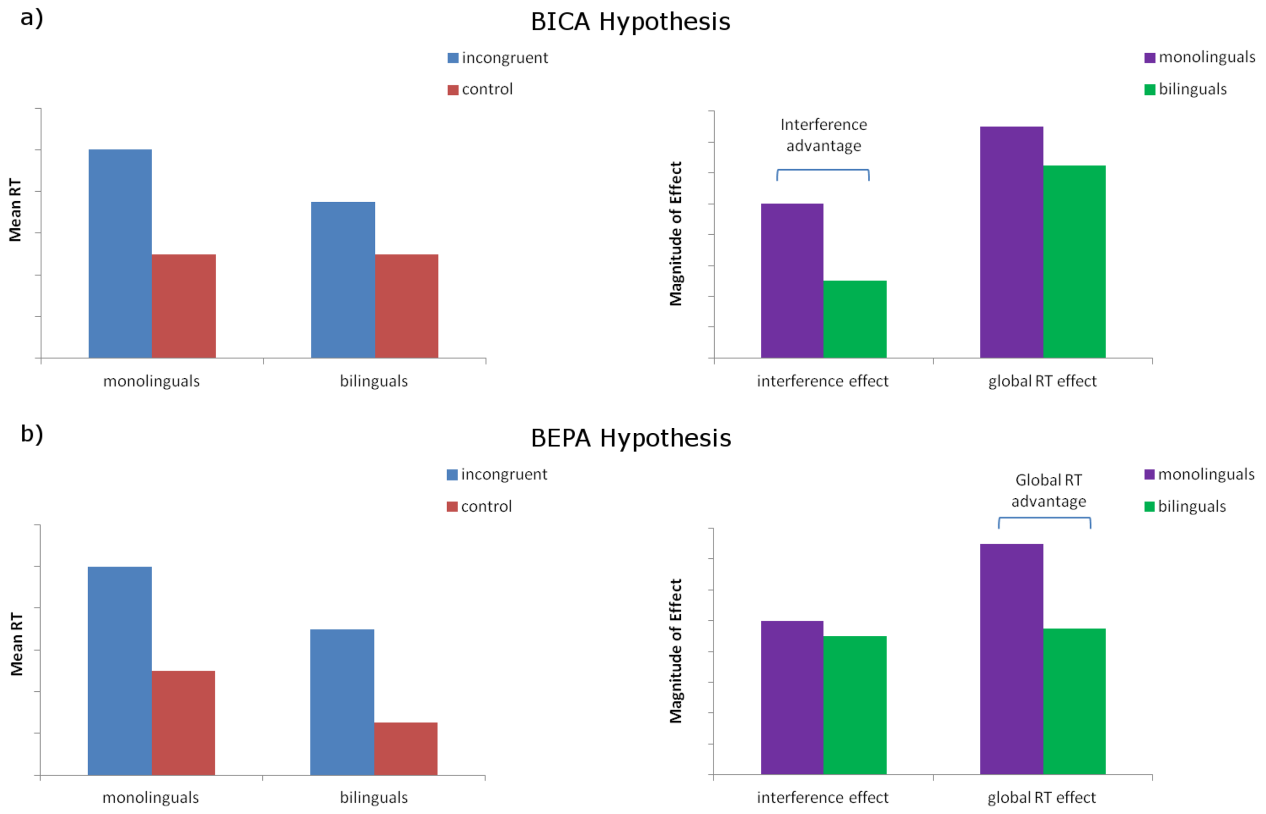
In contrast, the *BEPA hypothesis* states that bilinguals have an advantage in domain-general executive processing: “bilinguals enjoy domain-general executive functioning advantages, as indexed by largely equivalent performance benefits on all conditions in non-linguistic interference tasks” (Hilchey & Klein, 2011, pg. 629). Importantly, this hypothesis is not restricted to conflict processing, but rather predicts a more general advantage in executive processing, leading to faster processing in all contexts and on all trial types. As the reduction in processing speed occurs equally across conditions, bilinguals and monolinguals may not differ significantly when comparing interference effects (Figure 1.16b), which could explain the elusiveness of the bilingual interference advantage. However, the difference in cognitive abilities is clear when comparing the global RT (i.e. the average RT of all conditions).

More specifically, this global executive processing advantage may stem from superior bilingual abilities in monitoring and cognitive maintenance. This conjecture comes from studies showing a bilingual advantage only for high-conflict conditions (Costa et al., 2009; Martin-Rhee & Bialystok, 2008). For example, Costa et al. (2009) manipulated the proportions of incongruent and congruent trials in the ANT (see section 4.2) to create low-demand (mostly congruent or incongruent trials) or high-demand (equal proportions of congruent and incongruent trials) conditions. In low-demand conditions, no significant interference advantage or global RT advantage occurred, whereas in the high-demand condition, no interference advantage occurred but there was a robust global RT advantage. Costa et al. (2009) concluded that bilinguals are better at evaluating the situations in which conflict resolution is required, thereby possessing more efficient monitoring which benefits global processing speed. Martin-Rhee & Bialystok (2008) manipulated processing demands in a Simon task by introducing a delay in responding: high-demand conditions required an immediate response, whereas low-demand conditions required a delayed response that allowed time for conflict resolution. A global RT advantage, but not an interference advantage, occurred only in the high-demand condition, suggesting again that bilinguals have enhanced cognitive monitoring systems. Furthermore, Bialystok, Craik, & Ryan (2006) have proposed that presenting blocks of the same congruencies creates a low-demand condition which eradicates the bilingual global RT advantage; randomized congruency presentation, in contrast, requires constant monitoring for conflict, in which bilingual advantages in monitoring can be observed (Bialystok et al., 2009).

The BEPA therefore argues that bilingualism enhances a central executive system that regulates processing across a range of cognitive demands including, but not limited to, conflict resolution. This more efficient processing confers advantages on all trials, generating a global RT advantage. Specifically, researchers have proposed that the enhancement of general monitoring and maintenance abilities arises from the constant need to maintain the target language, or the ‘relevant attentional set’ (Bialystok et al., 2009; Colzato et al., 2008), which parallels the BIA+ model of language comprehension (see section 1.3.1). Recall that this model places the mechanism of language selection in the task/decision system, which performs goal maintenance and monitors incoming information from the word identification system. Such constant monitoring of the environment for language membership could enhance monitoring and selection abilities more generally, as proposed by the BEPA.

The BICA and BEPA hypotheses will be considered here under the larger term of ‘bilingual executive control’ or the ‘bilingual cognitive advantage’. Evidence of an interference advantage (i.e. smaller interference effects) in bilinguals will be considered support for the BICA hypothesis, while a global RT advantage (i.e. faster RTs in all trial types) will be considered support for the BEPA hypothesis. Throughout the experiments presented here, evidence will be gathered for and against these two subsets of the bilingual cognitive advantage.

Figure 1.16: Hypothetical predictions of the BICA and BEPA hypotheses. a) According to the BICA hypothesis, bilinguals have superior inhibitory control abilities, leading to faster RTs in the presence of conflict (i.e. incongruent trials) but no difference in control trials compared to monolinguals. This creates significantly smaller interference effects (the ‘interference advantage’), as well as marginally smaller global RT effects. b) According to the BEPA hypothesis, bilinguals experience a global processing advantage and are faster on all trial types, creating a relative equivalence of interference effects but a significant ‘global RT advantage’ compared to monolinguals.



4.6. Summary of the bilingual cognitive advantage

Bilingualism therefore places considerable demands on executive control during language production and comprehension. Over time, this enhanced use of the cognitive control system results in more efficient processing, observable in bilinguals’ superior performance across a range of executive processing tasks. Furthermore, neuroimaging studies have reported functional differences in the structure and recruitment of the executive control and language networks, suggesting that the non-selective nature of bilingual language processing creates an interdependence of these networks. Overall, this research demonstrates a domain-general advantage in cognitive control, referred to here as the *bilingual cognitive advantage hypothesis*. Specifically, the BICA hypothesis predicts that highly-developed inhibitory control mechanisms generate smaller interference effects in conflict tasks for bilinguals (interference advantage), whereas the BEPA hypothesis predicts that enhanced domain-general executive processing abilities lead to superior performance on all trial types (global RT advantage).

5. Summary of the Cognitive Effects of Bilingualism

Bilingualism leads to a myriad of cognitive changes, variable in their effects and complex in their interactions. This chapter has provided a broad overview of how the presence of two languages in one brain fundamentally affects the language system and cognitive functioning. As outlined in Part 1, bilingual lexical access is largely non-selective, as supported by empirical evidence of cross-linguistic effects during language processing. The IC model of language production and the BIA+ model of word recognition computationally model this non-selectivity and implement mechanisms of control and selection to explain how bilinguals successfully communicate in a target language. Part 2 reviewed the *bilingual lexical disadvantage hypotheses*, the proposals that reduced experience with language leads to weaker language connections and subsequent delays in lexical access, not only in the less-proficient language but also in the native language. Part 3 introduced executive control, a diverse cognitive ability involving conflict control and monitoring. Conflict paradigms like the Stroop, Simon, and flanker tasks quantify executive control via the magnitude of interference effects; neural effects of conflict are observable in the amplitude of ERP components and the extent and location of brain activation. Finally, Part 4 explained how the daily cognitive demands of bilingual communication enhance control abilities and lead to superior performance on executive control tasks. This *bilingual cognitive advantage hypothesis* may stem from enhanced conflict resolution abilities (as proposed by the *bilingual inhibitory control advantage (BICA) hypothesis*) and/or superior monitoring and maintenance abilities (as proposed by the *bilingual executive processing advantage (BEPA) hypothesis*). This thesis explores the factors of delayed lexical access and enhanced cognitive control in bilingual cognitive processing. To do so, a variation of the Stroop task is employed, which is introduced in the next chapter.

Chapter 2: Introduction to the Stroop Task

As discussed in Chapter 1, the daily use of multiple languages confers cognitive changes in both linguistic processing and executive control. Linguistically-based cognitive control tasks are valuable in identifying how these functional abilities interact. One such paradigm is the Stroop task, which is used throughout this thesis to explore lexical processing speed and cognitive control abilities in monolinguals and bilinguals. This chapter first provides an overview of the utility of the Stroop task in evaluating linguistic ability. Following this is an introduction to stimulus onset asynchrony (SOA) in the Stroop task, a manipulation which temporally varies word and colour presentation and thereby creates a unique way of assessing lexical and executive control abilities in bilingualism.

1. Using the Stroop Task to Investigate Lexical and Cognitive Processing

As described in Chapter 1 (section 3.1), the Stroop task presents a colour word in coloured ink and requires participants to name the ink colour. A robust interference effect is generated when the word and colour do not match, making it a reliable assessment of cognitive control abilities (see MacLeod, 1991 for a review). However, because the source of conflict relies on semantic activation of the word, the magnitude of interference can also be used as a proxy for language ‘strength’ or reading skill.

It is generally believed that Stroop interference arises from the need to inhibit or overcome the highly practised and therefore highly ‘automatic’ process of reading. Supporting this, the Stroop word-reading task, in which participants read the printed word and ignore the ink colour, produces much smaller interference effects than colour-naming, in which participants name the ink colour and ignore the word (Glaser & Glaser, 1982; MacLeod, 1991; although interference effects are occasionally reported in word-reading conditions: Atkinson, Drysdale, & Fulham, 2003; Blais & Besner, 2007; Smithson, Khan, Sharpe, & Stockman, 2006). The insignificant influence of colour on word reading, relative to the considerable influence of words on colour naming, illustrates that the processing pathways for reading are strong and well-established due to years of practice.

However, reading is not an inherent human skill. While spoken language has evolved in every human culture on earth and is acquired by children relatively effortlessly, learning to read and write takes years of practice and problems like dyslexia often persist into adulthood. This makes the Stroop task an interesting paradigm because it relies not only on language-based conflict but on reading ability. Conflict in the Stroop task hinges on the reading of the word: without a strong link between orthographic forms and concepts, incongruent words have little influence. Because this task relies so heavily on reading experience, it is often used in children and young adults as a measure of reading proficiency (e.g. Protopapas, Archonti, & Skaloumbakas, 2007): stronger interference effects indicate more proficient or more ‘automatic’ reading. Therefore the Stroop task can be used not only as a measure of cognitive control but also of language skill and proficiency.

2. The Stroop Task in Bilinguals

In bilingualism, the Stroop task is useful for evaluating not only the relative strengths of each language but also how languages conflict with each other. In the traditional ‘bilingual Stroop task’, words are presented in either the L1 or L2 and the participant vocally names the ink colour in either the L1 or the L2. This creates within-language conditions (e.g. both input word and response in L1) and between-language conditions (e.g. input word in L1 and response in L2). Interference effects are generally larger for within-language than between-language Stroop conditions (e.g. Goldfarb & Tzelgov, 2007; Naylor, Stanley, & Wicha, 2012). The difference (within-language minus between-language interference), termed the ‘within-language Stroop superiority effect’ or WLSSE (Goldfarb & Tzelgov, 2007; van Heuven, Conklin, Coderre, Guo, & Dijkstra, 2011), provides a measure of the relative strength of the languages. For example, the magnitudes of within- and between-language interference effects are dependent on subjective L2 proficiency (Chen & Ho, 1986; Mägiste, 1984; Naylor et al., 2012; Sumiya & Healy, 2004; Tzelgov, Henik, & Leiser, 1990). In proficient but unbalanced bilinguals, Tzelgov et al. (1990) observed a larger WLSSE for the non-dominant language than for the dominant language, whereas in balanced bilinguals the WLSSE magnitudes were similar. Tzelgov et al. interpreted this as evidence of word association in the unbalanced bilinguals and concept mediation in the balanced bilinguals (as proposed by the RHM: Kroll & Stewart, 1994; see Chapter 1, section 1.3.2).

The orthographic similarity of bilinguals’ languages also affects WLSSE magnitude. Languages with similar orthographies (e.g. English and German) generally show smaller WLSSE effects, whereas different orthographies (e.g. English and Chinese) generate larger WLSSE effects (e.g. Brauer, 1998; van Heuven et al., 2011). Orthography and proficiency also interact: for example, Brauer (1998) observed that low-proficiency bilinguals showed more within- than between-language interference when responding in their L1, regardless of script similarity, whereas the opposite pattern occurred when responding in the L2. High-proficiency participants of different scripts showed greater within- than between-language interference when responding in both languages, whereas high-proficiency bilinguals of similar languages showed equal amounts of within- and between-language interference. In light of this previous literature, the first three experiments presented in this thesis (Chapters 3-5) tested Chinese-English bilinguals in order to minimize the overlap between languages and avoid cross-linguistic facilitation effects. The effect of script is directly addressed and manipulated in Chapter 6. Language orthography is thus an influential but often overlooked factor of bilingualism that will play a substantial role in this thesis.

2.1. Stroop interference and L2 proficiency

Proficiency affects not only the magnitude of the WLSSE in the bilingual Stroop task, but also the magnitude of interference in each language. Generally, smaller interference effects occur in the L2 than in the L1 (Braet, Noppe, Wagemans, & Op de Beeck, 2011; Mohamed Zied et al., 2004; Naylor et al., 2012; Sumiya & Healy, 2004). This has been attributed to weaker language ties or 'reduced automaticity' of the second language. However, with higher proficiency this asymmetry is assuaged: for example, Mägiste (1984) observed more interference in the L1 than L2 in unbalanced bilinguals, whereas in balanced bilinguals the interference was equivalent. Naylor et al. (2012) also reported equivalent interference effects for both languages in balanced bilinguals, highlighting that this asymmetric effect is driven by proficiency.

The fact that the L1 and L2 generate different amounts of interference highlights the interaction of executive control abilities and linguistic processes in bilinguals. Specifically, it indicates that "the effects of language proficiency on cognitive control are secondary to its effects on automaticity" (Braet et al., 2011, page 4). In other words, cognitive control abilities cannot be the sole determinant of bilingual Stroop performance, otherwise both languages would generate equal amounts of interference. Instead, the relative strength of the language also plays a role. For example, Braet et al. (2011) normalized L2 interference by controlling for the magnitude of L1 interference, thereby eliminating the influence of individual differences in cognitive control ability. Braet et al. reported that these normalized Stroop interference scores were positively correlated with reading skill: the higher the proficiency, the stronger the interference effect. In sum, in the same way that Stroop interference reflects reading ability in monolinguals, the magnitude of interference in each language can reveal the relative proficiency of that language in bilinguals.

2.1.1. Computational models of interference and proficiency

Computational models of the Stroop task can explain the neural mechanisms underlying the role of proficiency in Stroop interference effects. The parallel distributed processing (PDP) model of Cohen et al. (1990) proposes that word and colour dimensions are processed in parallel; each dimension is weighted and evidence from both dimensions is gathered continuously until a response threshold is reached (Figure 2.1). Consistent evidence (i.e. a congruent trial) reduces the response threshold, creating facilitation, whereas inconsistent evidence (i.e. an incongruent trial) raises the response threshold, resulting in longer RTs and more interference. Importantly, Cohen et al.'s PDP model emphasizes the strength of pathway connections in interference: weaker pathways produce less conflict. Since word processing pathways are stronger and more 'automatic' than colour processing pathways, an incongruent word produces interference in colour naming. The PDP model also includes a strong role for attention, which modulates task goals such as colour-naming.

Cohen et al. (1990) also emphasize the role of language experience in generating Stroop interference. They propose that within a language or reading system, the strength of the connections between nodes varies as a function of practice, attention, and, in the case of conflict tasks, the relative strength of the two competing processes. Cohen et al. therefore advocate for a continuum of processing strength among network connections. Increased language experience strengthens the connections between words and concepts (see Chapter 1, section 2.1), generating larger interference effects with increasing language proficiency or more experience with reading.

Figure 2.1: Network architecture of the Stroop PDP model of Cohen et al. (1990).

Please refer to Figure 1; Cohen, J. D., Dunbar, K., & McClelland, J. L. (1990). On the control of automatic processes: a parallel distributed processing account of the Stroop effect. *Psychological Review, 97*(3), 332–361.

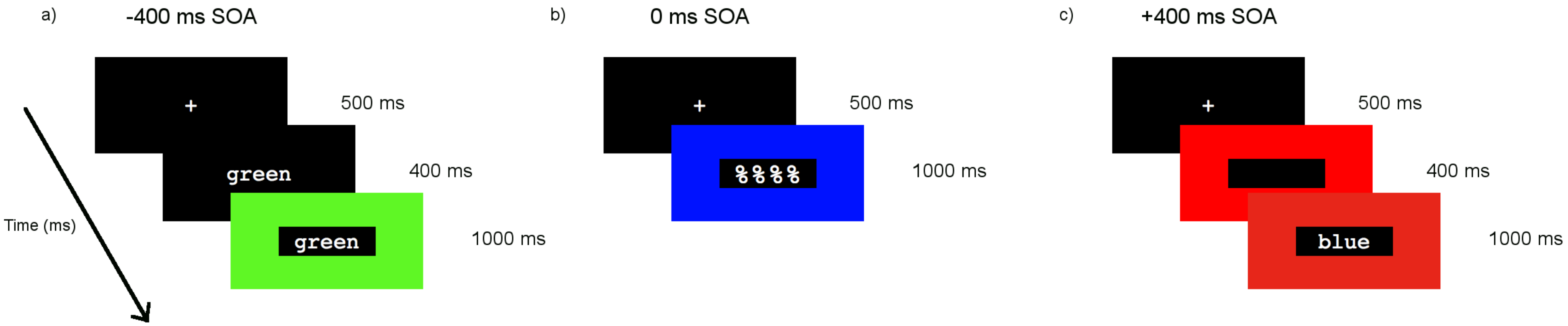
Other models also include a role of experience in Stroop performance (e.g. Logan, 1980; Lovett, 2002; MacLeod & Dunbar, 1988). For example, in Lovett's NJAMOS ('Not just another model of Stroop') model (Lovett, 2002), the knowledge required for a particular task (for example, reading experience for the Stroop task) is specified via production rules that each have a measure of 'utility' that is learned through past experiences. When the model encounters two conflicting production rules (e.g. reading and colour naming), the rule with the higher utility (i.e. experience) is executed. As the word-reading production rule has a higher utility than colour naming because of its extensive practice, large interference effects are generated when this production rule is executed.

Another explanation, not explicitly included in Stroop models but taken from the bilingualism literature, is that proficiency may also influence the magnitude of Stroop interference via lexical processing speed. As explained in Chapter 1 (section 2.1) weaker language connections require more processing time to activate a concept, leading to slower lexical access. Connection strengths (or resting-level activation, in the BIA+ model) can therefore be considered equivalent to processing speed. When measuring Stroop interference in the L1 and L2 at a static time point, conceptual activation in the L2 will be delayed due to slower lexical access, generating less interference compared to the faster processing of the L1. Thus the documented finding of smaller interference effects in the L2 may be specifically due to lexical processing speed. However, if delayed lexical access generates smaller Stroop effects in bilinguals, then allowing more time for lexical processing by pre-exposing the word might enhance conflict effects such that L2 interference equals that of the L1. Such temporal manipulation can be achieved by using a particular variation of the Stroop task which manipulates the stimulus onset asynchrony (SOA).

3. Stimulus Onset Asynchrony in the Stroop Task

Many variations of the Stroop task have arisen since its initial inception, including emotional, picture-naming, and matching Stroop tasks (Caldas et al., 2012; McKenna & Sharma, 1995; Roelofs, 2006; see MacLeod, 1991). One notable variation is stimulus onset asynchrony (SOA) manipulation, which spatially separates the colour and word stimuli (e.g. a coloured rectangle surrounding the word) and presents them at different times. A ‘negative SOA’ presents the irrelevant stimulus (e.g. the word) before the relevant target stimulus (the colour) at a specific interval (Figure 2.2). For example, a negative 200 ms SOA (‘-200 ms SOA’) pre-exposes the word for 200 ms before the colour appears. A ‘positive SOA’ presents the irrelevant stimulus after the relevant: for example, in a +400 ms SOA the word appears 400 ms after colour presentation. A ‘0 ms SOA’ presents the word and colour simultaneously, as in a traditional Stroop task.

Figure 2.2: Examples of a) a -400 ms SOA congruent condition; b) a 0 ms SOA control condition; and c) a +400 ms SOA incongruent condition. Duration (ms) of each stimulus is indicated to the right.



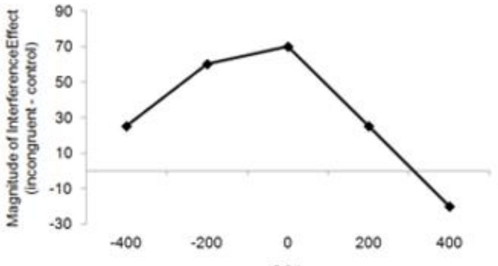
This Stroop variation initially gained popularity in the 1970's and 1980's (Dyer, 1971; Dyer & Severance, 1973; Glaser & Glaser, 1982; Glaser & Glaser, 1989). In a series of seminal experiments, Glaser & Glaser (1982) used nine SOAs (-400 ms to +400 ms in 100 ms intervals) in order to investigate the precise timing of interference. The peak interference effects occurred at 0 and ±100 ms SOAs, as seen in Figure 2.3. Interference effects decreased with increasing negative SOAs, but remained significant to -300 ms SOA, indicating that word reading is still strong enough to interfere with colour naming even at long pre-exposures of the word. Facilitation effects steadily increased with negative SOAs, indicating beneficial effects of word pre-exposure in congruent conditions. In positive SOAs, interference was diminished but still significant at +200 ms, but all effects were gone by later SOAs, indicating that the irrelevant word appeared too late to influence colour naming.

Figure 2.3: a) Original pattern of RTs in a Stroop task, from Glaser & Glaser (1982), with the resulting b) interference and c) facilitation effects, plotted in 200 ms intervals (only these SOAs are used throughout the current thesis).

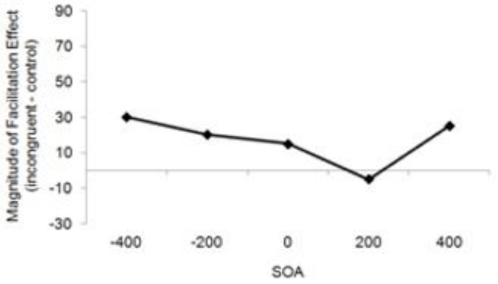
a)

Please refer to Figure 2; Glaser, M. O., & Glaser, W. R. (1982). Time course analysis of the Stroop phenomenon. *Journal of Experimental Psychology: Human Perception and Performance*, *8*(6), 875–894.

b) Interference



c) Facilitation



3.1. Modelling SOA effects

In attempts to integrate the immense literature on the Stroop task, many models of Stroop interference have been proposed, some of which have lost popularity with subsequent empirical data. SOA effects in the Stroop task have proven to be particularly difficult to simulate computationally and have been the downfall of many Stroop models. For example, the PDP model of Cohen et al. (1990), introduced in section 2.1.1, can account for SOA effects at and around the 0 ms SOA but simulates increasing interference effects in negative SOAs, which contradicts the empirical data showing weaker interference effects beyond -200 ms SOA.

One model that successfully simulates SOA patterns is Roelofs’s WEAVER++ model (Roelofs, 2003). WEAVER++ is a word production model that includes a production rule system which selects and ‘flags’ a goal concept based on task demands (Figure 2.4). The production rule mechanism is part of an executive system, localized tothe ACC, which performs goal and input control. In a Stroop task, the relevant target (the colour) is flagged as the goal concept based on the task demands (colour-naming), generating a processing advantage for the colour over the word. In a classic Stroop task in which incongruent stimuli are presented simultaneously, activations of the colour and word proceed in parallel, but because word pathways are stronger than colour pathways, flagging the colour as the goal concept takes longer, consequently delaying RTs.

At short negative SOAs, WEAVER++ proposes that pre-exposure of an irrelevant distractor (the word) sets off spreading activation of that concept. When the target stimulus (the colour) is subsequently presented it is flagged as the goal concept, leading to response selection with some interference from the distractor. However, with long pre-exposure (i.e. longer negative SOAs), the activation of the pre-exposed irrelevant stimulus begins to decay because it has not been tagged as a goal concept, reducing interference at longer SOAs of -200 and -400 ms. In all positive SOAs, the post-exposure of the irrelevant information does not cause any interference because the goal concept has already been tagged.

Other models can also account for SOA effects in the Stroop task, particularly the DO’97 model (Kornblum, Stevens, Whipple, & Requin, 1999) and the NJAMOS model (Lovett, 2002). The WEAVER++ remains one of the more popular and powerful Stroop models, in part because of its integration of neuroimaging data (e.g. Roelofs et al., 2006). However, as will be discussed next, SOA manipulation in the Stroop task has not been extensively explored using neuroimaging techniques: only two previous studies have investigated this paradigm using EEG, while the first study to use this paradigm with fMRI is presented in Chapter 7 of this thesis.

Figure 2.4: From Roelofs (2003): a) Network architecture of the WEAVER++ model; b) RT patterns of SOA effects, including Glaser & Glaser (1982)'s observed data and WEAVER++'s simulated data.

Please refer to Figures 8 and 13; Roelofs, A. (2003). Goal-referenced selection of verbal action: Modeling attentional control in the Stroop task. *Psychological Review, 110*(1), 88–125.

3.2. Stroop SOA effects in EEG

Investigations of SOA manipulation with EEG primarily concern how the latencies of the N_{inc} and LPC conflict-related components (see Chapter 1, section 3.2.2) are modulated by word pre- or post-exposure. In the first study to employ this paradigm with EEG, Appelbaum, Meyerhoff et al. (2009), using short-latency SOAs of ±200, ±100 and 0 ms, reported a linear modulation of the N_{inc} and LPC with SOA manipulation. Specifically, in the -100 ms SOA these components appeared 100 ms earlier than in the 0 ms SOA; in the -200ms SOA both were shifted forward (i.e. occurred earlier) by 200 ms (Figure 2.5). In both positive SOAs, the components were shifted ‘backwards’ (appeared later) by 100 ms. These findings were replicated in Appelbaum et al. (2012) and demonstrate that the latency of conflict components are modulated by SOA. However, as these studies employed short-latency SOA manipulation, the behaviour of these ERP components at long-latency SOAs (i.e. ±400 ms) remains undefined; this issue will be investigated in Chapter 5 of this thesis.

Figure 2.5: Difference waves (incongruent minus congruent) from Appelbaum, Meyerhoff et al. (2009), showing the effects of negative (‘irrelevant-first’) and positive (‘relevant-first’) SOA manipulation on the timing of the N_{inc} peak.

Please refer to Figure 5; Appelbaum, L. G., Meyerhoff, K. L., & Woldorff, M. G. (2009). Priming and backward influences in the human brain: Processing interactions during the Stroop interference effect. *Cerebral Cortex, 19*(11), 2508–2521.

3.3. Blocked vs. mixed SOA presentation

Addressing an important aspect of paradigm design, Appelbaum et al. (2012) contrasted the shifts of the N_{inc} and LPC when SOA was blocked versus randomized. They theorized that blocked SOAs might create strategic effects during performance, as the stimuli are temporally predictable. As in Appelbaum, Meyerhoff et al. (2009), the latency of the N_{inc} was modulated by SOA in both conditions; however, the amplitude of the N_{inc} was differentially affected, with a larger component in the -200 ms SOA for randomized SOAs but in the 0 ms SOA for blocked SOAs. Appelbaum et al. (2012) concluded that participants adopted a strategy of attentional orientation in blocked SOAs in order to reduce the influence of the temporally predictable distractor.

Blocked and mixed SOA presentations have also been contrasted by Roelofs (2010a), who tested this ‘temporal predictability hypothesis’ with SOAs of -400, -200, 0, and +200 ms. However, Roelofs reported no differences between presentation methods, arguing against temporal predictability and strategic attentional orientation. SOA is blocked throughout all of the studies presented here, in order to maintain the original paradigm of Glaser & Glaser (1982). However, the issue of blocked versus mixed SOAs is an important factor to consider and will be addressed again in Chapter 7.

3.4. Manual vs. vocal responses in a Stroop SOA task

Another influential factor is that of response modality. Manual Stroop tasks, in which participants indicate the colour with a button press, generally elicit overall faster RTs than vocal responses, in which participants name the colour aloud (Barch et al., 2001; MacLeod, 1991; Weekes & Zaidel, 1996). These faster manual RTs result in smaller (but still significant) interference effects compared to vocal Stroop tasks (MacLeod, 1991). Most studies investigating SOA effects have employed a vocal response (Dyer, 1971; Dyer & Severance, 1973; Glaser & Glaser, 1982; Roelofs, 2010a); the ‘typical’ pattern of SOA effects reported in Glaser & Glaser (1982), with peak interference effects at the 0 ms SOA, comes from a vocal response modality. However, the temporal differences between response modalities could affect the overall patterns of RTs in SOA manipulation.

EEG studies often use manual rather than vocal responses to reduce movement artifacts from speaking. The EEG studies of Appelbaum et al. are the only studies to investigate SOA manipulation with a manual response; however, their results are contradictory. Appelbaum et al. (2012) reported that randomized SOAs created peak behavioural interference at the -200 ms SOA, whereas constant SOAs elicited peak interference at the 0 ms SOA. Yet Appelbaum, Meyerhoff et al. (2009), also using constant SOA presentation, reported peak interference effects in the -200 ms SOA. This therefore renders the effects of response modality unclear.

Every study presented in this thesis utilizes a manual response modality. To establish how response modality affected RT patterns, two behavioural pilot studies were run during my

Master’s year. These pilot studies, tested with English monolingual participants, used five SOAs (with blocked SOA presentation), covering the same time spectrum as Glaser & Glaser (1982): ±400, ±200, and 0 ms. The study procedures were identical, with the exception that in one case participants named the ink colour aloud, whereas in the other they indicated the colour by pressing a button[4]. The data indicated different patterns of RTs for vocal and manual responses (Figure 2.6). In the vocal task, the peak interference occurred at the 0 ms SOA, which replicates previous vocal tasks (Glaser & Glaser, 1982; Roelofs, 2010a). However, in the manual task, the peak interference occurred at the -200 ms SOA, which replicates Appelbaum, Meyerhoff et al. (2009). This illustrates a negative shift of interference effects in manual responses compared to vocal responses.

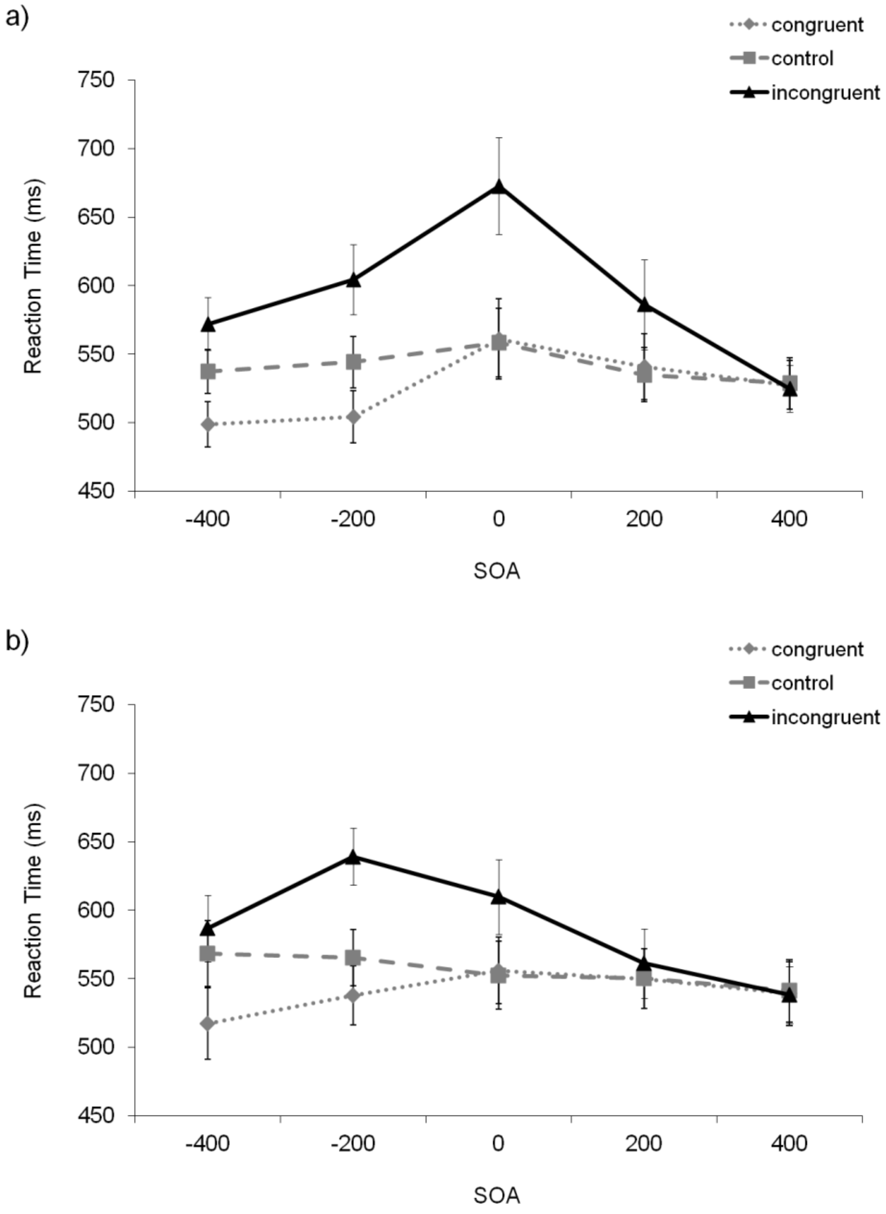
The different patterns of peak interference are likely due to differences in response speed. For instance, although processing of the word stimulus presumably proceeds at the same rate regardless of response modality, in a vocal task the colour concept must be translated into a vocal response, which takes longer than a manual modality in which the colour is mapped directly to a motor response. With simultaneous colour and word presentation in a vocal task, word semantics and vocalization of the colour may run at similar time courses and therefore cause stronger interference. But word pre-exposure in a vocal task gives semantic processing a head start such that it may be inhibited by the time the colour word is vocalized, resulting in smaller interference. In contrast, in a manual response modality, when colour and word are presented simultaneously the faster and more direct colour mapping allows for a response to be selected before the word is fully active, creating smaller interference. However, with a pre-exposed word in a manual task, the time courses of word and colour processing once again line up, creating maximal interference at a more negative SOA.

These pilot studies thus demonstrate that response modality significantly affects SOA patterns. Specifically, simultaneous stimulus presentation at the 0 ms SOA interferes more strongly with the slower vocal response, whereas word pre-exposure at the -200 ms SOA in a manual task interferes with the faster motor response. Therefore vocal tasks elicit the peak interference effect at the 0 ms SOA, whereas manual tasks elicit peak interference at the -200 ms SOA. This is an important point to keep in mind, as all of the studies presented here use a manual task.

---

[4] The data from the manual task is used in the next chapter as the monolingual control group.

Figure 2.6: RTs for the behavioural pilot studies, showing SOA patterns in a) vocal and b) manual modalities.



3.5. SOA manipulation in bilinguals

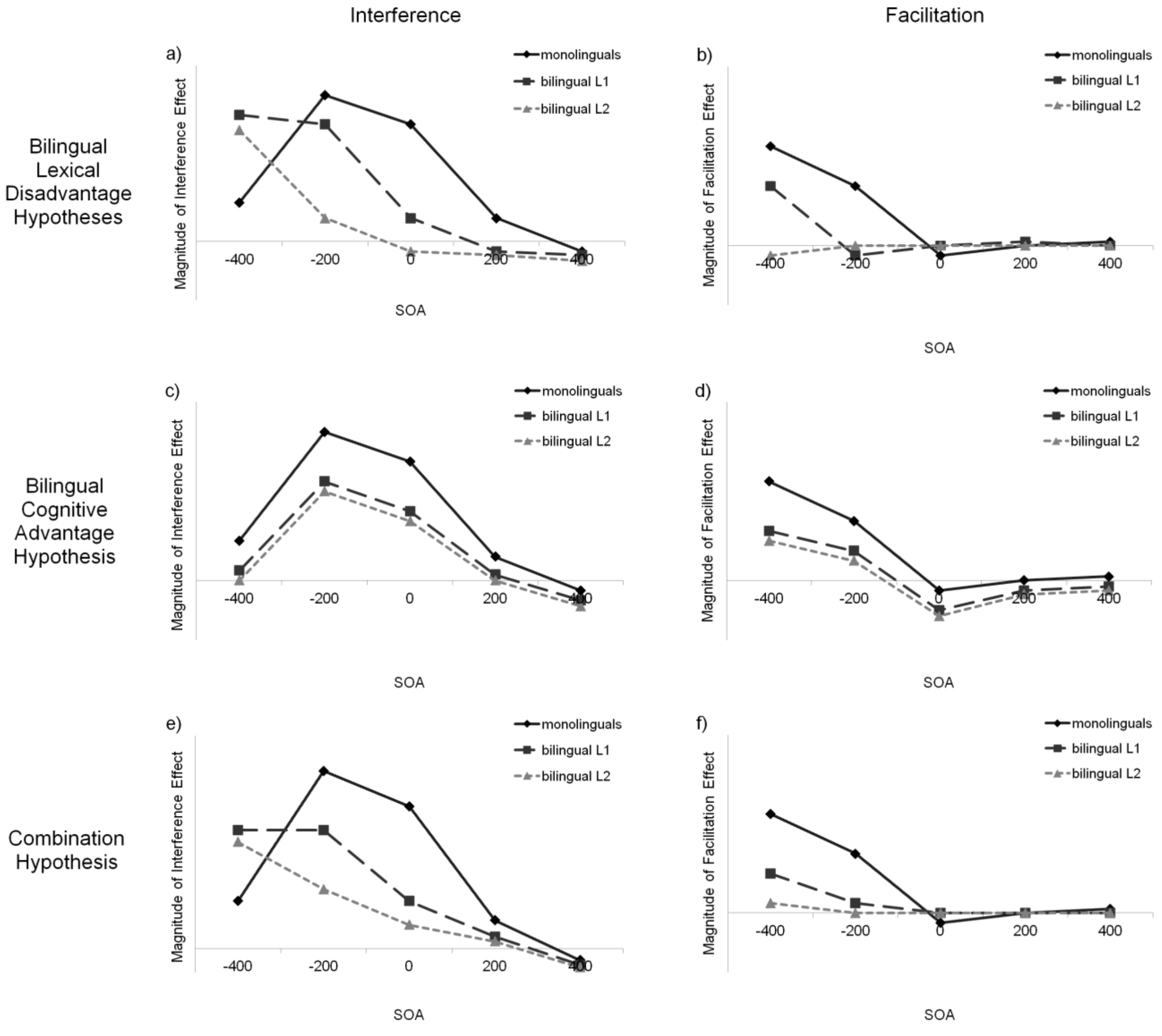
As discussed in section 2 of this chapter, interference effects in the Stroop task provide a measure of cognitive control abilities as well as language proficiency and processing speed. This makes the Stroop task an ideal paradigm to use in bilinguals to investigate the two theories presented in Chapter 1 regarding delayed lexical processing (the bilingual lexical disadvantage hypotheses) and enhanced executive control abilities (the bilingual cognitive advantage hypothesis). However, the factors of language processing speed and control abilities are difficult to separate when using a static SOA: smaller interference effects in bilinguals could result from enhanced cognitive control or from weaker language interference due to slower lexical processing. SOA manipulation in the Stroop task allows for a separation of these previously-confounded factors, as it provides a wider temporal spectrum in which to investigate interference effects. Critically, each theory discussed in Chapter 1 predicts different patterns of interference in a Stroop SOA task (initially tested with a manual response modality and five SOAs: ±400, ±200, and 0 ms). This paradigm may therefore allow for a better understanding of how cognitive control and lexical access speed interact in bilingual linguistic cognitive control.

3.5.1. Predictions of the bilingual lexical disadvantage hypotheses

As reviewed in Chapter 1 (section 2.2), the bilingual L1 lexical disadvantage hypothesis predicts that bilinguals experience delayed lexical access in their native language due to the reduced frequency of use. If so, then pre-exposure of the word in negative SOAs should allow this delayed lexical access a head-start, shifting the peak interference to an earlier time window than that typically found in a manual task (e.g. -400 ms SOA rather than -200 ms SOA). The bilingual L2 lexical disadvantage hypothesis (Chapter 1 section 2.1) predicts further delays in the L2 compared to the L1 or to monolinguals, also due to reduced proficiency and weaker language connections. If lower proficiency requires more time for lexical access, then this 'negative shift' in interference effects should be even more pronounced: i.e. the negative shift should increase with decreasing proficiency. Therefore the bilingual L1 should experience the most interference at an earlier negative SOA than monolinguals, and the bilingual L2 at an earlier negative SOA than the L1 (see Figure 2.7a), due to the relatively slower lexical access resulting from reduced frequency of language use. Importantly, as these hypotheses are based only on lexical processing speed, the *magnitude* of interference effects should be similar for each group: only the *latency* of peak interference should be affected by the varying strengths of language ties in each group. By the same rationale, a negative shift may also be apparent in the Stroop facilitation effects for each group (Figure 2.7b); however, because peak facilitation occurs at the -400 ms SOA, any further negative shifts would be outside the current range of SOAs and may not be observed.

Note that due to the large SOA intervals used in the current studies, the precise locus of peak interference may be difficult to identify. In other words, lexical access in the bilingual L1 may only be delayed by 50 or 100 ms, making the peak interference effect fall between the -200 and -400 ms pre-exposure. If the peak interference falls in the middle of an SOA window, a relative plateau of interference is predicted between the SOAs, as in the bilingual L1 line in Figure 2.7a.

<u>Figure 2.7</u>: Panels a and b: Based on the bilingual lexical disadvantage hypotheses, earlier negative SOAs will cause more a) interference and b) facilitation in the weaker language due to word pre-exposure, such that peak effects will be negatively shifted in the L1 vs. monolinguals and in the L2 vs. the L1. Panels c and d: Based on the bilingual cognitive advantage hypothesis, bilinguals will have better cognitive control than monolinguals, but this control will be unaffected by SOA manipulation, resulting in an overall downward shift in c) interference and d) facilitation effects. Panels e and f: A combination of all three hypotheses would lead to a slightly negative shift in bilingual L1, even more of a negative shift in bilingual L2, but still overall reduced e) interference and f) facilitation as compared to monolinguals. Monolingual predictions are based on the interference and facilitation effects from the pilot study with a manual response.



3.5.2. Predictions of the bilingual cognitive advantage hypothesis

The bilingual cognitive advantage hypothesis (specifically, the BICA hypothesis[5]) predicts that bilinguals will show smaller interference effects in both L1 and L2 compared to monolinguals because of enhanced executive control processes (Chapter 1, section 4.4). However, the bilingual advantage is sensitive to the degree of conflict present and is often only elicited in situations of high conflict (Costa et al., 2009). The bilingual cognitive advantage hypothesis therefore predicts smaller interference effects for bilinguals as compared to monolinguals, especially – or perhaps only – at SOAs requiring the most cognitive control (i.e. the -200 ms SOA). Importantly, however, as this theory does not take lexical processing speed into account, interference should not be modulated by SOA between the groups (i.e. all groups should show the peak interference effects at the same SOAs; Figure 2.7).

As well as smaller interference effects, bilinguals may also experience smaller facilitation effects. Previous work has found that populations with impaired cognitive control, such as children (e.g. Zelazo, Craik, & Booth, 2004) and adults with Alzheimer's disease (e.g. Milham et al., 2002) show not only increased Stroop interference but also increased facilitation effects compared to cognitively-normal adults (Spieler, Balota, & Faust, 1996; Wright & Wanley, 2003). Ignoring the word in a colour-naming Stroop task – whether congruent or incongruent – requires cognitive control, so individuals with decreased executive control abilities may be more susceptible to the linguistic influences of the word, leading to increased facilitation as well as increased interference (MacLeod & MacDonald, 2000; Wright & Wanley, 2003). Therefore bilinguals may show a decrease in facilitation compared to monolinguals, especially at the -400 ms SOA where peak facilitation is generally observed in monolinguals (Figure 2.7d).

3.5.3. Combination hypothesis

Because the bilingual lexical disadvantage hypotheses and the bilingual cognitive advantage hypothesis implicate different variables in governing Stroop performance (lexical access speed and cognitive control abilities, respectively), they are not mutually exclusive and may interact. A combination of these hypotheses would therefore predict that bilinguals show less interference overall than monolinguals, but that interference and facilitation are also shifted to negative SOAs in the L1 and L2 such that the peak effects occur earlier for bilinguals (Figure 2.7, panels e and f).

In sum, SOA manipulation in the Stroop task provides a unique way of investigating bilingual delays in lexical access and executive control abilities in the context of a linguistic cognitive control task. As the hypotheses of interest predict different patterns of RTs with

---

[5] The BEPA hypothesis will be evaluated by comparing global RT effects; as it does not relate to the patterns of interference predicted here, it is evaluated in separate analyses in each chapter.

SOA manipulation, a comparison of the overall RT patterns in monolinguals and bilinguals may elucidate the relative influences of these factors.

4. Conclusions on the Stroop Task with SOA

The elegant simplicity of the Stroop task has made it one of the most popular and widely-studied paradigms in cognitive psychology. Because it relies on language-based conflict, it assesses not only executive control abilities but also language proficiency and processing speed. SOA manipulation is a valuable variation of the Stroop task, especially in bilingualism, as it can tease apart the interacting factors of lexical access speed and cognitive control. Specifically, if lexical access is delayed in bilinguals, pre-exposure of the word may allow the slower processing a head-start such that interference effects would be shifted to an earlier SOA. By assessing the timecourse and magnitude of peak interference effects, SOA manipulation may provide a better understanding of how these factors interact in determining bilingual Stroop performance.

5. Thesis Outline

This thesis explores the cognitive effects of bilingualism, focusing predominantly on the dual factors of lexical access speed (via the bilingual lexical disadvantage hypotheses) and cognitive control abilities (via the bilingual cognitive advantage hypothesis and BICA/BEPA hypotheses) as well as exploring other issues affecting bilingual cognition. In five experiments, these factors are investigated in monolinguals and bilinguals via behavioural, EEG, and fMRI techniques. A Stroop SOA paradigm is primarily employed throughout (with the exception of Chapter 8).

Chapter 3 first tests the Stroop SOA paradigm behaviourally in monolinguals and bilinguals to establish how bilingual lexical processing speed and executive control abilities modulate interference patterns across SOAs. A similar paradigm is then utilized with EEG to examine, with more precise temporal resolution, the factors of lexical processing speed (Chapter 4) and executive control (Chapter 5). Chapters 4 and 5 draw from the same dataset, but are broken into different chapters for clarity. The influence of script is evaluated in Chapter 6, specifically whether the orthographic similarity of a bilingual’s languages modulates cognitive control abilities. Chapter 7 translates the Stroop SOA paradigm to fMRI, performing a preliminary study in monolinguals in order to identify how the executive control network is differentially recruited in negative SOAs. Finally, Chapter 8 identifies the neural overlap of linguistic and non-linguistic cognitive control (via an adapted flanker task) and language processing in monolinguals and bilinguals, in order to better understand the neural origins of the bilingual cognitive advantage. In the General Discussion, presented in Chapter 9, the results of these experiments are synthesized into a holistic discussion regarding bilingual lexical processing and cognitive abilities. The implications of this work are also considered with regards to the greater field of cognitive psychology.

Chapter 3: Behavioural Investigations of Lexical Processing Speed and Cognitive Abilities in Monolinguals and Bilinguals

As reviewed in the introductory chapters, bilingualism exerts substantial cognitive effects on executive control and linguistic processing. The Stroop task indexes both of these abilities; furthermore, SOA manipulation provides a means to separate these factors and thereby evaluate their relative influences on bilingual Stroop performance. To initiate the first in a series of studies employing this SOA manipulation, the current chapter administers a behavioural Stroop task with a full range of SOAs (-400 to +400 ms) to monolinguals and bilinguals; the patterns of interference and facilitation generated by Stroop SOA manipulation are evaluated in light of the cognitive effects of bilingualism.

1. Introduction to the Current Studies

As reviewed in Chapter 1 (Part 2), the bilingual lexical disadvantage hypotheses propose that bilinguals use each of their languages less frequently than monolinguals use their single language, leading to weaker connections between words and concepts and consequently slower lexical processing. This delayed lexical access occurs both in the L1 compared to monolinguals (the bilingual L1 lexical disadvantage hypothesis) and in the L2 compared to the L1 or to monolinguals (the bilingual L2 lexical disadvantage hypothesis). In a Stroop task with SOA manipulation, delayed lexical access predicts a negative shift in the latency of peak interference (Chapter 2, section 3.5.1). The bilingual lexical disadvantage hypotheses therefore predict that the bilingual L1 should experience the most interference at an earlier negative SOA than monolinguals and the bilingual L2 at an earlier negative SOA than the L1 (see Figure 2.7a in Chapter 2). Importantly, the magnitude of interference effects should be the same for each group, with only the latency of peak interference being shifted by proficiency or frequency of language use.

In contrast, the bilingual cognitive advantage hypothesis proposes that bilinguals have superior cognitive control abilities than monolinguals due to the daily experience of managing cross-linguistic influences arising from non-selective lexical access. Specifically, as discussed in Chapter 1 (sections 4.4 and 4.5), the BICA hypothesis predicts improved performance in the presence of conflict and consequently smaller interference effects for bilinguals (an ‘interference advantage’), while the BEPA hypothesis predicts superior monitoring abilities, resulting in faster RTs on all trial types (a ‘global RT advantage’), for bilinguals. The current experiments sought to compare bilingual performance to the established pattern of SOA effects presented by Glaser & Glaser (1982); therefore interference effects (and the BICA hypothesis) are primarily investigated here, although overall RTs are also evaluated. The bilingual cognitive advantage hypothesis therefore predicts smaller interference effects in both bilinguals’ L1 and L2 compared to monolinguals because of enhanced executive control processes (see Chapter 2, Figure 2.7b). This interference advantage was expected only at the most cognitively-demanding SOA (i.e. the -200 ms SOA, as this was a manual task). The bilingual cognitive advantage also predicts smaller facilitation effects for bilinguals at the -400 ms SOA (which experiences maximal facilitation). Importantly, because the bilingual cognitive advantage hypothesis makes no claims about the speed of lexical access, these effects should not be shifted by SOA modulation. Finally, bilinguals may also show an interaction of these factors, such that they show less interference overall but peak interference effects are also shifted to negative SOAs in the L1 and L2 compared to monolinguals (Chapter 2, Figure 2.7c).

The current study administered a Stroop SOA task with five SOAs (±400, ±200, and 0 ms) to monolinguals (Experiment 1) and two groups of bilinguals in both L1 and L2: English-Chinese (L1 English, L2 Mandarin; Experiment 2) and Chinese-English (L1 Mandarin, L2 English; Experiment 3). Chinese and English were chosen to avoid the issue of cognate effects in colour word translations. In most European languages the colour words are highly similar, either in orthography, phonology, or both. This overlap could create language-related facilitation and/or interference effects (see Chapter 2, section 2) which would be confounded with conflict-related effects. The factors of cognitive control and lexical access speed were examined in the context of the above-mentioned theories in order to more accurately explain the differences in Stroop performance: 1) between monolinguals and bilinguals in their native languages (monolinguals vs. bilingual L1); and 2) between bilinguals' two languages (L1 vs. L2).

A manual Stroop task was employed to avoid the issue of overt word production processes. A vocal-response Stroop task involves not just word recognition but also verbal response processes, which are both influenced by L2 proficiency, L2 AoA, word frequency, and semantic context (e.g. Gollan et al., 2011; Thornburgh & Ryalls, 1998). A manual Stroop task avoids these complexities of L2 production and eliminates the influence of overt word production processes, thereby more efficiently assessing how word recognition speed, as modulated by language proficiency, determines Stroop performance. Importantly, as discussed in Chapter 2 (section 3.4), the peak interference effect in a manual task occurs at the -200 ms SOA. The current experiments evaluated lexical processing speed and cognitive control abilities in monolinguals and bilinguals via the latency and amplitude of their peak interference effects.

2. Experiment 1: English Monolinguals

2.1. Methods

2.1.1. <u>Participants</u>

Twenty-four English monolinguals from the University of Nottingham participated in Experiment 1 (see Table 3.1). One subject was removed from analyses due to having learned another language besides English from birth. The remaining 23 participants were 14 females and 9 males, who all were right-handed, reported no colour-blindness, had normal or corrected-to-normal vision, and were not fluent in any other language besides English.

2.1.2. Materials and Design

Word stimuli were the words ‘red’, ‘green’, and ‘blue’ in lowercase font. Control word stimuli consisted of ‘xxxx’; this was included as a non-word, non-colour control condition. As SOA manipulation in the Stroop task necessitates a spatial separation of the colour and word stimuli, words were presented inside a coloured rectangle, as in Glaser & Glaser (1982; see Chapter 2, Figure 2.2). Colour stimuli consisted of red, green and blue filled rectangles of 284 x 142 pixels with a smaller black-filled rectangle inside. Word stimuli were presented in white ink inside the black rectangle. Congruent stimuli presented converging word and colour information (e.g. ‘red’ surrounded by a red rectangle). Incongruent stimuli presented inconsistent words and colour information (e.g. ‘green’ surrounded by a blue rectangle). Control stimuli presented the letter string ‘xxxx’ surrounded by red, green, or blue rectangles.

2.1.3. Procedure

Written informed consent was obtained prior to testing, for this and all of the studies presented in this thesis. Stimuli were presented using E-Prime software (Psychology Software Tools, Pittsburgh, PA). The experimental session consisted of a total of 10 blocks, two for each SOA. The order of SOA block presentation was counterbalanced and congruency was randomized within blocks. Each block consisted of 54 stimuli (18 each of congruent, control, and incongruent trials), resulting in a total of 540 trials. In each trial, a fixation cross appeared for 500 ms, followed by a blank screen for 300 ms, and then the word and/or colour stimulus appeared, depending on the specific SOA.

Five SOAs were included: -400, -200, 0, +200, and +400 ms. In negative SOAs, the word stimulus appeared on the screen alone for either 400 or 200 ms, followed by the coloured rectangle. In positive SOAs, the coloured rectangle appeared on the screen alone for either 200 or 400 ms before the word stimulus appeared in the centre of the rectangle. In the 0 ms SOA, the word stimulus and the coloured rectangle appeared simultaneously. Once both stimuli were presented they remained on the screen until participants made a response; if no response was made in 2000 ms, the stimuli disappeared and the next trial began. Participants manually responded to the colour using an external button-box (right index finger for red, right middle finger for green, right ring finger for blue). To help with the initial finger-to-colour mappings, the button-box was labelled with colour patches, although subjects were instructed to fixate their gaze in the centre of the screen once the experiment began. Participants conducted a brief practice session to familiarize them with the mappings between buttons and colours. Following the completion of the experimental session, participants completed a language background questionnaire and received an inconvenience allowance for their participation.

Table 3.1: Participant demographics and bilingual subjective proficiency scores (scale: 1 = very poor to 10 = very fluent). Numbers in parentheses indicate standard deviation.

Experiment	**Group**	***n***	**Age**	**Gender**	**L1**	**Age of first L2 contact**	**Self-rated L2 proficiency**				
							Speaking	Listening	Reading	Writing	Overall
1	English monolinguals	23	23.0 (4.1)	14 female, 9 male	English	N/A	N/A	N/A	N/A	N/A	N/A
2	English-Chinese bilinguals	15	21.8 (2.4)	10 female, 5 male	English	10.3 (7.3)	7.0 (1.3)	7.0 (1.6)	6.7 (1.6)	5.4 (2.5)	6.5 (1.3)
3	Chinese-English bilinguals	22	21.0 (1.6)	19 female, 3 male	Mandarin Chinese	11.0 (2.7)	6.4 (1.3)	6.6 (1.4)	7.1 (1.4)	6.3 (1.5)	6.6 (1.2)

2.2.Results and Discussion

Data were first trimmed to remove incorrect responses (3.8%) and outliers (RTs of less than 250 ms or greater than 1500 ms: 0.4%). The mean number of errors per condition ranged between 0.2%-0.4%. Because error rates were very low no error analyses were conducted. Since Stroop effects (incongruent vs. congruent RTs) combine both interference and facilitation effects (see Chapter 1, section 3.1) they are not reported in this chapter; the current analyses instead focus on the patterns of interference and facilitation generated by the SOA Stroop task.

A 3 (congruency: congruent, control, incongruent) x 5 (SOA) repeated-measures ANOVA on the mean RTs (Figure 3.1a, presented on page 71) showed significant main effects of congruency ($F(2,44) = 71.31$, $p < 0.0001$) and SOA ($F(4,88) = 5.49$, $p < 0.01$) and an interaction between congruency and SOA ($F(8,176) = 21.33$, $p < 0.0001$). Paired-sample *t*-tests with Bonferroni corrections (10 comparisons per group) were run between the incongruent vs. control and control vs. congruent conditions to compare interference and facilitation effects, respectively, at each SOA. Only significant results or trends ($p < 0.10$) after correction are reported. Significant interference occurred at -200 ms (74 ms, $SE = 7$ ms; $t(22) = 10.78$, $p < 0.0001$) and 0 ms (57 ms, $SE = 10$ ms; $t\ (22) = 5.68$, $p < 0.0001$). Significant facilitation occurred at -400 ms (51 ms, $SE = 8$ ms; $t(22) = 6.46$, $p < 0.0001$) and -200 ms (27 ms, $SE = 8$ ms; $t(22) = 3.29$, $p < 0.05$). As seen in Figure 3.2a (presented on page 72), the largest interference effect occurred at the -200 ms SOA (74 ms, $SE = 7$ ms).

As discussed in Chapter 2 (section 3.4), the monolingual data with a manual task clearly showed a different pattern of RTs from vocal tasks, such that the peak interference effects occurred at the -200 ms SOA rather than the 0 ms SOA. Apart from this disparity, the RT patterns were similar to those of Glaser & Glaser (1982): facilitation increased at negative SOAs, peaking at the -400 ms SOA, and interference and facilitation were diminished at positive SOAs when the word was exposed too late to affect colour naming.

3. Experiment 2: English-Chinese Bilinguals in L1 and L2

Experiment 2 tested a group of bilinguals with the same native language as the English monolinguals of Experiment 1, to compare the impact of bilingualism on lexical access speed and executive control abilities.

3.1. Methods

3.1.1. Participants

Participants were 15 English-Chinese bilinguals (English L1, Mandarin Chinese L2) from the University of Nottingham (10 female, 5 male). All were right-handed, reported no colour-blindness, and had normal or corrected-to-normal vision. Participants were native English speakers who rated themselves dominant in English but also proficient in Mandarin. All participants completed a language background questionnaire after the testing session (Table 3.1). Most spoke other languages (*n* = 11), including Spanish, French, German, and Malay, and some (*n* = 4) considered themselves more proficient in other languages than in Chinese (overall self-rated proficiency in other languages: 6.3, on a 10-point scale). They had an overall self-reported Chinese proficiency of 6.5 (*SD* = 1.3) and first contact with Chinese at a mean age of 10.3 years (*SD* = 7.3).

3.1.2. Materials and Design

Word stimuli for the English (L1) version of the task were identical to Experiment 1, with the exception that the English control stimulus was '%%%%'.[6] This was changed from Experiment 1 to make the control stimuli look less like Chinese characters (as there are no round lines in Chinese). Word stimuli for the Chinese (L2) version of the task consisted of the simplified Chinese characters '红', '绿', and '蓝' (red, green and blue, respectively). The Chinese control character was '%', in order to match the approximate physical size of a character. Words/characters were printed in white font against a black background. As in Experiment 1, five SOAs were used; SOA was blocked and counterbalanced between participants.

3.1.3. Procedure

The procedure was similar to that of Experiment 1, with the exception that participants completed two sessions on two consecutive days, during which they performed the Chinese or English version of the Stroop task. Language order was counterbalanced between participants. Bilinguals therefore had more practice with the task than the monolinguals of Experiment 1; however, practice effects in the Stroop task are highly specific and transient (MacLeod, 1991), so this should not affect the results. Following the completion of both sessions, participants completed a language background questionnaire and received an inconvenience allowance for their participation.

3.2. Results and Discussion

Incorrect responses (4.5% for L1; 4.4% for L2) and outliers (0.4% for L1, 0.3% for L2) were removed before statistical analysis. The mean number of errors per condition ranged between 0.1%-0.6% for L1 English and between 0.2%-0.4% for L2 Chinese.

---

[6] To confirm that the different control stimuli between Experiment 1 ('xxxx') and Experiment 2 ('%%%%') did not affect the results, the control condition RTs were compared between the monolinguals and the bilingual L1 English. A 5-way (SOA) ANOVA on the control RTs only with language as a between-subjects factor showed no main effects of SOA or language group (all *F's* < 1), although there was a weak trend of an interaction ($F(4,143) = 2.02$, $p = 0.09$). The lack of a main effect of participant group indicates that the difference in control conditions between the experiments did not affect the results.

3.2.1. L1 English

Overall, the mean RT patterns for the L1 English (Figure 3.1b) appeared similar to that of the monolinguals. A 3 (congruency) x 5 (SOA) ANOVA showed significant main effects of congruency ($F(2,26) = 60.23$, $p < 0.0001$) but not of SOA ($F(5,54) = 1.69$, $p = 0.17$) and a significant interaction ($F(8,109) = 14.31$, $p < 0.0001$). Paired-sample t-tests with Bonferroni corrections showed significant interference effects at -400 ms (47 ms, $SE = 9$ ms; $t(14) = 5.11$, $p < 0.001$), -200 ms (70 ms, $SE = 10$ ms; $t(14) = 7.33$, $p < 0.01$), and 0 ms (56 ms, $SE = 9$ ms; $t(14) = 6.23$, $p < 0.01$). Significant facilitation effects occurred at -400 ms (44 ms, $SE = 11$ ms; $t(14) = 4.10$, $p < 0.05$) and -200 ms (32 ms, $SE = 9$ ms; $t(14) = 3.70$, $p < 0.05$) SOAs. As can be seen in Figure 3.2b, the -200 ms SOA elicited the largest interference effect (70 ms, $SE = 10$ ms).

3.2.2. L2 Chinese

The RT patterns in the L2 Chinese (Figure 3.1c) appeared notably different than those of the English conditions, especially in the control condition. A 3 (congruency) x 5 (SOA) ANOVA revealed main effects of congruency ($F(2,24) = 17.93$, $p < 0.001$) and SOA ($F(4,53) = 3.45$, $p < 0.05$) and a significant interaction ($F(8,106) = 4.57$, $p < 0.001$). Significant interference effects occurred at -200 ms (38 ms, $SE = 11$ ms; $t(14) = 3.44$, $p < 0.05$) with a trend at 0 ms (41 ms, $SE = 13$ ms; $t(14) = 3.03$, $p = 0.09$ corrected; $p = 0.009$ uncorrected). There were no significant facilitation effects after correction at any SOA (all p's > 0.17), although the largest effect occurred at -400 ms SOA (29 ms, $SE = 11$ ms). As seen in Figure 3.2c, the peak interference occurred at the 0 ms SOA (41 ms, $SE = 13$ ms).

The data therefore revealed similar RT patterns for the English Stroop task when performed in a native language. However, the RT pattern for L2 Chinese was notably different, eliciting stronger interference effects at the 0 ms SOA than the -200 ms SOA. It is unclear whether this discrepancy arose from differences in native and non-native processing due to bilingualism, or from differences in linguistic processing between Chinese and English. To investigate these possibilities, Experiment 3 tested native Chinese speakers with an English L2.

4. Experiment 3: Chinese-English Bilinguals in L1 and L2

4.1. Methods

4.1.1. Participants

Twenty-four Chinese-English bilinguals (Mandarin Chinese L1, English L2) were tested in Experiment 3. Two participants were English-dominant and were removed from analyses. The remaining 22 consisted of 19 females and 3 males who were all right-handed, reported no colour-blindness, and had normal or corrected-to-normal vision. Of the 22 participants, twelve were tested at the University of Nottingham Ningbo campus in Ningbo, China, and ten were tested at the University of Nottingham in England. The University of Nottingham Ningbo campus is an English-immersion environment, in which all classes are taught in English, so all participants tested in China were immersed in their non-native language despite being in their native country. The subjects tested in England had all just arrived in the country from the Ningbo campus and had been living in England for no more than two months. Analyses of the data with location as a between-subjects factor showed no significant effects of testing environment on SOA or congruency effects (all p's > 0.25), so all Chinese-English bilinguals were considered together in subsequent analyses. All participants were native Mandarin Chinese speakers from mainland China who rated themselves dominant in Chinese but also proficient in English (Table 3.1). Although some had learned other languages ($n = 9$), none rated themselves as highly proficient (overall self-rated proficiency in other languages = 2.3). Most participants ($n = 20$) also spoke a Chinese dialect from their hometown, but as these dialects also use simplified Chinese characters in written language this should not be a confounding factor. Their overall self-reported English proficiency was 6.6 ($SD = 1.2$) and first contact with English was at a mean age of 11 years ($SD = 2.7$). Importantly, they did not differ statistically from the English-Chinese bilinguals in overall self-rated proficiency scores ($p = 0.89$) or L2 AoA ($p = 0.76$).

4.1.2. Materials and Design

The materials and design were identical to that of Experiment 2.[7]

4.1.3. Procedure

The procedure was identical to that of Experiment 2.

4.2. Results and Discussion

Incorrect responses (2.6% for L1; 2.3% for L2) and outliers (0.3% for L1, 0.2% for L2) were removed before statistical analysis. The mean number of errors per condition ranged between 0.1%-0.2% for L1 Chinese and between 0.1%-0.4% for L2 English.

4.2.1. L1 Chinese

The RT patterns in the L1 Chinese data (Figure 3.1d) exhibited a similar pattern to that of the

---

[7] To confirm again that the different control conditions used in Experiment 1 ('xxxx') and Experiment 3 ('%%%%') did not affect the magnitude of interference, the control condition RTs were compared between the monolinguals and the bilingual L1 Chinese. A 5 (SOA)-way ANOVA with language as a between-subjects factor showed a main effect of SOA ($F(4,172) = 2.47$, $p < 0.05$), but no effect of language group ($F(1,43) < 1$) or interaction ($F(4,172) = 1.06$, $p = 0.38$). The non-significant effect of participant group indicates that the different control conditions between the experiments did not affect the results.

L2 Chinese data from Experiment 2. A 3 (congruency) x 5 (SOA) ANOVA showed a significant main effect of congruency ($F(2,42) = 22.18$, $p < 0.0001$) but not SOA ($F(4,84) < 1$), and a significant interaction ($F(8,168) = 5.53$, $p < 0.0001$). Significant interference occurred at -200 ms (26 ms, $SE = 8$ ms; $t(21) =3.17$, $p < 0.05$) and 0 ms (40 ms, $SE = 11$ ms; $t(21) = 3.62$, $p < 0.05$). Significant facilitation occurred at -400 ms (35 ms, $SE = 8$ ms; $t(21) = 4.37$, $p < 0.01$) and -200 ms (23 ms, $SE = 5$ ms; $t(21) = 4.49$, $p < 0.01$). As in the L2 Chinese data, the most interference occurred at the 0 ms SOA (40 ms, $SE = 11$ ms; Figure 3.2d).

4.2.2. L2 English

The L2 English data (Figure 3.1e) showed a similar pattern as that of the monolingual and L1 English data in Experiments 1 and 2. A 3 (congruency) x 5 (SOA) ANOVA revealed a significant main effect of congruency ($F(2,42) = 19.72$, $p < 0.0001$) but not SOA ($F(4,84) = 1.44$, $p = 0.23$) and a significant interaction ($F(8,168) = 4.71$, $p < 0.0001$). Significant interference occurred at -200 ms (30 ms, $SE = 9$ ms; $t(21) = 3.18$, $p < 0.05$) and facilitation at -200 ms (25 ms, $SE = 6$ ms; $t(21) = 3.89$, $p < 0.01$) only. As seen in Figure 3.2e, the most interference occurred at the -200 ms SOA (30 ms, $SE = 9$ ms).

Figure 3.1: Mean RTs (ms) for the a) monolinguals (Experiment 1); b) bilingual L1 English (Experiment 2); c) bilingual L2 Chinese (Experiment 2); d) bilingual L1 Chinese (Experiment 3); and e) bilingual L2 English (Experiment 3).

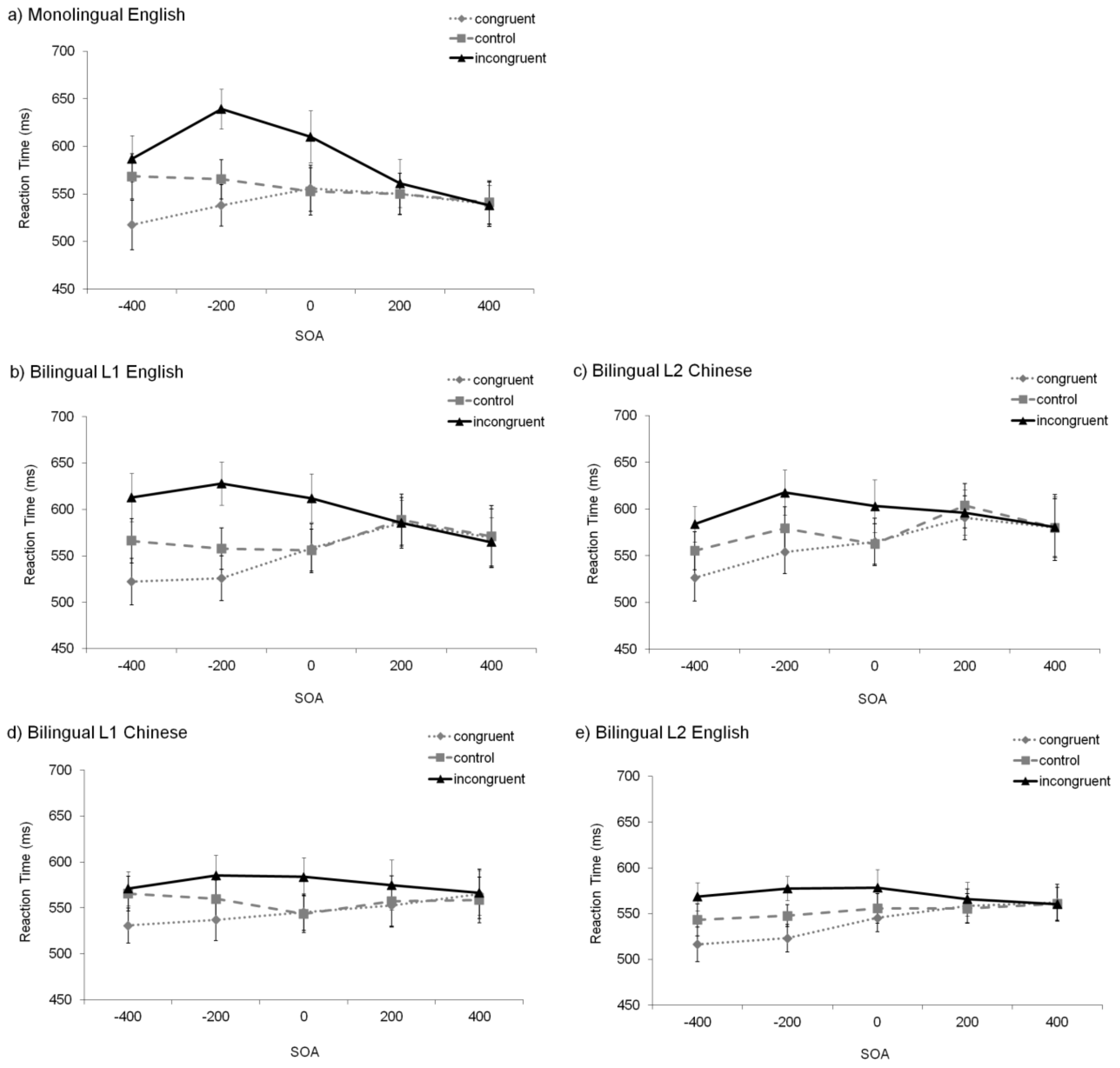
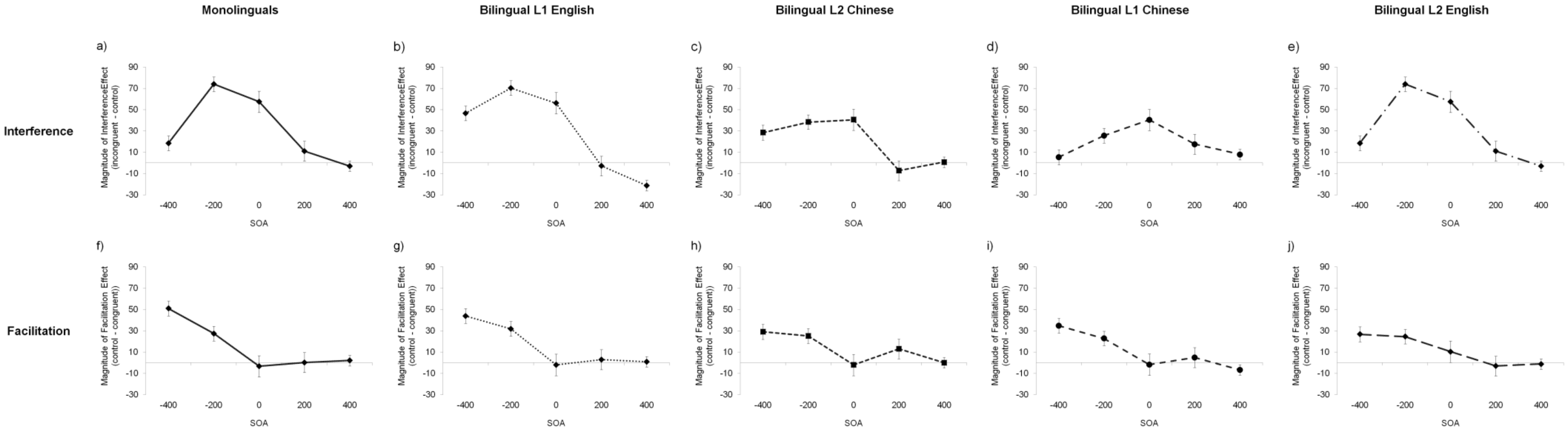


Figure 3.2: Comparison of the magnitude of interference (panels a-e) and facilitation (panels f-j) effects in monolinguals, L1 English, L2 Chinese, L1 Chinese, and L2 English.



5. Results: Comparison of All Groups (Experiments 1-3)

To investigate the initial questions regarding bilingual lexical processing speed and cognitive abilities, all three groups from Experiments 1-3 were directly compared. An initial visual comparison of the RT patterns for each group (Figure 3.1) revealed an interesting effect of script such that the English and Chinese languages elicited different RT patterns, independent of language status (native or non-native). This suggests that an underlying effect of script may be driving these patterns. Specifically, the control condition behaved differently in Chinese and English at the 0 ms SOA; as the groups were compared on interference effects (incongruent minus control), this disparity could have modulated the effects discussed in the next sections. Comparisons of the Stroop effect (incongruent minus congruent) may have been more appropriate; however, as SOA manipulation also affects facilitation magnitudes (e.g. increasing facilitation in the -400 ms SOA), interpretations of the Stroop effects are just as difficult. These script effects are evaluated below and will be considered at length in the General Discussion (Chapter 9, sections 2.3.1 and 3.6).

5.1. Evaluation of the bilingual lexical disadvantage hypotheses

As outlined in Chapter 2 (section 3.5.1), delays in lexical processing should create a negative shift in peak interference effects. To evaluate this proposal, latency analyses were performed by identifying the SOA which generated the peak interference effect for each subject (Figure 3.2) and comparing between groups using *t*-tests. (Welch corrections on the degrees of freedom were performed where the assumption of sphericity was violated. These corrections create non-integer degrees of freedom, as are sometimes reported throughout the statistical analyses in this thesis.) All groups showed maximum effects at the -400 ms SOA and there were no significant differences between any of the groups (all *p*'s > 0.16), so no further analyses were performed.

Between-subject analyses were first conducted for each language to investigate the effects of bilingualism on peak interference latency within the same language. In all groups performing in English (i.e. monolinguals, L1 English, L2 English), the peak interference occurred at the -200 ms SOA (Figure 3.2, panels a, b, and e), with no differences between any groups (all *p*'s > 0.14). This indicates that bilingual status did not modulate peak interference latencies within the English script. The two Chinese conditions were also compared (L2 Chinese vs. L1 Chinese; Figure 3.2, panels c and d) to evaluate the effects of native-speaker status on the latency of peak interference effects in Chinese. There was a trend towards a significant difference in peak interference latency ($t(30.5) = 1.98$, $p = 0.06$) such that the majority of L1 Chinese bilinguals showed peak interference effects at the 0 ms SOA, whereas in the L2 Chinese the peak interference effects were more evenly spread over the -200 ms and 0 ms SOAs.

To investigate the bilingual L1 lexical disadvantage hypothesis, monolinguals were compared to L1 performance in each group. There were no differences between the peak interference of

English monolinguals and L1 English bilinguals ($t(27.2) = 1.01$, $p = 0.32$). However, monolinguals experienced peak interference at the -200 ms SOA whereas the L1 Chinese elicited maximal interference at the 0 ms SOA, which was a statistically significant latency difference ($t(37.3) = 2.27$, $p < 0.05$; Figure 3.2, panels a and d).

Finally, to investigate the bilingual L2 lexical disadvantage hypothesis, the L1 and L2 were contrasted for the two groups of bilinguals. Within the Chinese-English bilinguals, a negative shift in interference effects occurred in L2 English compared to L1 Chinese ($t(21) = 4.16$, $p < 0.001$) such that the peak interference occurred at the 0 ms SOA for the L1 but at the -200 ms SOA for the L2 (Figure 3.2, panels d and e). In contrast, peak interference latencies in the English-Chinese bilinguals did not differ between L1 and L2 ($t(14) = 0.54$, $p = 0.60$; Figure 3.2, panels b and c). Therefore the Chinese-English bilinguals, but not the English-Chinese bilinguals, demonstrated a negative shift in peak interference effects as predicted by the bilingual L2 lexical disadvantage hypothesis.

To investigate whether proficiency modulated the latency of peak interference effects within bilinguals' L2, a median split of each bilingual group was performed using self-rated L2 proficiency (English-Chinese median proficiency = 6.0, Chinese-English median proficiency = 6.3). However, there were no differences in the latency of L2 peak interference between high- and low-proficiency participants in either bilingual group (all p's > 0.18).

5.2. Evaluation of the bilingual cognitive advantage hypothesis

To investigate the bilingual cognitive advantage, comparisons of effect magnitudes (interference and facilitation) were made across native languages: monolinguals vs. L1 English; and monolinguals vs. L1 Chinese. Monolingual English and L1 English interference effects (Figure 3.2, panels a and b) were compared at the -200 ms SOA using an independent-samples t-test. There were no significant differences in interference magnitudes ($p = 0.76$) between the two groups of native English speakers. Comparing peak interference effects for English monolinguals (at the -200 ms SOA) vs. L1 Chinese bilinguals (at the 0 ms SOA; Figure 3.2, panels a and d), the L1 Chinese showed significantly smaller interference effects (40 ms, $SE = 5$ ms) than monolinguals (74 ms, $SE = 3$ ms; $t(35.1) = 2.56$, $p < 0.05$).

The bilingual cognitive advantage hypothesis (specifically, the BICA hypothesis) proposes that bilingualism improves inhibitory control abilities but makes no claims about language-related processing differences; it therefore predicts a reduction of interference effects in *both* the L1 and L2. To investigate bilingual interference advantages in the second language, interference effects were compared between monolinguals and bilingual L2s. Comparing interference effects for monolinguals (at the -200 ms SOA) to the English-Chinese bilinguals in L2 Chinese (at the 0 ms SOA; Figure 3.2, panels a and c), there were significantly smaller interference effects for L2 Chinese (41 ms, $SE = 13$ ms) than for monolinguals (74 ms, $SE = 3$ ms; $t(21.4) = 2.22$, $p < 0.05$). When comparing monolinguals to the Chinese-English bilinguals in their L2 English, the bilinguals showed significantly smaller interference effects in their L2 (30 ms, $SE = 9$ ms) compared to monolinguals (74 ms, $SE = 3$ ms; $t(38.8) = 3.79$,

$p < 0.001$) at the -200 ms SOA (the SOA of peak interference for both groups; Figure 3.2, panels a and e).

Turning to the facilitation effects, Figure 3.2 (panels f-j) illustrates that, in the -400 ms SOA, monolinguals showed the greatest facilitation (51 ms, *SE* = 8 ms; Figure 3.2f), followed by the bilingual L1 Chinese (37 ms, *SE* = 10 ms; Figure 3.2i), L1 English (44 ms, *SE* = 11 ms; Figure 3.2g), L2 Chinese (29 ms, *SE* = 11 ms; Figure 3.2h) and L2 English (27 ms, *SE* = 12 ms; Figure 3.2j). However, overall there were no statistical differences in facilitation magnitudes between groups, although there was a trend between monolinguals and L2 English ($p = 0.09$ uncorrected).

Previous research has suggested that bilingual executive control abilities are strengthened with increasing language proficiency (Bialystok, Craik et al., 2006). To investigate whether the bilingual advantage was mediated by proficiency within bilinguals, a median split of each bilingual group was again performed using self-rated L2 proficiency (Figure 3.3 and Figure 3.4) and performance was compared for the low- and high-proficiency groups.

5.2.1. English-Chinese bilingual performance split by L2 (Chinese) proficiency

When comparing the high- and low-proficiency English-Chinese bilinguals on L1 English performance, there were no significant differences between the groups in either interference (all *p*’s > 0.42) or facilitation effects (all *p*’s > 0.25) at any SOAs. Thus, L2 proficiency did not influence Stroop performance in the L1.

However, when comparing the English-Chinese bilinguals on L2 Chinese performance, there was an interesting effect of L2 proficiency on the overall RT patterns. Specifically, low-proficiency bilinguals (Figure 3.3a) showed an RT pattern similar to English (Figure 3.1, panels a and b), whereas the high-proficiency bilinguals (Figure 3.3b) showed an RT pattern similar to native Chinese (Figure 3.1d). However, there were no significant differences in interference effects between the low- and high-proficiency groups at any SOA (all *p*’s > 0.68; Figure 3.4a), indicating that the overall magnitude of interference in the L2 was not affected by proficiency. Additionally, no differences in facilitation effects occurred in the L2 Chinese between low-proficiency (27 ms, *SE* = 20 ms) and high-proficiency (31 ms, *SE* = 9 ms) bilinguals ($p = 0.87$).

5.2.2. Chinese-English bilingual performance split by L2 (English) proficiency

When comparing the low- and high-proficiency Chinese-English bilinguals on L1 Chinese performance, there were no significant differences between the groups at any SOAs in interference (all *p*’s > 0.32) or facilitation effects (all *p*’s > 0.21). Thus once again, L2 proficiency did not influence Stroop performance in the L1.

When comparing groups on L2 English performance, the RT patterns for low-proficiency bilinguals (Figure 3.3c) appeared similar to those of English (Figure 3.1, panels a and b), but high-proficiency participants (Figure 3.3d) showed a different pattern, unlike English or Chinese. Furthermore, at the -200 ms SOA the low-proficiency participants showed larger interference effects (50 ms, *SE* = 15 ms) than high-proficiency bilinguals (10 ms, *SE* = 8 ms; *t*(15.9) = 2.38, *p* < 0.05; Figure 3.4b) and there was a trend of a similar effect at the 0 ms SOA (*t*(15.2) = 1.97, *p* = 0.07). The high-proficiency L2 English bilinguals (9 ms, *SE* = 12 ms) also showed reduced facilitation effects in the -400 ms SOA compared to the low-proficiency group (44 ms, *SE* = 19 ms), though this was only a statistical trend (*t*(106.4) = 1.72, *p* = 0.08).

<u>Figure 3.3</u>: Mean RTs after the L2-proficiency split in each bilingual group: a) low-proficiency English-Chinese bilinguals on the L2 Chinese Stroop task; b) high-proficiency English-Chinese bilinguals on the L2 Chinese Stroop; c) low-proficiency Chinese-English bilinguals on the L2 English Stroop task; d) high-proficiency Chinese-English bilinguals on the L2 English Stroop.

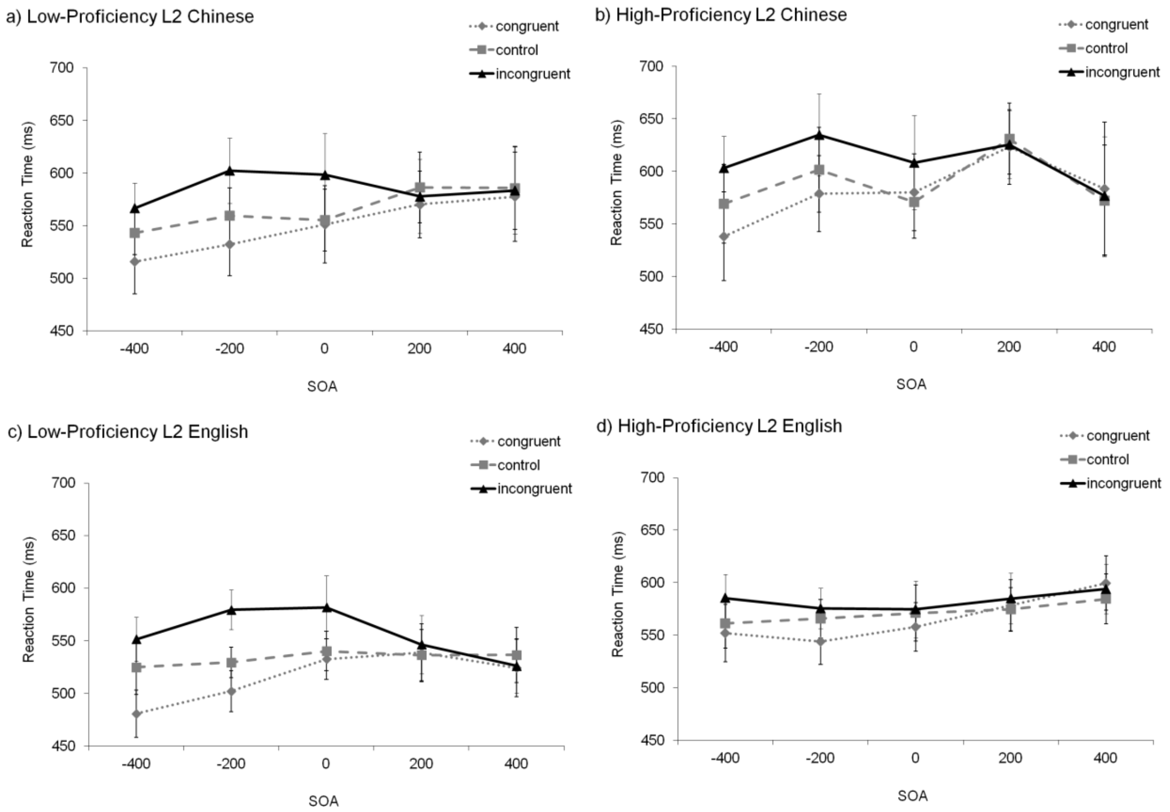
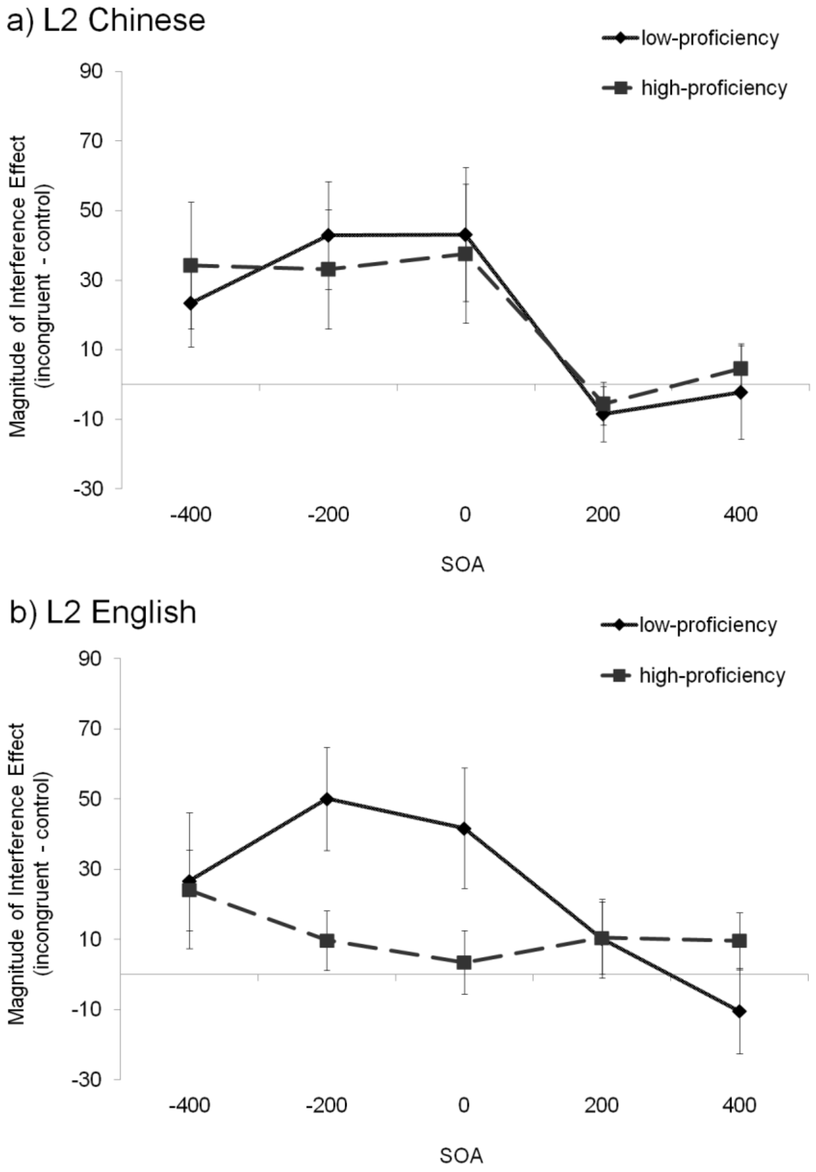


Figure 3.4: Mean L2 interference effects for each bilingual group split by proficiency: a) low- vs. high-proficiency English-Chinese bilinguals on the L2 Chinese Stroop task; b) low- vs. high-proficiency Chinese-English bilinguals on the L2 English Stroop task.



5.2.3. Global RT advantage

To investigate the presence of a bilingual global RT advantage in the current data, as predicted by the BEPA hypothesis, the mean RTs for the control conditions (collapsed across SOA) were directly compared. The control conditions were chosen for this analysis because the linguistic information of the word could influence processing time in the incongruent and congruent conditions; a comparison of the control condition more accurately reflected executive processing independent of conflict or linguistic information. The English-Chinese bilinguals showed the slowest RTs overall, in Chinese first (575 ms, *SE* = 24 ms) and then in

English (568 ms, *SE* = 26 ms); the monolinguals (556 ms, *SE* = 22 ms) and L1 Chinese (557 ms, *SE* = 22 ms) were relatively even; and L2 English was fastest (553 ms, *SE* = 16 ms). However, there were no significant differences between any of the bilingual groups when comparing to monolinguals (all *p*’s > 0.18, uncorrected). There was a trend of faster control RTs for L2 English compared to L2 Chinese (*p* = 0.08), but no significant effect in the L1.

6. Discussion

The current experiments administered a Stroop SOA task to monolinguals and bilinguals to investigate how lexical access speed and executive control abilities modulate Stroop performance. Experiment 1, with monolinguals, showed a similar pattern of interference effects as Glaser & Glaser (1982), with the exception that the peak interference effects occurred at the -200 ms SOA; this is most likely due to the use of a manual response modality. In both the English-Chinese and Chinese-English bilingual data of Experiments 2 and 3, the RT patterns in all languages demonstrated significant interference effects in negative SOAs but no interference or facilitation at positive SOAs, replicating the overall patterns of the monolingual data and of Glaser & Glaser (1982). However, noticeably different RT patterns emerged between English and Chinese, with maximal interference occurring at the 0 ms SOA in Chinese and at the -200 ms SOA in English. As these patterns occurred in both native and non-native speakers, they are likely driven by script effects. Evidence for the two hypotheses regarding lexical processing speed and cognitive abilities are first reviewed, followed by a discussion of the effect of script and its potential influence on the results seen here.

6.1. The bilingual lexical disadvantage hypotheses

The bilingual L1 lexical disadvantage hypothesis predicted a negative shift in peak interference effects for bilinguals in their L1 compared to monolinguals due to reduced frequency of language use and subsequently delayed lexical access. There was no evidence for this proposal; in fact, the L1 Chinese demonstrated a positive shift, eliciting the peak interference effect at 0 ms rather than -200 ms as in monolinguals. However, as Chinese and English demonstrated the peak interference at these respective SOAs across both bilingual groups, this positive shift is more likely an effect of script rather than differences in lexical access speed. When comparing within the same language (e.g. English monolinguals vs. L1 English bilinguals), no differences in peak interference latency were observed, indicating no differences in native-language processing speed between bilinguals and monolinguals.

The bilingual L2 lexical disadvantage hypothesis predicted a further negative shift in interference effects for the L2 compared to the L1 or to monolinguals due to delayed lexical access resulting from reduced second-language proficiency. In within-group comparisons, the Chinese-English bilinguals experienced peak interference effects at 0 ms in the L1 Chinese and at negative SOAs in the L2 English; however, as discussed below (section 6.3), this is likely an effect of script.In the between-group comparison of the L1 Chinese vs. the L2

Chinese, the L2 elicited the peak interference at more negative SOAs than the L1. This supports the L2 lexical disadvantage hypothesis and is in line with previous literature documenting an L2 processing delay in unbalanced bilinguals as a result of reduced proficiency (see Chapter 1 section 2.1 and reviews in Dijkstra & van Heuven, 2002 and van Heuven & Dijkstra, 2010).

As mentioned in Chapter 1 (section 2.3), language processing delays associated with bilingualism may be more robust in production than comprehension modalities (Gollan et al., 2011). Therefore despite the current lack of evidence for an L1 delay in comprehension, a vocal colour-naming task or an alternative language production paradigm may expose L1 processing difficulties. However, as production and comprehension delays may originate from different cognitive sources, more research is required to understand how bilingualism differentially affects lexical delays in each modality.

6.2. The bilingual cognitive advantage hypothesis

The bilingual cognitive advantage hypothesis predicted superior cognitive control abilities in bilingualism – evident as smaller interference effects, in both languages – resulting from the interdependence of executive control and language processing. The current data revealed some evidence for the bilingual cognitive advantage hypothesis, although the benefit in executive control was sensitive to individual variables such as proficiency and language immersion. The English-Chinese bilinguals experienced smaller interference effects than monolinguals in the L2. This ostensibly suggests enhanced cognitive control in the L2 for the English-Chinese bilinguals. However, this group did not show a similar advantage in the L1 English, so it is unclear whether the smaller L2 interference effects result from enhanced cognitive control or from reduced second-language proficiency: as discussed in Chapter 2 (section 2.1), a weaker language would also create smaller interference effects due to slower lexical access. Therefore because an advantage in interference effects did not occur in both languages for the English-Chinese bilinguals, they did not show a significant bilingual cognitive advantage. In contrast, the Chinese-English bilinguals demonstrated significantly smaller interference effects in both languages compared to monolinguals, indicating enhanced cognitive control abilities in this group.

It is possible that script differences could have contributed to the smaller interference effects in the L1 Chinese, as some studies have reported smaller Stroop interference effects for Chinese than for alphabetic languages (e.g. van Heuven et al., 2011). However, other studies directly comparing Stroop performance in monolingual speakers of Chinese and alphabetic languages have reported larger interference effects for Chinese (Biederman & Tsao, 1979; Saalbach & Stern, 2004; Tsao, Wu, & Feustel, 1981). Thus although the present results indicated a bilingual advantage in the L1 Chinese compared to English monolinguals, the possibility remains that script differences may influence the magnitude of the interference effect.

The proficiency splits in the current data also suggested that bilingual cognitive abilities can be modulated by proficiency. In the Chinese-English bilinguals performing in L2 English, high-proficiency bilinguals exhibited smaller interference effects than low-proficiency bilinguals. If lower proficiency in the second language creates delayed lexical access, smaller interference effects would be expected in the L2 for low-proficiency than high-proficiency bilinguals because the word generates less interference. However, in the present data, low-proficiency bilinguals showed larger interference effects in the L2, suggesting poorer cognitive control abilities. In contrast, high-proficiency bilinguals, who presumably experience increased language conflict due to the stronger L2 representations, demonstrated superior cognitive control abilities and smaller interference (and facilitation) effects. Therefore these data support the bilingual cognitive advantage, indicating that higher proficiency generates superior cognitive control abilities (Bialystok, Craik, & Ruocco, 2006).

Curiously, the Chinese-English bilinguals exhibited a bilingual cognitive advantage but the English-Chinese bilinguals did not, despite similar levels of subjective proficiency (see Methods, Experiment 3; section 4.1.1). One explanation for this could be language immersion experience, as the Chinese-English bilinguals were immersed in the foreign language while the English-Chinese bilinguals were not. Living in the foreign country and/or hearing the non-native language every day may have created more long-term and sustained language conflict, consequently boosting the bilingual advantage in the Chinese-English bilinguals. Few studies have considered the role of immersion on the bilingual advantage, but one study by Linck et al. (2009) suggested that L2 speakers immersed in the foreign-language environment exerted more inhibition over their L1 (see Green, 1998). In other words, bilinguals immersed in their weaker language engaged more cognitive control on a daily basis to avoid interference from the dominant language, predicting larger cognitive advantages for immersed bilinguals. Unpublished data from Baus et al. (2011) has even demonstrated that executive control abilities can benefit after only one month in an immersion environment. Future research should seek to balance the immersion background of participants in order to fully explore how such experience affects the bilingual advantage. Nevertheless, the current finding of smaller interference effects only in one bilingual group highlights the sensitivity of the bilingual cognitive advantage and its modulation by factors such as proficiency and L2 immersion experience (see Chapter 9, section 3.6).

The current evidence for the bilingual cognitive advantage offers specific support for the BICA hypothesis, as smaller interference effects were observed for the L1 Chinese compared to monolinguals and for high-proficiency L2 English bilinguals compared to low-proficiency. In contrast, the lack of a global RT advantage in any bilingual group contradicts the BEPA hypothesis. These data therefore suggest that bilinguals are better at resolving conflict, although this advantage is elusive and sensitive to a number of variables including proficiency, language immersion, and script.

6.3. The effects of script

The present experiments were conducted with Chinese and English bilinguals to minimize the effects of phonological and orthographic overlap between languages. However, as is apparent from Figure 3.1, English and Chinese elicited different RT patterns in SOA manipulation. In particular, English experienced the peak interference effects at the -200 ms SOA, whereas Chinese peak interference occurred at the 0 ms SOA. This pattern was similar across English-Chinese and Chinese-English bilinguals, suggesting that this was not an effect of proficiency but rather an underlying difference in language processing mechanisms in these two scripts.

The precise ways in which linguistic processing differs between alphabetic and logographic languages are highly debated in the literature. In visual word recognition in particular, a central question is whether lexical access involves phonology. In alphabetic writing systems like English, in which letters map directly onto sounds, phonology is a critical step in word recognition (e.g. Frost, 1998; see review in Perfetti, Liu, & Tan, 2005). In Chinese, however, the role of phonology is more contentious. Being a logographic writing system, Chinese does not have letters that map onto sounds; rather, each character has a specific pronunciation. The same pronunciation is shared by many other characters, creating a high number of homophones. In other words, phonology is much less reliable in Chinese. Consequently, some theorize that Chinese uses a ‘direct-access’ route in word recognition, proceeding directly from orthography to semantics and bypassing phonology altogether (Saalbach & Stern, 2004; Taft & van Graan, 1998). In contrast, alternative evidence demonstrates that phonology is activated – obligatorily and even in the absence of lexical activation – in Chinese word recognition (Chua, 1999; Guo, Peng, & Liu, 2005; Liu, Perfetti, & Hart, 2003; Perfetti et al., 2005; Saalbach & Stern, 2004; Spinks, Liu, Perfetti, & Tan, 2000; Tan, Laird et al., 2005; Xu, Pollatsek, & Potter, 1999).

Assimilating these two viewpoints, the lexical constituency model of word recognition (Perfetti et al., 2005) argues that phonological access is a key constituent of word recognition in all languages; however, the degree to which phonological activation is useful and contributes to lexical access can be mediated by script. For example, Tan & Perfetti (1997), using a phonologically-mediated priming paradigm in Chinese, demonstrated that the mediation effect was determined by homophone density: the more homophones a Chinese character had, the smaller the mediation priming. They proposed that in the presence of a large number of homophones, phonology is activated but does not aid in semantic access due to a very distributed spread of activation. In the presence of fewer homophones, however, phonological activation can aid in semantic access, making phonology a more central feature of word recognition. Therefore in Chinese, which has a large number of homophones, phonology is activated but is not helpful, so lexical access is effectively a direct link between orthography and semantics (supporting the direct access hypothesis). In English, consisting of fewer homophones, the role of phonology is more pronounced and lexical access is phonologically mediated.

If phonology is the major difference between English and Chinese word recognition, the fact that English and Chinese demonstrated peak interference at different SOAs may indicate that phonological access and/or mediation occurs at different speeds in each language. Specifically as English experienced a negative shift in peak interference effects compared to Chinese (-200 ms in English, 0 ms SOA in Chinese), English phonological mediation may be slower than Chinese (in the same way that delayed lexical access leads to negatively-shifted interference effects). This supports a previous finding by Saalbach & Stern (2004) reporting faster activation of phonology in Chinese than in German: the stronger influence of phonology in alphabetic languages could require an extra step in processing, making lexical access slower. In contrast, the more direct pathway from orthography to semantics in Chinese may expedite word recognition, creating different timings of lexical interference. Further research is required to fully understand the mechanisms and timecourse of phonological mediation in alphabetic and logographic writing systems.

Another factor to consider is the use of a manual task in the current experiments, which may have downplayed the influence of phonology. Although naming aloud necessarily requires phonological access, this activation could theoretically be bypassed altogether in a manual task. If so, the manual modality used here may have diminished the role of phonology in English, making it more like Chinese. Other manual tasks in Chinese have also documented evidence of phonological access (e.g. Liu et al., 2003; Xu et al., 1999), indicating that the use of a manual modality does not completely eliminate phonological processing; nevertheless, this is a potentially important point to consider in future research.

As seen in Figure 3.1 (panels c and d), the larger interference effects in the 0 ms SOA in Chinese were driven by the control condition, which elicited shorter RTs at the 0 ms SOA compared to the -200 ms or +200 ms SOAs. It is unclear why this discrepancy in the control RTs occurred only in one SOA. One possibility is that the use of blocked SOAs in the current task design affected the strategies that participants adopted (see Chapter 2, section 3.3). For example, in the 0 ms SOA, participants may have invested less attentional effort into word or character recognition because it occurred simultaneously with the target colour, whereas in negative SOAs the pre-exposure of the word allowed time to decipher the stimulus. However, if participants were not attending to the character in the 0 ms SOA, the incongruent condition would not have elicited a longer RT. The cross-linguistic similarity of bilinguals’ languages may also impact processing speed (e.g. Bates et al., 2003; Liu, Hao, Li, & Shu, 2011), so it remains to be seen whether this pattern is replicated with other logographic languages.

In sum, the patterns of interference effects in the current data suggest that script may influence both lexical processing and interference magnitude in the Stroop task. Early processing differences between English and Chinese will be addressed in the next chapter using EEG; furthermore, the role of script will be considered in depth in Chapter 6 and in the General Discussion.

7. Conclusions

The current study provided a preliminary behavioural investigation of how Stroop interference and facilitation effects are affected by SOA manipulation in monolinguals and bilinguals, with specific regards to lexical processing speed and enhanced cognitive control. The bilingual lexical disadvantage hypotheses predicted delayed lexical access in bilinguals, reflected as a negative shift in the peak interference effects. There was no evidence for a lexical delay in the L1 compared to monolinguals in either bilingual group, but there was some limited evidence for an L2 delay both within and between groups. The bilingual cognitive advantage hypothesis predicted smaller interference effects for bilinguals in both their L1 and L2 compared to monolinguals. There was evidence for a bilingual interference advantage, supporting the BICA hypothesis; however, this advantage was sensitive to individual variables such as language proficiency and language immersion experience. In contrast, the lack of a global RT advantage did not support the BEPA hypothesis.

The data thus suggested that both executive control abilities and lexical access speed contribute to bilingual Stroop performance. The use of SOA manipulation in the Stroop task has proven useful in investigating the bilingual cognitive advantage and lexical disadvantage hypotheses. However, the use of a behavioural paradigm is limited by virtue of relying on reaction times as the sole indicators of cognitive function. Linguistic processes occur rapidly, so the interpretation of an RT at 400 ms overlooks a number of cognitive functions that occur before a response is made. To gather more fine-grained temporal information on the lexical processing speed of bilinguals, the next chapter utilizes electroencephalography (EEG), which has a temporal resolution on the order of milliseconds.

Chapter 4: Electrophysiological Measures of Bilingual Lexical Processing Speed

The behavioural study in the previous chapter provided significant, although limited, evidence for a bilingual cognitive advantage and the bilingual lexical disadvantage. However, a clear pattern was difficult to discern due to the influence of script differences between Chinese and English. The current chapter further investigates bilingual delays in lexical access by utilizing EEG to obtain accurate temporal information on linguistic processing speed. A Stroop task with SOA manipulation is again employed to assess automatic reading. Building on the abundance of previous literature identifying bilingual delays at late ERP components like the N400, the focus of the current chapter is on very early time windows of orthographic processing, namely the N170 ERP component. While this chapter focuses on early lexical access speed, the next chapter uses the same dataset to address the bilingual cognitive advantage by investigating how conflict-related ERP components are affected by SOA manipulation in monolinguals and bilinguals.

1. Introduction

As detailed in Chapter 1 (Part 2), behavioural and EEG evidence has suggested that bilinguals experience delayed lexical access in both their L1 (as proposed by the bilingual L1 lexical disadvantage hypothesis) and L2 (as proposed by the bilingual L2 lexical disadvantage hypothesis) compared to monolinguals, due to the relatively reduced frequency of use and weaker connections of their languages (e.g. Dijkstra & van Heuven, 2002; Gollan et al., 2008; Gollan, Montoya, Fennema-Notestine, et al., 2005; Pyers et al., 2009; van Heuven & Dijkstra, 2010). However, it is unclear precisely when these delays occur: do bilinguals have difficulties with higher-level linguistic processes such as semantic integration and syntactic parsing, or is the disadvantage rooted in lower-level orthographic processing? Determining how early in lexical processing these difficulties manifest themselves, especially in the native language, is critical in understanding the source of the difficulties in non-native language processing.

1.1. Bilingual delays at early stages of linguistic processing

The bilingual L2 lexical disadvantage hypothesis (see Chapter 1, section 2.1) is well-supported by empirical behavioural evidence documenting L2 processing delays across a range of tasks (production and comprehension) and individual factors (e.g. L2 proficiency, AoA; Gollan et al., 2011, 2008; Ivanova & Costa, 2008; Ransdell & Fischler, 1987; see van Heuven & Dijkstra, 2010 for a review). In EEG, L2 delays are also documented across a range of time windows of language processing. The majority of studies have focused on the N400, a component reflecting semantic integration during comprehension that peaks at approximately 400 ms (see Lau et al., 2008 for a review). Bilinguals usually exhibit a significantly delayed N400 in their L2 compared to the L1 or to monolinguals (Ardal et al., 1990; Hahne, 2001; Hahne & Friederici, 2001; Moreno & Kutas, 2005; see Moreno et al., 2008 for a review), indicating that higher-level semantic integration processes operate differently in a native versus a non-native language. Importantly, delays have also been reported very early in L2 lexical processing. Differences are observable among native and non-native languages as early as 150 ms after word presentation, indicating difficulties in basic, low-level lexical processes such as visual letter decoding or distinguishing words from symbol strings (Liu & Perfetti, 2003; Proverbio et al., 2009). Furthermore, an L2 delay has been reported for bilinguals from various language backgrounds, including Chinese (Liu & Perfetti, 2003; Weber-Fox & Neville, 1996), Spanish (Moreno & Kutas, 2005; Newman et al., 2012), French (Ardal et al., 1990), German (Proverbio et al., 2009; Spalek et al., 2011), Italian, and Slovenian (Proverbio et al., 2009), suggesting that temporal difficulties do not stem from processing differences between writing systems or scripts, but rather from slower processing due to the reduced proficiency of the second language.

In contrast, EEG evidence for a processing delay in the bilingual L1 compared to monolinguals is limited, although behavioural evidence exists (see Chapter 1, Table 1.1; Gollan, Montoya, Fennema-Notestine, et al., 2005; Ivanova & Costa, 2008; Lehtonen et al., 2012; Lehtonen & Laine, 2003; Ransdell & Fischler, 1987). Only two previous studies have employed EEG to directly compare L1 processing speed to that of monolinguals (Ardal et al., 1990; Proverbio et al., 2002). Proverbio et al. (2002) compared monolinguals and bilinguals on a syntactic comprehension task: although differences occurred between native and non-native languages in the lateralization and amplitude of the N1 (at 100 ms) and N2 (at 200 ms) components, latency analyses in the EEG data were not reported. Ardal et al. (1990) tested monolinguals and bilinguals in L1 and L2 and observed a linear trend in peak latency, such that the monolingual N400 peaked first, followed by the bilingual L1, then the bilingual L2. However, this study focused on later semantic integration processes at the N400. As demonstrated by evidence from L2 delays, proficiency effects can emerge as early as 150 ms (e.g. Proverbio et al., 2009); however, it is currently unclear whether an L1 is also delayed at low-level linguistic processes because previous studies have not directly compared the L1 to monolinguals at these early time windows. Importantly, delays in low-level language processing in bilinguals' L1 may have downstream effects such that later, higher-level processes are impeded not because they are slower but because they started later. Identifying how early bilingual L1 language processing diverges from that of monolinguals is therefore crucial in understanding the later effects that may arise.

The current study aimed to establish whether a bilingual processing delay occurred in early linguistic processing in bilinguals' L1 and L2 compared to monolinguals. To address these questions, EEG was employed to investigate early orthographic recognition in monolinguals and unbalanced (L1-dominant) Chinese-English bilinguals, using a Stroop task with SOA manipulation to assess automatic reading.

1.2. The N170 component

Early linguistic processing was investigated via the N170 component. This ERP (sometimes called an N1) is characterized by a negative-going wave over posterior parietal and occipito-temporal scalp that peaks approximately 170 ms after stimulus presentation (see Chapter 1, section 1.2.1). An N170 is elicited for a range of visual stimuli, such as faces, objects, and words (Bentin, Allison, Puce, Perez, & McCarthy, 1996; Rossion, Joyce, Cottrell, & Tarr, 2003; Rousselet, Macé, & Fabre-Thorpe, 2004; Tanaka & Curran, 2001). Importantly, this component is sensitive to expertise, showing a larger negative amplitude or longer latency for familiar stimuli than for control stimuli or unfamiliar objects (e.g. Bentin et al., 1996; Boehm, Dering, & Thierry, 2011; Itier, Latinus, & Taylor, 2006; Maurer, Rossion, & McCandliss, 2008; Tanaka & Curran, 2001). Given this sensitivity to expertise, the N170 is specifically thought to reflect experience with perceptual processing of visual stimuli (Rossion et al., 2003; Thierry, Martin, Downing, & Pegna, 2007).

Although the N170 is not language-specific, it is language-sensitive. In visual word recognition, this component distinguishes between orthographic (words, pseudowords) and non-orthographic (consonant strings, symbols) stimuli, generally generating an enhanced negative amplitude for words than for symbols over parietal scalp (Appelbaum, Liotti et al., 2009; Bentin et al., 1999; Hauk, Pulvermüller, Ford, Marslen-Wilson, & Davis, 2009; Maurer et al., 2005; Wong, Gauthier, Woroch, DeBuse, & Curran, 2005). This ‘N170 effect’ (i.e. the amplitude difference between word and symbol stimuli, at or around the N170 peak) is usually larger over the left hemisphere than the right (Appelbaum, Liotti et al., 2009; Bentin et al., 1996, 1999; Grossi et al., 2010; Hauk & Pulvermüller, 2004; Maurer et al., 2005; Rossion et al., 2003; Sereno et al., 1998). As the N170 is sensitive to experience, this word vs. non-word N170 effect is believed to reflect orthographic processes that are dependent on language experience (Appelbaum, Liotti et al., 2009; Bentin et al., 1999; Grossi et al., 2010; Maurer et al., 2005; Ruz & Nobre, 2008). For example, adults show a typical N170 distinction between letters and symbol strings, but pre-literate children do not (Maurer et al., 2005), suggesting that the N170 effect to words requires extensive reading experience. As the N170 is sensitive to language experience and proficiency, any low-level orthographic processing differences associated with reduced experience with language, as in bilingualism, should manifest at this early window of linguistic processing. Crucially, the latency of the N170 is also affected by familiarity and experience with language (Boehm et al., 2011; Maurer et al., 2008): for example, Maurer et al. (2008) reported shorter N170 latencies when viewing a familiar orthographic script. Therefore because unfamiliarity with language is associated with delays in N170 latency, this component should be specifically sensitive to lexical processing delays resulting from reduced language experience.

The current study tested Chinese-English bilinguals, as in the previous chapter, in order to minimize the effects of homophones or script overlap across languages which could interfere with or facilitate lexical access. Given that the N170 indexes orthographic processing, a consideration of the role of orthography on the N170 effect is warranted in light of the script differences between these languages. Language-specific script differences have occasionally been reported at the N170: for example, investigating the two scripts in Hebrew that contain different orthographic depths, Bar-Kochva (2011) demonstrated that the shallow[8] Hebrew script generated a larger N170 than the deep orthographic script. Importantly, however, while script may modulate N170 amplitude, the *latency* of the effect is the same: the distinction between words and symbol strings (i.e. the N170 effect) occurs at the N170 peak across languages regardless of other linguistic differences (e.g. in Chinese: Lin et al., 2011; in French and Arabic: Simon, Bernard, Lalonde, & Rebaï, 2006; Simon, Petit, Bernard, & Rebaï, 2007; in Hebrew: Bar-Kochva, 2011). Therefore while the different native languages between monolinguals and bilinguals in the current study (English and Chinese, respectively) might affect the amplitude of the N170, delays in lexical processing driven by bilingualism should only affect the latency of the N170 effect.

1.3. The Stroop task and language automaticity

The use of a Stroop task is valuable in the context of this study because it allows for an investigation of automatic and low-level linguistic processes. Unlike an explicit reading paradigm, a colour-naming Stroop task does not emphasize overt reading; in fact, doing so is detrimental to performance. The Stroop task can therefore be used not just as an index of the strength of language processing, but also of language automaticity in native and non-native languages (Braet et al., 2011; Protopapas et al., 2007; see Chapter 2). For the purposes of the present study, a cognitive process is considered to be ‘automatic’ if it is initiated in all contexts, even when its engagement is unnecessary or could be detrimental to performance (as in a Stroop task), and if it always proceeds at the same speed once initiated (see Besner, 2001 and Reynolds & Besner, 2006 for discussions of automaticity in reading).

Three SOAs (-400 ms, 0 ms, +400 ms) were chosen for the current study. The -400 ms SOA provided a measure of pure word reading before the colour arrived. The 0 ms SOA was included to investigate whether the bilingual delay is stable under situations of cognitive conflict. Finally, the +400 ms SOA was included to investigate language automaticity in the L1 and L2: as the target stimulus (the colour) has already appeared, activation of the word is unnecessary, so any word-reading ERP components observed in this SOA should indicate reading automaticity. Importantly, the inclusion of a symbol-string control condition on a third of trials established distinctions between words and non-words at the N170 peak.

The current study assessed the automaticity of low-level orthographic processing by establishing whether word recognition in all groups: a) occurred in all SOAs; and b) occurred at the same time in each SOA. If word recognition follows the same timecourse – i.e. if the N170 effect occurs at the same latency – in all SOAs, this would provide evidence for the automatic nature of early orthographic word recognition processes. In contrast, if an N170 effect is present in some SOAs but not others – if it is absent, for example, in the +400 ms SOA when the word does not need to be activated – this would indicate that orthographic

---

[8] Shallow orthographies have consistent grapheme-phoneme conversion rules, whereas deep orthographies contain common irregularities; see Chapter 6 for further discussion.

processes can be controlled and are only engaged when necessary. Furthermore, if an N170 effect were absent in the L2, this would suggest that the more effortful second-language processing was bypassed because reading is superfluous in the Stroop task. In sum, if word recognition is controllable, an N170 effect should be absent in situations when reading is unnecessary, as in the +400 ms SOA or in the L2; but if word recognition is automatic, even in a second language when processing is more effortful, an N170 effect should be present and should occur at the same latency in all SOAs. Importantly, although the onset latency of orthographic recognition should be the same *within* language, the latency of lexical processing may differ between participants based on bilingualism and/or second-language proficiency.[9]

In summary, the current study sought to establish whether the latency of early, low-level orthographic recognition processing, as reflected by the N170 component, was modulated by bilingualism in the context of automatic reading in the Stroop task. Conflict-related Stroop components arise after the time window of early lexical processing, at approximately 300-500 ms (e.g. Liotti et al., 2000), so the N170 component should not be affected by these later conflict processes (conflict analyses of this dataset are presented in Chapter 5). Furthermore, although the same words are presented multiple times in a Stroop task, repetition effects generally affect N170 amplitude (Simon et al., 2007) rather than latency; importantly, only familiarity effects have been found to modulate the timing of the N170 effect (e.g. Bentin et al., 1996; Itier et al., 2006; Maurer et al., 2008; Rossion et al., 2003). If orthographic processing speed is modulated by proficiency, as predicted by the bilingual L2 lexical disadvantage hypothesis, the N170 effect should be delayed in bilinguals' L2; if it is modulated by frequency of language use, as proposed by the L1 lexical disadvantage hypothesis, it should be delayed in both bilinguals' L1 and L2 compared to monolinguals.

2. Methods

2.1. Participants

2.1.1. Bilinguals

The bilingual participants were nineteen Chinese-English bilinguals from the University of Nottingham (see Table 4.1 for full participant demographics). All participants were native Mandarin speakers from mainland China who had acquired English at approximately 11 years of age (*SD* = 2.2 years) but were dominant in Mandarin. All lived in England at the time of testing and considered themselves fluent in English. Participants also completed a language background questionnaire prior to testing. Their overall self-reported English

---

[9] As mentioned in Chapter 2 (section 2.1.1), the strength of language connections, and therefore the speed of processing, can change with experience. In an L2, therefore, the latency of word reading may change with proficiency. However, this presumably occurs over the course of months or years, not within a single experimental session; thus for the purposes of the current study the delay is expected to be static across SOAs.

proficiency, averaged across reading, writing, speaking and listening, was 7.1 on a 10-point scale. They rated their daily use of L1 as 3.6 (*SD* = 1.1), on a scale from 1 (rarely) to 5 (always), and daily use of L2 as 2.7 (*SD* = 1.0), indicating that they used Chinese more often than English. Some participants (*n* = 12) reported a basic knowledge of other languages in addition to Chinese and English (average overall proficiency in other languages = 2.33, *SD* = 1.3). All participants reported no colour-blindness and were right-handed.

2.1.2. Monolinguals

The monolingual participants were twenty-eight[10] monolingual native English speakers from the University of Nottingham (Table 4.1) who reported no colour-blindness and were right-handed. A language background questionnaire was administered after testing to gather more information about native and foreign language skills. The majority of participants (*n* = 24) reported studying other languages (average overall proficiency in other languages = 4.12, *SD* = 1.6), but none considered themselves proficient in anything but English.

---

[10] The monolingual group was therefore larger than the bilingual group. However, when analyzing the data of only the first 20 monolingual participants, the patterns were very similar to those of the full dataset, so the unequal sample sizes likely did not affect the results.

Table 4.1: Participant demographics and bilingual subjective proficiency scores (scale: 1 = very poor to 10 = very fluent). Numbers in parentheses indicate standard deviation.

Group	***n***	**Age**	**Gender**	**Age of first L2 contact**	**Self-rated L2 proficiency**				
					Speaking	**Listening**	**Reading**	**Writing**	**Overall**
Chinese-English bilinguals	19	23.1 (2.5)	15 female, 4 male	11.0 (2.2)	6.6 (1.4)	7.2 (0.9)	7.5 (1.3)	7.0 (1.3)	7.1 (1.0)
English monolinguals	28	22.3 (5.4)	16 female, 12 male	N/A	N/A	N/A	N/A	N/A	N/A

2.1.3. Materials and Design

The English and Chinese stimuli were identical to those in Experiments 2 and 3 of Chapter 3, with symbol-string control conditions of ‘%%%%’ in English and ‘%’ in Chinese. Participants responded to the colour of the rectangle by pressing a button on the keyboard (right index finger for red, right middle finger for green, right ring finger for blue).

2.1.4. Procedure

All procedures were approved by the Ethics Committee of the University of Nottingham School of Psychology. Bilingual participants performed two sessions, one for each language (L1 Chinese and L2 English), on consecutive days. The order of language administration was counterbalanced across participants. Monolingual participants performed only one session (in English). All testing sessions were approximately 1.5 hours including EEG net application and set-up. Participants were given a brief practice session with only colour stimuli before each session to become familiarized with the colour-response mappings, followed by the experimental session which was approximately 50 minutes long.

Stimuli were presented using E-Prime. The experimental session included twelve blocks of approximately 4 minutes each. Three SOAs (-400 ms, 0 ms, +400 ms) were used: SOA was blocked and counterbalanced across participants. Each SOA included 216 randomly presented trials (72 congruent, 72 control, 72 incongruent), resulting in 648 trials total. The trial procedure was otherwise identical to the corresponding SOAs in all experiments of Chapter 3 (see Chapter 2, Figure 2.2), with the exception that once both word and colour stimuli had appeared, both remained on the screen for a set duration of 1000 ms, followed by a blank screen presented at an inter-stimulus interval (ISI) varying from 1500-2000 ms before the start of the next trial.

2.2. Data acquisition

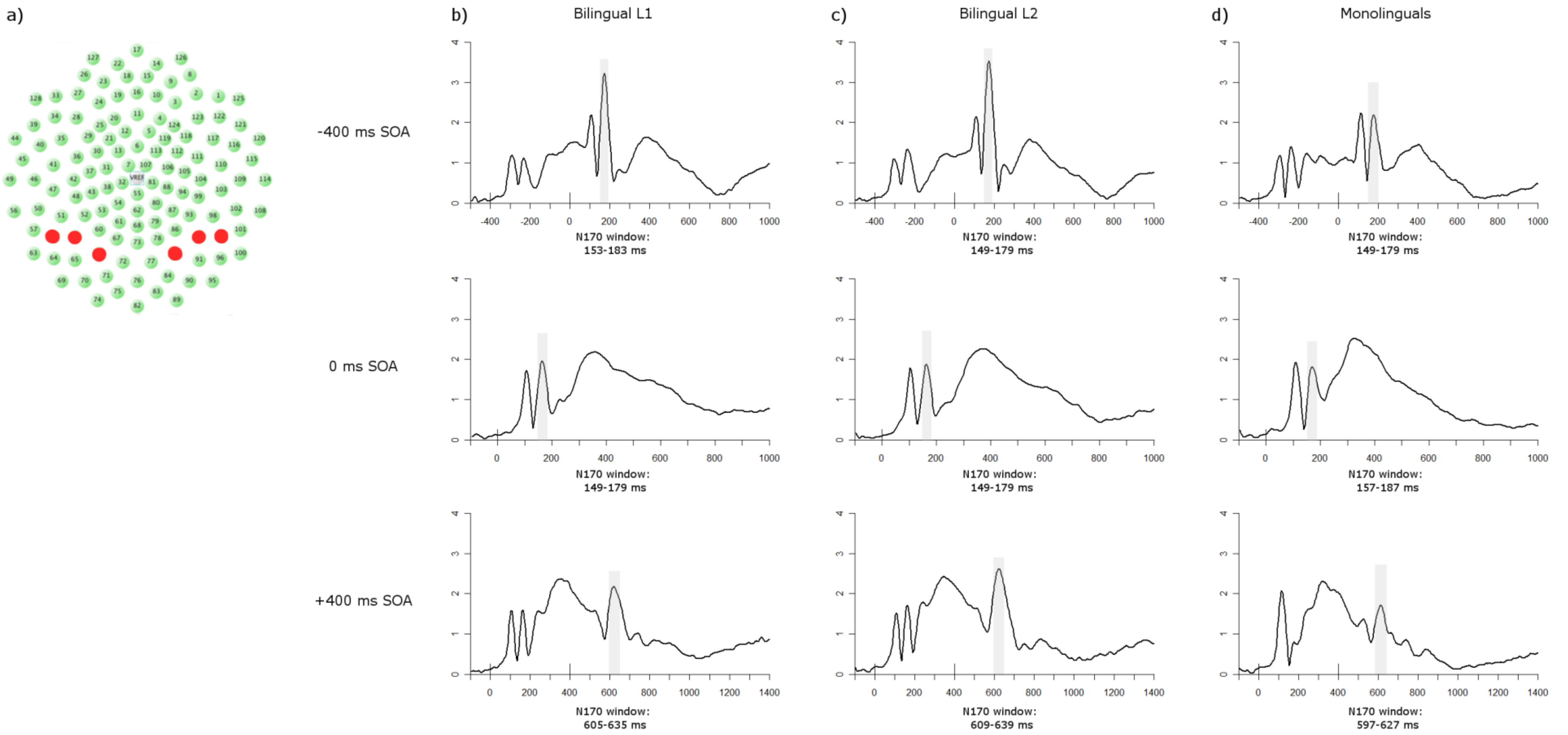
High-density ERPs were recorded at 250Hz using a Geodesics 128-channel sensor net and NetStation version 4.3. Impedences were kept under 50 kΩ, where possible. Data were pre-processed using EEGlab version 6.0 and Matlab version 7.9. The data were first filtered using a 0.5-40Hz bandpass filter, and transformed using an average reference transform to the Cz electrode. Correction for eye movement artifacts was performed using a combination of principal component analysis (PCA) and independent component analysis (ICA): a PCA was first run to identify the number of components required to explain 99% of the data. ICA was then performed using the number of components specified by the PCA. Following ICA decomposition eye movements, blinks, and other noise components were visually identified and manually removed from the data.

The resulting cleaned continuous data were segmented into epochs time-locked to the onset of the colour stimulus. Segments in the -400 ms SOA extended from 500 ms before to 1000 ms after the colour stimulus, in order to include the response to the word (presented at -400 ms). Segments in the 0 ms SOA extended from 100 ms before to 1000 ms after stimuli presentation. Segments in the +400 ms SOA extended from 100 ms before to 1400 ms after the colour stimulus, to include the full response to the word (presented at +400 ms). Additional bad epochs were identified and rejected using a joint probability computation. Segments in which the behavioural response was an error or outlier (RTs below 250 ms or above 2000 ms) were also rejected. The resulting segments were baseline corrected using data from the first 100 ms of the segment. For bilinguals, an average of 95% of trials was retained for both the L1 and L2 conditions, with an average of 67 trials per trial type included in the final analyses for each subject and language. For monolinguals, an average of 93% of trials was retained per participant, with an average of 67 trials per trial type included in the final analyses.

2.3. ERP statistical analysis

The N170 component was investigated at six electrodes over three bilateral temporo-parietal sites: P7/8, P9/10, and PO7/8 (Figure 4.1a). These sites were chosen based on previous reports that the N170 is typically located over posterior parietal and occipitotemporal sites (e.g. sites TO1/2 and P3/4 used for analysis in Appelbaum, Liotti et al., 2009; T5/6 in Maurer et al., 2005 and Bentin et al., 1999; P7/8, PO7/8 and PO9/10 in Grossi et al., 2010) and because these sites showed the largest N170 effects in the current data. The N170 analysis window was defined for each SOA separately by collapsing the waveforms across subjects and conditions and taking the root mean square (RMS) at every time point (Hauk et al., 2006). For each SOA, the N170 peak was identified as the time point between 150-250 ms after word presentation where the maximum RMS amplitude occurred. The N170 window extended 15 ms before and after this peak, giving a 30 ms analysis window for each SOA (Figure 4.1, panels b-d). For each group/language, a 3 (congruency) x 3 (SOA) x 3 (electrode site) x 2 (hemisphere) repeated-measures ANOVA was performed on the average amplitude within the N170 window. As the N170 is typically left-lateralized, only the waveforms from the left-hemisphere clustered electrodes are presented in figures. However, topographic maps of the incongruent-control differences and electrodes showing significant differences ($p < 0.05$) between incongruent and control amplitudes over the analysis windows are also presented in Figures 4.2, 4.3, and 4.4, to show the full extent and significance of scalp polarity. Difference waves were calculated by subtracting the amplitudes of the control condition from those of the incongruent condition at every time point. Peak negative amplitudes in the data were calculated by identifying the minimum amplitude within a specified window. Peak latencies were identified as the time point within a specified window containing the peak amplitude for each subject.

Figure 4.1: a) The 129-channel electrode map with the three bilateral temporo-parietal sites used for statistical analyses (P7/8, P9/10, PO7/8) indicated with red dots. Panels b-d: Root mean square (RMS) amplitudes (uV) for the b) bilingual L1; c) bilingual L2; and d) monolingual waveforms. Shaded regions indicate the N170 window, defined as the maximum RMS amplitude ±15 ms. The specific N170 windows are labelled for each group and SOA.



3. Results

3.1. Bilingual L1 (Chinese)

The bilingual L1 ERP data[11] showed a temporo-parietal N170 in response to both word and colour stimuli in every SOA (Figure 4.2). Following word presentation, word and control waveforms were distinguished at the N170 peak in every SOA, demonstrating an N170 effect. To evaluate this statistically, the average amplitudes over the N170 window at each electrode were subjected to a 3 (congruency) x 3 (SOA) x 3 (electrode site: P7/8, P9/10, PO7/8) x 2 (hemisphere) repeated-measures ANOVA (see Table 4.2 for full results). Across both hemispheres and all SOAs, the incongruent and congruent conditions were more negative than the control condition, as indicated by a significant main effect of congruency ($p < 0.01$). There was also a three-way interaction of congruency, SOA, and site ($p < 0.05$), which was driven by an interaction of congruency and site in the +400 ms SOA ($F(4,72) = 2.50$, $p = 0.05$) such that the P9/10 sites showed a larger effect of congruency ($F(2,36) = 3.05$, $p = 0.06$) than the P7/8 or PO7/8 sites (all p's > 0.66). Importantly, the lack of a main effect of hemisphere ($p = 0.12$) or an interaction of hemisphere and congruency ($p = 0.87$) in the overall ANOVA indicates that neither the amplitude of the N170 peak nor the magnitude of the N170 effect were modulated by hemisphere. Therefore although the N170 component showed a typical enhancement to words compared to symbol strings, the N170 effect was bilaterally distributed, in contrast to the typical left-lateralization reported in the literature (Appelbaum, Liotti et al., 2009; Bentin et al., 1999; Grossi et al., 2010; Hauk et al., 2009; Maurer et al., 2005; Rossion et al., 2003; Wong et al., 2005).

---

[11] The behavioural Stroop data for all groups will be presented in the next chapter.

Figure 4.2: Bilingual L1 (Chinese) incongruent, congruent and control waveforms, clustered over the left-hemisphere temporo-parietal sites (P7, PO7, P9) for the -400 ms, 0 ms and +400 ms SOAs. Negativity is plotted upwards. Grey shaded windows indicate the N170 effect. Topographic maps show the incongruent - control differences, averaged over the N170 window (±15 ms around the N170 peak as determined by RMS analysis). Black dots illustrate electrodes showing a significant difference ($p < 0.05$) between the averaged amplitudes of the incongruent and control conditions over the relevant window.

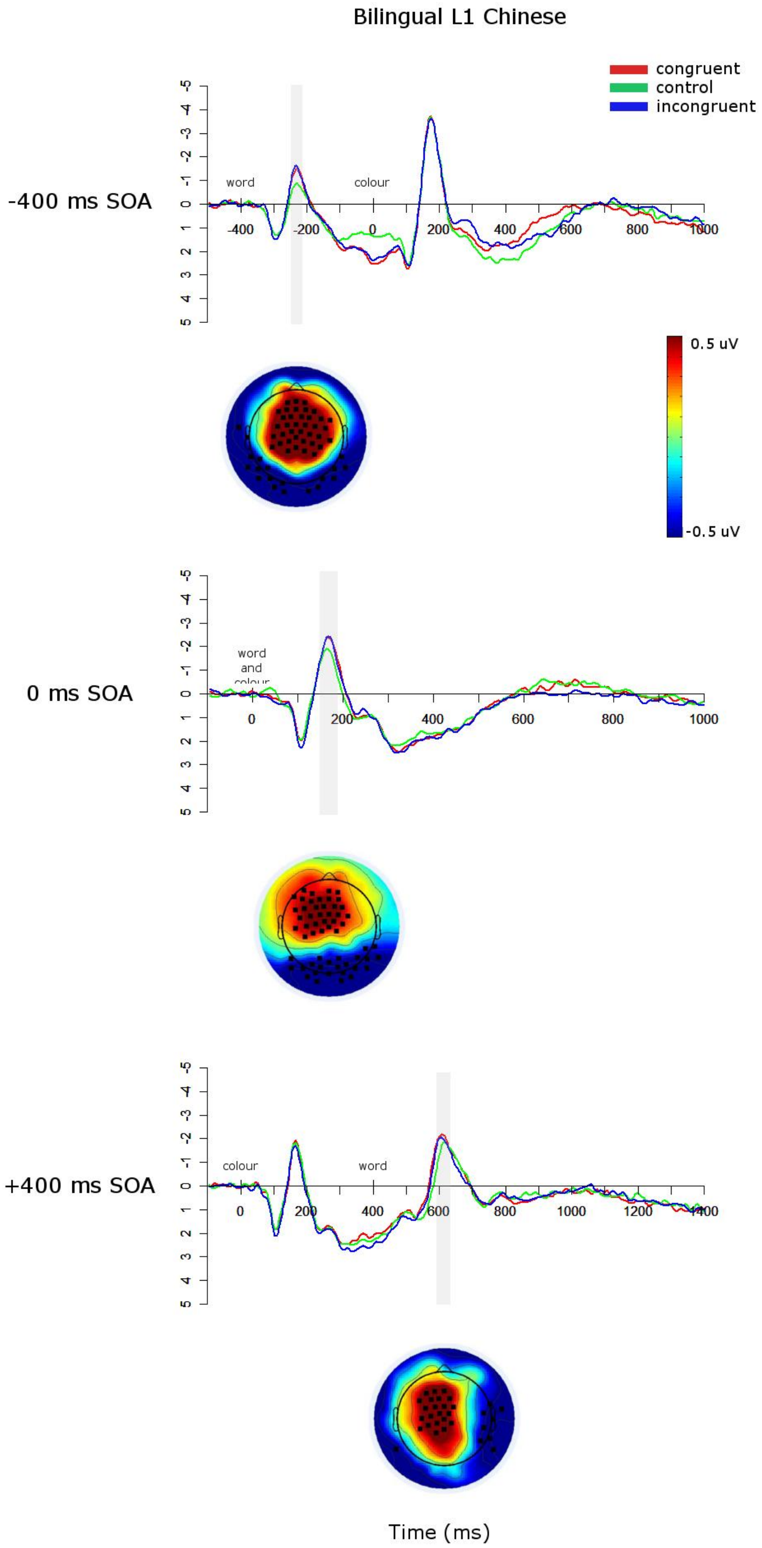


Table 4.2: Results of the 3 (congruency) x 3 (SOA) x 3 (electrode site) x 2 (hemisphere) repeated-measures ANOVAs for the N170 component in the bilingual L1, bilingual L2, and monolinguals, and for the bilingual L2 N2 component. Cong = congruency (congruent/control/incongruent); hem = hemisphere; site = electrode site (P7/8, PO7/8, P9/10); n.s. = not significant ($p > 0.10$).

Effect or Interaction	**N170 component (±15 ms around N170 peak)**			**N2 component (200-350 ms)**
	Bilingual L1	**Bilingual L2**	**Monolinguals**	**Bilingual L2**
Hemisphere	n.s.	n.s.	n.s.	n.s.
Congruency	$F(2,36) = 7.35$, $p < 0.01$	n.s.	$F(2, 54) = 33.18$, $p < 0.0001$	$F(2,36) = 31.80$, $p < 0.0001$
SOA	n.s.	n.s.	n.s.	$F(2,36) = 41.82$, $p < 0.0001$
Electrode site	$F(2,36) = 3.14$, $p = 0.06$	$F(2,36) = 3.69$, $p < 0.05$	n.s.	$F(2,36) = 34.68$, $p < 0.0001$
Cong x hem	n.s.	n.s.	n.s.	$F(2,36) = 3.15$, $p = 0.05$
SOA x hem	n.s.	$F(2,36) = 3.04$, $p = 0.06$	n.s.	n.s.
SOA x cong	n.s.	n.s.	n.s.	$F(4,72) = 4.83$, $p < 0.01$
Hem x site	$F(2,36) = 4.42$, $p < 0.05$	n.s.	$F(2,54) = 6.00$, $p < 0.01$	$F(2,36) = 5.50$, $p < 0.01$
Cong x site	$F (4,72) = 3.01$, $p < 0.05$	n.s.	$F(4,108) = 12.42$, $p < 0.0001$	n.s.
SOA x site	$F (4,72) = 2.79$, $p < 0.05$	$F(4,72) = 4.09$, $p < 0.01$	n.s.	$F(4,72) = 7.65$, $p < 0.0001$
SOA x cong x hem	n.s.	$F(4,72) = 3.01$, $p < 0.05$	n.s.	n.s.
Cong x hem x site	n.s.	n.s.	$F(4,108) = 4.15$, $p < 0.01$	n.s.
SOA x hem x site	$F(4,72) = 3.58$, $p < 0.05$	n.s.	n.s.	n.s.
SOA x cong x site	$F(8,144) = 2.13$, $p < 0.05$	n.s.	n.s.	n.s.
SOA x cong x hem x site	n.s.	$F(8,144) = 1.83$, $p = 0.08$	n.s.	n.s.

3.2. Bilingual L2 (English)

In the bilingual L2 ERP data, a temporo-parietal N170 peak occurred following word and colour presentation in every SOA. However, in contrast to the L1 data, following word presentation the word and control conditions did not differ in amplitude at the N170 peak (Figure 4.3), as indicated by a non-significant main effect of congruency (see Table 4.2). There was, however, a 3-way interaction between congruency, hemisphere and SOA ($p < 0.05$). Breaking this down by SOA and collapsing over site, the -400 ms SOA showed no main effects or interactions of congruency (all p's > 0.24). In the 0 ms SOA there was a main effect of hemisphere ($F(1,18) = 5.25$, $p < 0.05$) such that the N170 peak was more negative over the right hemisphere, but no main effect of congruency ($p = 0.89$) or interaction of congruency and hemisphere ($p = 0.95$). The +400 ms SOA showed an interaction of hemisphere and congruency ($F(2,36) = 5.45$, $p < 0.01$), but follow-up analyses indicated no effects of congruency in either hemisphere (all p's < 0.23). The lack of significant congruency effects in any analysis indicates that the word and symbol string elicited similar N170 amplitudes; in other words, there was no N170 effect in the bilingual L2.

The word vs. non-word discrimination instead occurred at a later component, referred to here as an N2[12] (approximately 200-350 ms after word presentation in every SOA). Statistical investigation of the N2 was performed with running t-tests, as this component was not detected by the RMS calculations. The raw data was collapsed into 24 ms bins with 12 ms overlap. Within each bin, the average amplitude was compared between conditions using paired-sample t-tests. As shown in Figure 4.3, the running t-tests revealed significantly more negative waveforms for incongruent and congruent word conditions than for control conditions. The L2 waveforms thus demonstrated a fundamentally different pattern than the L1, such that orthographic discrimination occurred at a later N2 component rather than at the N170.

To investigate the N2 component further, a 3 (congruency) x 3 (SOA) x 3 (electrode site) x 2 (hemisphere) ANOVA was performed with the amplitudes over the N2 window (see Table 4.2). A main effect of congruency occurred ($p < 0.0001$) as well a strong trend of an interaction of congruency and hemisphere ($p = 0.05$), which stemmed from a stronger effect of congruency in the left hemisphere ($F(2,36) = 35.8$, $p < 0.0001$) than in the right ($F(2,36) = 17.18$, $p < 0.0001$), although in both hemispheres the incongruent and congruent conditions were more negative than the control. There was also an interaction of SOA and congruency ($p < 0.01$): all SOAs showed significant main effects of congruency but the effect was strongest in the -400 ms SOA ($F(2,36) = 34.40$, $p < 0.0001$), followed by the +400 ms SOA ($F(2,36) = 14.31$, $p < 0.0001$) and the 0 ms SOA ($F(2,36) = 9.57$, $p < 0.001$). This indicates that the N2 congruency effect was smaller following simultaneous word and colour

---

[12] An N2 component is commonly reported in the executive control literature as being indicative of conflict processing (e.g. Kousaie & Phillips, 2012). The bilingual L2 component is referred to as an N2 due to its latency and polarity, but it is not meant to be synonymous with this other N2 component.

presentation in the 0 ms SOA and larger in the -400 ms and +400 ms SOAs, when the word was presented alone and sufficient time was allowed for its processing.

3.3.English monolinguals

The English monolingual ERP data elicited an N170 effect following word presentation in all SOAs, demonstrating a main effect of congruency ($p < 0.0001$) such that the control stimuli were more negative than word stimuli (Figure 4.4, Table 4.2). There was also a significant three-way interaction of hemisphere, congruency, and site ($p < 0.01$): all sites showed main effects of congruency (all p's < 0.0001) but no effects of hemisphere (all p's > 0.11) and no interactions of hemisphere and congruency (all p's > 0.46). The lack of any significant interactions between hemisphere and congruency, either in the overall ANOVA or in the follow-up analyses, indicates that, as in the bilingual L1 data, the N170 effect was bilateral, contrary to the left-lateralization that is usually reported in the literature. Therefore the monolingual data showed a significant N170 effect at a similar latency as the bilingual L1. Interestingly, however, the more negative N170 peak for control stimuli was opposite to the pattern seen in the bilingual data, which showed a more negative wave for the word stimuli than symbol strings in both the L1 and L2.

Figure 4.3: Bilingual L2 (English) incongruent, congruent and control waveforms, clustered over the left-hemisphere temporo-parietal sites (P7, PO7, P9) for each SOA. N170 windows (grey shading) and N2 windows (green shading) are indicated; bars along the bottom indicate significant differences in the N2 window as determined by running *t*-tests. Topographic maps show the incongruent - control differences, averaged over the N170 and N2 windows, respectively. Black dots illustrate electrodes showing a significant difference ($p < 0.05$) between the averaged amplitudes of the incongruent and control conditions over the relevant windows.

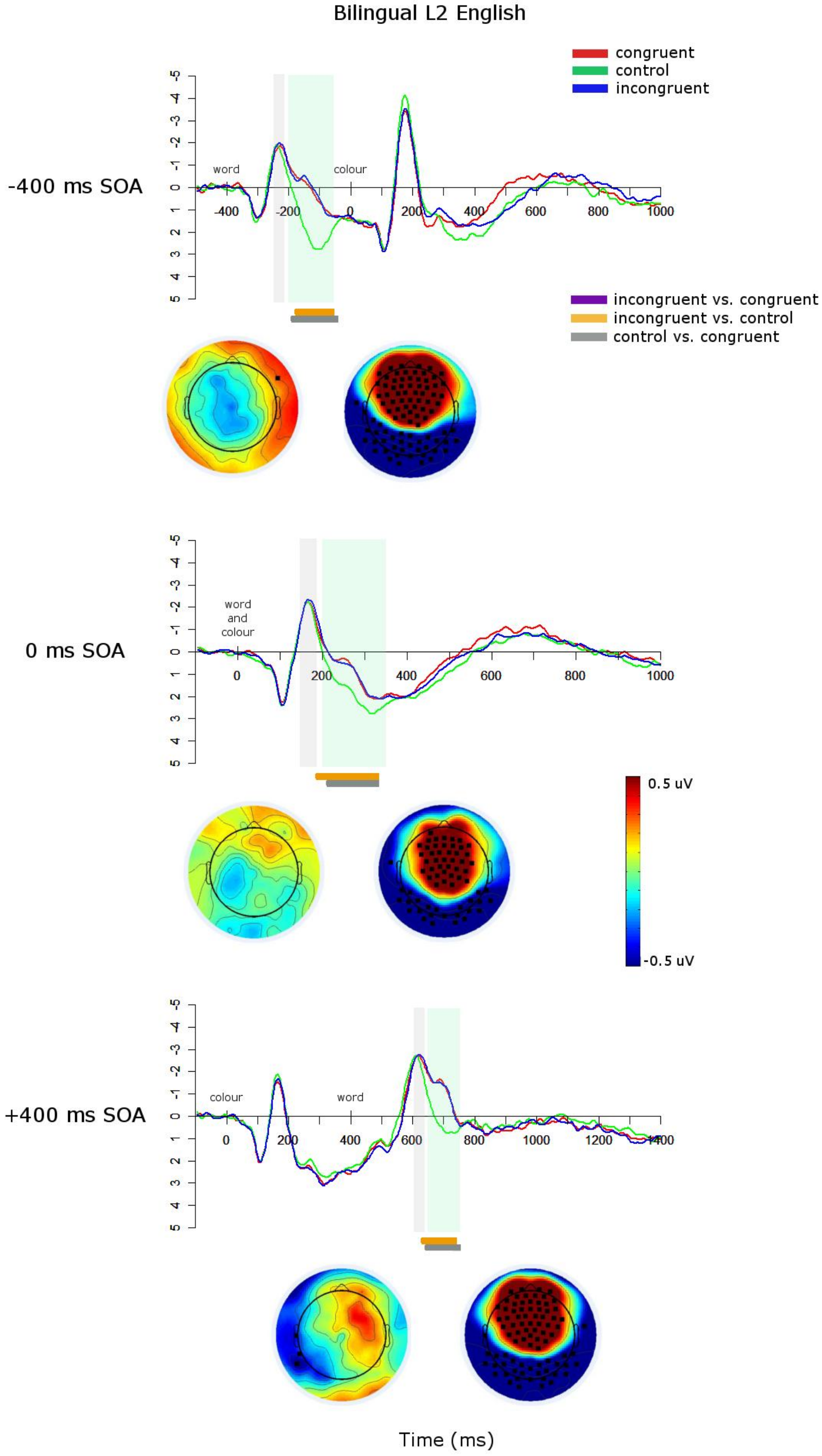
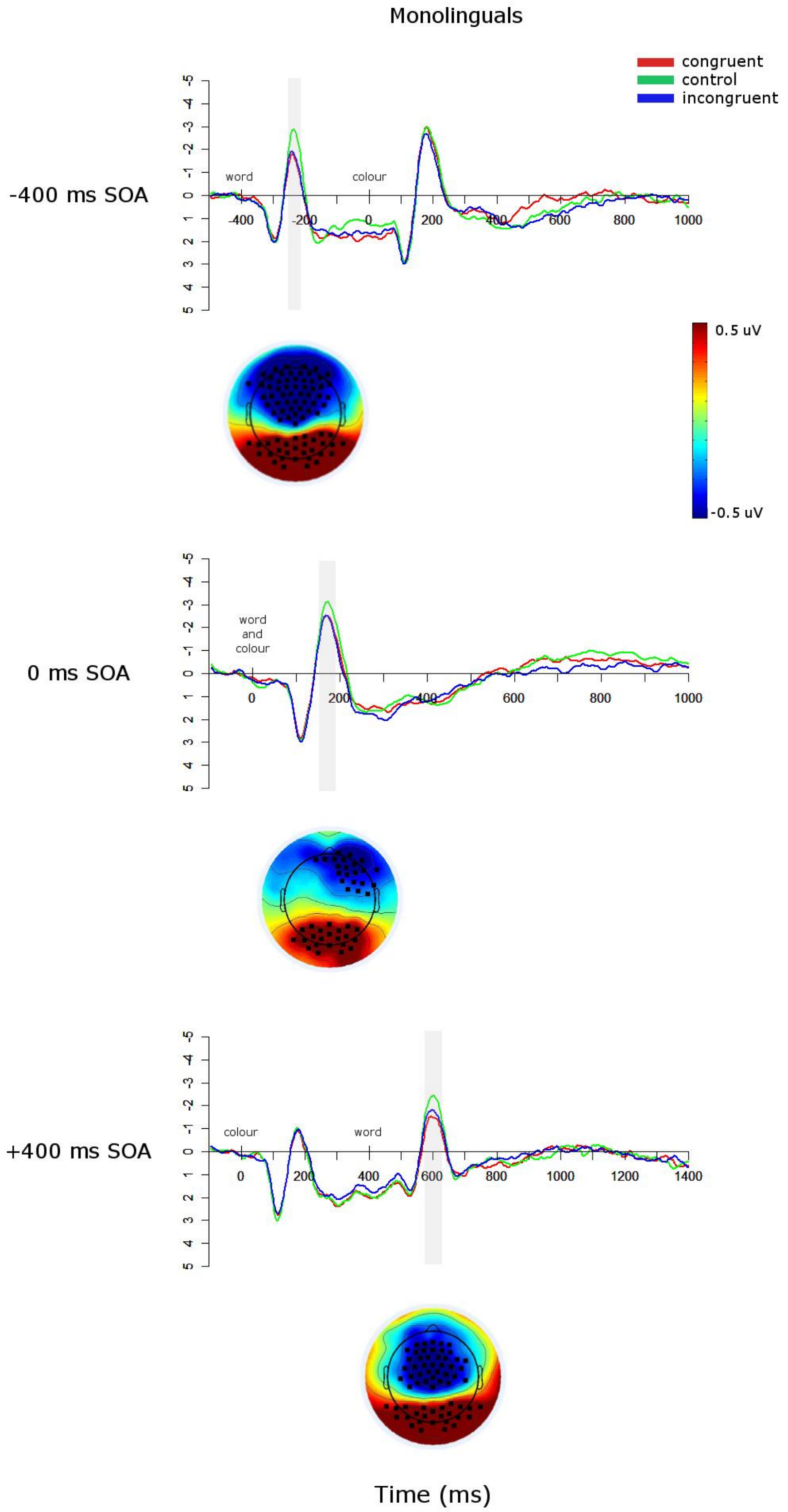


Figure 4.4: Monolingual incongruent, congruent and control waveforms, clustered over the left-hemisphere temporo-parietal sites (P7, PO7, P9) for each SOA. Grey shaded windows indicate the N170 effect. Topographic maps show the incongruent - control differences, averaged over the N170 window. Black dots illustrate electrodes showing a significant difference ($p < 0.05$) in the averaged amplitude of the incongruent and control conditions over the relevant window.

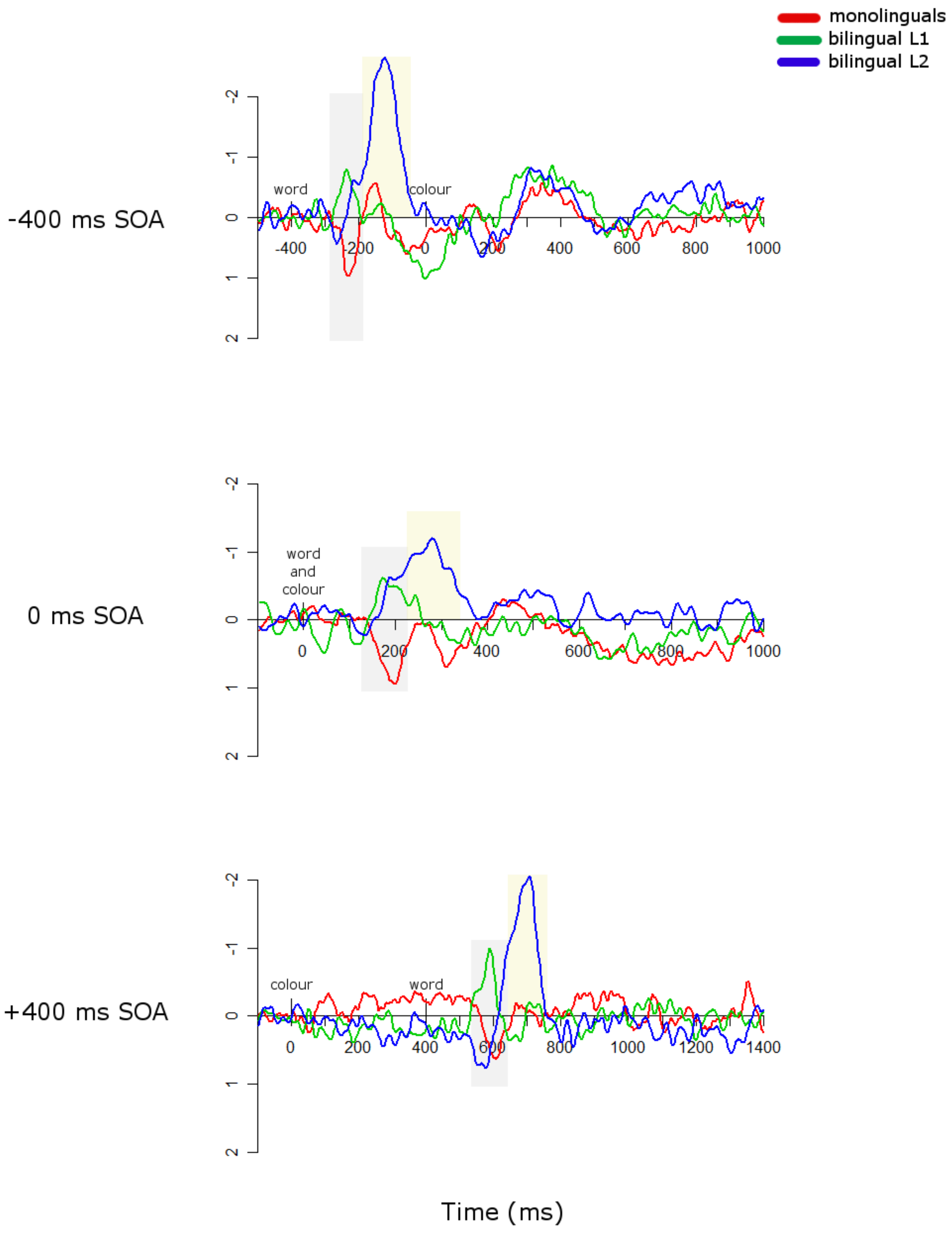


3.4. Comparisons of monolinguals and bilinguals

To better visualize the differences between early word recognition components in each group, difference waves (incongruent minus control) were computed. (Incongruent-control difference waves were chosen to contrast word-vs.-non-word processing: as the incongruent and congruent conditions elicited similar amplitudes at these early time windows, the use of the incongruent condition should provide an accurate reflection of word processing.) The difference waves (presented in Figure 4.5) showed large peaks following word presentation in all groups; as these peaks arose from the separation of words and symbol strings in the original waveforms, they are interpreted as reflecting early orthographic discrimination and lexical processing. The latencies of these difference-wave peaks were compared between groups in each SOA with Bonferroni-corrected *t*-tests (data collapsed over hemisphere and site). The monolingual and bilingual L1 difference-wave peaks occurred at a similar latency in all SOAs (monolingual average latency = 185 ms after word presentation, *SE* = 6 ms; bilingual L1 = 188 ms, *SE* = 8 ms; all *p*'s > 0.82). However, the bilingual L2 peaks were significantly delayed in all SOAs (average latency 287 ms, *SE* = 8 ms), both compared to monolinguals (all *p*'s < 0.0001) and to the L1 (all *p*'s < 0.0001). This indicates a fundamental difference in second-language processing, such that the discrimination between words and non-words occurred significantly later than in native-language processing. There was also a polarity difference such that monolinguals showed a negative difference wave peak whereas bilinguals showed a positive peak: this difference arose because, as noted previously, bilinguals showed a more negative N170/N2 for words than symbol strings, whereas monolinguals showed an enhanced N170 negativity to symbol strings compared to words.

To quantify the L2 delay, an 'L2 shift' value was calculated by subtracting the latency of the L1 difference wave peak from the L2 peak for each subject. Collapsed over all SOAs, electrodes, and hemispheres, the average L2 shift was exactly 100 ms (*SE* = 2 ms). Full semantic activation generally occurs within 200 ms of word presentation (Dell'Acqua, Pesciarelli, Jolicoeur, Eimer, & Peressotti, 2007; Pulvermüller, Assadollahi, & Elbert, 2001), so an L2 shift of 100 ms indicates a robust delay in L2 lexical processing compared to a native language. To investigate whether SOA modulated the L2 shift, a 3 (SOA) x 3 (electrode site) x 2 (hemisphere) repeated-measures ANOVA was performed on the bilingual L2 shift magnitudes. This analysis revealed no main effect of SOA ($F < 1$) but a trend towards an interaction of SOA and hemisphere ($F(2,36) = 2.55$, $p = 0.09$), which arose from a slightly larger L2 shift in the left hemisphere for the +400 ms SOA (115 ms, *SE* = 7 ms) compared to the 0 ms SOA (89 ms, *SE* = 11 ms; $t(56) = 3.68$, $p < 0.01$ adjusted). However, the lack of any main effects, especially of SOA, and the weakness of these interactions indicate no differences in the magnitude of the delay across SOAs.

Figure 4.5: Difference waves (incongruent – control) clustered over the left-hemisphere temporo-parietal sites (P7, PO7, P9) in the -400 ms, 0 ms, and +400 ms SOAs for monolinguals, bilingual L1 and bilingual L2. Shaded regions indicate the significant orthographic processing peaks for monolinguals and bilinguals' L1 (grey boxes) and bilinguals' L2 (yellow boxes).



3.4.1. Proficiency analyses

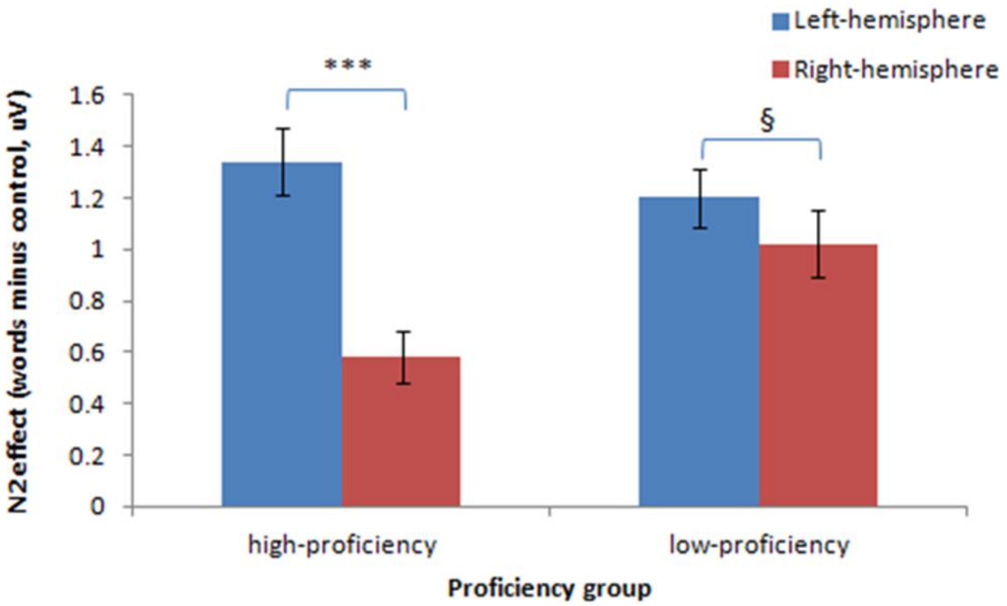
The N2 component was unique to bilingual L2 language processing: this ERP did not occur in the control condition, nor in the bilingual L1 or in monolinguals. The fact that the N2 only occurred in the bilingual L2 suggests that it may be affected by L2 proficiency. To investigate this possibility, post-hoc proficiency analyses were performed by taking a median split of the L2 data based on self-rated proficiency scores (median = 7.13) and comparing the N2 amplitude and latency between proficiency groups. It must be stressed that this was a purely post-hoc investigation, as the current study did not explicitly manipulate proficiency; therefore only significant effects or interactions ($p < 0.05$) were investigated.

N2 amplitude was compared within a window from 200-350 ms after word presentation using a 3 (SOA) x 3 (congruency) x 2 (hemisphere) x 3 (electrode site) repeated-measures ANOVA with L2 proficiency as a between-subjects factor (see Table 4.3 for full results). Importantly, a significant three-way interaction occurred between hemisphere, congruency, and proficiency ($p < 0.01$). To investigate this, the congruency effect was evaluated in each hemisphere (collapsed over SOA and site) for each group. In high-proficiency bilinguals, in both hemispheres the incongruent and congruent conditions experienced significantly more negative amplitudes than the control condition (all p's < 0.0001). To quantify these congruency effects, an 'N2 effect' value was calculated as the amplitude difference between the word conditions (averaged over incongruent and congruent) minus the control condition. A significantly larger N2 effect occurred in the left hemisphere (1.34 uV, $SE = 0.13$) than in the right (0.58 uV, $SE = 0.11$; $t(80) = 8.29$, $p < 0.0001$; Figure 4.6). This indicates a left-lateralized N2 component for the high-proficiency bilinguals. In the low-proficiency bilinguals, again the incongruent and congruent conditions showed significantly more negative waveforms than the control condition in both hemispheres (all p's < 0.01). However, the hemispheric comparisons showed only a trend of a larger N2 effect in the left hemisphere (1.20 uV, $SE = 0.10$) compared to the right (1.02 uV, $SE = 0.13$; $t(80) = 1.70$, $p = 0.09$; Figure 4.6), indicating a more bilateral N2 effect. A direct comparison of the N2 lateralization (calculated as the magnitude of the N2 effect (words minus control) in the left hemisphere minus the right hemisphere) confirmed a larger N2 left-lateralization for high-proficiency bilinguals (0.75 uV, $SE = 0.09$) compared to a more bilateral N2 effect (i.e. smaller lateralization) in low-proficiency bilinguals (0.18 uV, $SE = 0.11$; $t(156.2) = 4.10$, $p < 0.0001$).

Table 4.3: Bilingual L2 analyses of N2 amplitude: results of the 3 (SOA) x 3 (congruency) x 2 (hemisphere) x 3 (electrode site) repeated-measures ANOVA with L2 proficiency as a between-subjects factor. Hem = hemisphere; cong = congruency (incongruent, control, congruent); prof = proficiency (low, high); site = electrode site (P7/8, PO7/8, P9/10); n.s. = not significant ($p > 0.10$). No significant effects occurred above 3-way interactions, so they are not reported here.

Effect	**Bilingual L2 N2 (200-350 ms) amplitude**
Proficiency	n.s.
Hemisphere	n.s.
Hem x proficiency	$F(1,16) = 4.06$, $p = 0.06$
Congruency	$F(2,32) = 26.66$, $p < 0.0001$
Cong x prof	n.s.
SOA	$F(2,32) = 38.31$, $p < 0.0001$
SOA x proficiency	n.s.
Electrode site	$F(2,32) = 31.23$, $p < 0.0001$
Site x prof	n.s.
Cong x hem	$F(2,32) = 4.54$, $p < 0.05$
Cong x hem x prof	$F(2,32) = 6.10$, $p < 0.01$
SOA x hem	n.s.
SOA x hem x prof	n.s.
SOA x cong	$F(4,64) = 4.18$, $p < 0.01$
SOA x cong x prof	n.s.
Hem x site	$F(2,32) = 7.20$, $p < 0.01$
Hem x site x prof	$F(2,32) = 2.56$, $p = 0.09$
Cong x site	n.s.
Cong x site x prof	n.s.
SOA x site	$F(4,64) = 6.17$, $p < 0.001$
SOA x site x prof	n.s.

Figure 4.6: Average N2 effects (word condition amplitudes (averaged over congruent and incongruent conditions) minus control condition amplitudes) in each hemisphere for each proficiency group. Significant differences between groups are indicated with asterisks (§ = trend (*p* < 0.10); * = *p* < 0.05; ** = *p* < 0.01; *** = *p* < 0.001). High-proficiency bilinguals demonstrated a left-lateralized N2 effect, whereas the effect was more bilateral in low-proficiency bilinguals.



To evaluate differences in N2 latency between proficiency groups, analyses were performed on the averaged incongruent and congruent waveforms (as the control condition did not elicit an N2 peak). Within the N2 window (200-350 ms), the latencies of the N2 peak in the averaged word conditions were subjected to a 3 (SOA) x 3 (electrode site) x 2 (hemisphere) ANOVA with L2 proficiency as a between-subjects factor. This revealed a trend towards an interaction of hemisphere and SOA (*F*(2,32) = 2.63, *p* = 0.09), an interaction of hemisphere and site (*F*(2,32) = 3.97, *p* < 0.05), a trend of an interaction of hemisphere and site (*F*(4,64) = 2.04, *p* = 0.10) and a trend of a four-way interaction of hemisphere, SOA, site, and L2 proficiency (*F*(4,64) = 2.08, *p* = 0.09). Because this four-way interaction was only a trend, it was not investigated further. There were no other interactions with proficiency.

Finally, an additional post-hoc proficiency analysis compared the magnitude of the L2 shift (L2 difference-wave peak minus L1 peak) between proficiency groups. However, no significant differences occurred between high- and low-proficiency bilinguals (*p* = 0.21), even when comparing each SOA (all *p*'s > 0.24). The magnitude of the L2 shift also did not correlate with self-rated L2 proficiency in any SOA (all *p*'s > 0.26, uncorrected).

4. Discussion

The current study used EEG to evaluate early orthographic recognition speed in bilinguals' L1 and L2 (Chinese and English, respectively) compared to monolingual English speakers. Of particular interest was whether a delay occurred for the bilingual L1 relative to monolinguals, as early delays in L1 processing have never been investigated with EEG. The inclusion of SOA manipulation in the Stroop task also assessed the automaticity of these effects in native and non-native languages.

4.1. Delays in L1 processing

For the monolinguals and the bilingual L1, words and symbol strings were distinguished at the N170 peak in every SOA and word-vs.-non-word difference waves showed no differences in the latency of lexical processing peaks. This indicates that the bilingual L1 did not experience a delay in early orthographic recognition compared to monolinguals, contrary to the predictions of the bilingual L1 lexical disadvantage hypothesis. The N170 effect also occurred at the same latency in all SOAs, demonstrating that reading is a highly automatic process in an L1 regardless of bilingual status. The speed of lexical processes in the native language were also not affected by differences in language script, as the monolinguals and bilinguals had different L1s (English and Chinese, respectively) yet showed similar effects. Thus this data demonstrated that although bilinguals use each language less often than monolinguals, the relatively reduced frequency of use does not affect early orthographic processing speed in the native language.

This is in contrast to the findings of Ardal et al. (1990), who reported a delayed N400 component for the bilingual L1 compared to monolinguals. Reduced fluency in the L1 may impact higher-level language processing, such as semantic integration and syntactic parsing, to a greater degree than it does lower-level processing. For example, the N400 is sensitive to proficiency differences among monolingual speakers as well as bilinguals (Newman et al., 2012). Delays in bilingual L1 processing may therefore be more prominent in later ERP components such as the N400 or the P600 which index these complex, proficiency-driven facets of language. Further research is needed to assess precisely at what level of linguistic processing the L1 delay begins. Nevertheless, the current data illustrated for the first time that bilinguals do not experience a delay in early orthographic recognition in their native language compared to monolinguals.

4.2. Delays in L2 processing

Reduced proficiency does, however, impact low-level orthographic recognition speed in a second language. In the bilinguals' L2, the distinction between words and symbol strings arose not at the N170 peak, as was observed in the L1 and in monolinguals, but 100 ms later at an N2 component. This documented L2 delay adds to a large body of literature suggesting that reduced proficiency leads to inherent delays in language processing across a range of time windows and linguistic levels (e.g. Ardal et al., 1990; Hahne, 2001; Moreno & Kutas, 2005; Newman et al., 2012; Phillips et al., 2006). Importantly, the present study is one of only a few demonstrating delays at early stages of L2 processing (Liu & Perfetti, 2003; Proverbio et al., 2009). The magnitude of this 100 ms delay is especially significant considering that full semantic access generally occurs within 200 ms of word presentation (Dell'Acqua et al., 2007; Pulvermüller et al., 2001). Early delays in processing may be compounded at higher-level stages, which could explain the delays in later, higher-level processing reported at the semantic and sentence level (Ardal et al., 1990; Hahne, 2001; Moreno & Kutas, 2005; Newman et al., 2012). A significant delay so early in processing, which is potentially escalated throughout the entire linguistic process, could have substantial detrimental effects on bilingual communication and everyday functioning.

It is possible that the L2 processing delay reflects the different writing systems of Chinese and English. For example, Maurer et al. (2008) have shown that the N170 effect is driven by familiarity not with individual words but with script, with a more left-lateralized N170 effect for a familiar script. However, this script familiarity effect was limited to lateralization differences and would not explain why the N170 effect was delayed in the current L2 data. The observed temporal difficulties may alternatively indicate more effortful word recognition processing for the less-familiar alphabetic script. However, this is also a tenuous possibility, as Chinese speakers from mainland China are exposed to alphabetic script from an early age in the form of pinyin, a Romanization of Chinese phonology used to teach Chinese characters. Pinyin is used extensively in modern technology such as emails, text messages, and typing, so Chinese speakers are not unfamiliar with alphabetic script. The robust delay in linguistic processing instead seems to extend beyond unfamiliarity with the script, suggesting a fundamental slowing in L2 processing.

4.3. Automaticity of reading

A Stroop task with SOA manipulation was employed in the present study, rather than an explicit reading paradigm, to focus on automatic aspects of visual word recognition and to explore whether these processes were modulated by bilingual status and SOA. Similar latencies of the N170 in every SOA would be indicative of similar timecourses of orthographic processing, even when reading is detrimental to performance. Specifically, in the +400 ms SOA the word appears after the colour and its semantic activation is unnecessary; evidence of orthographic processing in this SOA would therefore highlight the automaticity of reading. In the current data, the discrimination between words and symbol strings occurred in all SOAs and at the same latency in every SOA. This was true for all groups including the L2, although the discrimination emerged significantly later. Therefore even in a non-native language, orthographic recognition – although delayed – occurred automatically.

4.4. The N170 component

As predicted, the N170 window produced the earliest differences in linguistic processing between monolinguals and bilinguals. However, there are a number of issues to consider regarding the observed topography and polarity of this component.

4.4.1. Lateralization of the N170

In the current data, the N170 effect for both the monolinguals and bilinguals was bilaterally distributed across the scalp, in contrast to the majority of literature reporting a left-lateralized N170 effect for language (Appelbaum, Liotti et al., 2009; Bentin et al., 1996, 1999; Grossi et al., 2010; Hauk & Pulvermüller, 2004; Maurer et al., 2005; Rossion et al., 2003; Sereno et al., 1998). This more bilateral distribution may be an effect of the nature of the Stroop task. For example, attention to the orthographic or lexical properties of words during a task can modulate the amplitude of the N170 effect (Proverbio & Adorni, 2009; Ruz & Nobre, 2008). In the current Stroop paradigm, the direction of attention away from the word stimulus, in order to respond to the colour, may have attenuated the left-lateralized N170, resulting in a more bilateral scalp distribution. Nevertheless, all participants still noticed and recognized the word stimuli, as evidenced by the separation of word and symbol string waveforms following word, but not colour, presentation.

4.4.2. Polarity of the N170 effect

Another discrepancy is apparent in the polarity of the N170 effect in each group: in monolinguals, the N170 was more negative for control stimuli, whereas in bilinguals, the N170 and the N2 were more negative for word stimuli. N170 amplitudes are generally enhanced (i.e. more negative) for words relative to pseudowords or non-orthographic stimuli such as symbol strings (Appelbaum, Liotti et al., 2009; Bentin et al., 1999; Hauk et al., 2009; Lin et al., 2011; Maurer et al., 2005; Proverbio et al., 2009; Wong et al., 2005). The current monolingual data is therefore in contrast to the typical findings in the literature. As explained in the Introduction (section 1.2), the N170 component is not specific to language; therefore a number of factors could have influenced the polarity of the N170 effect. For example, the N170 is sensitive to perceptual variability (Thierry et al., 2007), which could have differed between English and Chinese scripts. However, the observed polarity difference occurred between monolinguals and bilinguals, not between English and Chinese, so orthographic differences between the languages cannot explain this effect (otherwise the monolingual and L2 English waveforms would have differed from the L1 Chinese).

One potential explanation for the observed polarity differences between monolinguals and bilinguals is that native Chinese speakers may process both Chinese and English differently from native English speakers. To illustrate, native speakers of an alphabetic writing system learning a logographic writing system (e.g. English speakers learning Chinese) have been shown to use an *accommodation* strategy in L2 reading, recruiting additional neural structures not usually used for alphabetic languages to processes the logographic language

(Nelson, Liu, Fiez, & Perfetti, 2009; Perfetti et al., 2007). In contrast, native speakers of a logographic writing system learning an alphabetic writing system (e.g. Chinese speakers learning English) adopt an *assimilation* strategy, using language areas already in place for logographic writing systems; in other words, they "try to read English as if it were Chinese" (Perfetti et al., 2007, pg. 136). Logographic and alphabetic language processing differ both in neural regions and cognitive mechanisms (see Bolger et al., 2005 and Tan et al., 2005 for reviews): for example, Chinese places more reliance on visuo-spatial mechanisms in reading and activates a more bilateral language network (Siok, Spinks, Jin, & Tan, 2009; Tan et al., 2001). Different orthographic processing techniques in native Chinese speakers may therefore have affected the recognition of English words such that native Chinese speakers were reading English words in 'Chinese mode'. The observed polarity difference between monolinguals and bilinguals may thus reflect a fundamental difference in how languages are processed in each group. Nevertheless, as specified in the Introduction, the current study was interested in the latency of this effect: regardless of the scalp distribution or the polarity of the N170 effect, the distinction between words and symbol strings occurred 100 ms later in the bilingual L2 than in the L1 or in monolinguals, indicating that early orthographic processing is delayed in a second language.

4.5. The N2 component

In the bilingual L2, the discrimination between words and symbol strings arose not at the typical N170 peak but in the window of an N2 component, occurring from approximately 200-350 ms. This finding replicates Proverbio et al. (2009), who also reported L2 differences at an N2 window from approximately 260-320 ms, although the authors did not speculate on its underlying cognitive function. As the N2 did not occur in the control condition, nor in the L1 or in monolinguals, it cannot be attributed to differences in Chinese and English orthographic processing. The N2 was instead exclusive to the bilingual L2 and therefore seems to be a neural signature specific to second-language processing.

One possibility is that the N2 reflects translation from the L2 to the L1. Translation effects can occur extremely rapidly: for example, Zhang et al. (2011) reported significant L2-L1 priming effects in Chinese-English bilinguals with a prime duration of only 59 ms. A component occurring at a similar latency, known as an N250, is also often reported in the translation priming literature and is particularly sensitive to priming from the L2 to the L1 (Schoonbaert, Holcomb, Grainger, & Hartsuiker, 2011). This N250 has been traced using source localization to the supplementary motor area (Liu & Perfetti, 2003), a region implicated in articulatory preparation and speech production in both English and Chinese (Fiez & Petersen, 1998; Tan et al., 2000). Therefore the N2 component in the bilingual L2 may index a similar cognitive process, reflecting a rapid, unconscious translation into the L1 after presentation of an L2 word, which could explain the delayed orthographic distinction in a second language.

Because the N2 component only occurred in the bilingual L2, post-hoc analyses were performed to investigate how proficiency modulated the amplitude and latency of this component. There were no differences in the latency of the N2 component, and consequently no differences in the magnitude of the L2 delay between proficiency groups. However, the congruency effect at the N2 component (i.e. the amplitude differences between words and symbol strings) was left-lateralized in high-proficiency bilinguals, but more bilaterally-distributed for low-proficiency bilinguals. These laterality effects may reflect more native-like processing in high-proficiency bilinguals. For instance, neuroimaging evidence has shown that increased L2 proficiency leads to more native-like patterns of neural language organization (Perani & Abutalebi, 2005). Alphabetic languages generally recruit left-lateralized brain areas, while logographic languages recruit bilateral areas (Perfetti et al., 2007), so the left-lateralized N2 component in the high-proficiency group could reflect a more native-like processing of the second language. In contrast, the low-proficiency participants may use Chinese-like bilateral brain areas to process English (Bolger et al., 2005; Perfetti et al., 2007). There is some evidence for experience-driven changes in component lateralization: for example, Grossi et al. (2010) reported increasing left-lateralization of the N170 with increasing years of language experience. Similarly, Maurer et al. (2008) reported that the N170 effect was more left-lateralized when native speakers viewed a familiar orthographic script, compared to a bilateral topography when viewing an unfamiliar script. Although these proficiency-driven lateralization effects have been documented in the N170 rather than the N2, a similar effect may have emerged here. Therefore while individual L2 proficiency did not affect the magnitude of the lexical processing delay, the current results suggest subtle effects of L2 proficiency on the laterality of the N2 component.

No latency differences occurred between high- and low-proficiency participants in these post-hoc analyses. Because the current study did not explicitly manipulate proficiency, the range of subjective proficiency levels in this bilingual sample may have been too narrow to observe any differences in lexical processing speed. It may be the case that improved L2 proficiency over years of language use decreases the L2 delay as language connections become stronger and faster (see Chapter 1, section 2.1). The full impact of proficiency on the L2 delay remains unclear: for example, some studies explicitly manipulating this factor have reported non-significant effects and have instead suggested that L2 AoA is the more important variable in determining the magnitude of the delay (e.g. Ardal et al., 1990; Newman et al., 2012). It is also unclear how proficiency and/or AoA might affect lexical processing speed in the L1: balanced, highly-proficient bilinguals who speak both languages with equal frequency may experience lexical processing delays equally in both languages. Investigations of the roles of proficiency and AoA in the modulation of the bilingual delay, especially in these very early processes of orthographic recognition, are therefore interesting avenues for future research.

4.6. Repetition effects

As explained in Chapter 1 (section 2.1), the temporal delay assumption of the BIA+ model proposes that an L2 processing delay in unbalanced bilinguals occurs because the lower word frequencies and reduced proficiency lead to a lower ‘resting-level’ activation (Dijkstra & van Heuven, 2002). If so, word repetition could potentially raise the resting-level activation in the L2, diminishing or abolishing the language processing delay. However, all previous studies reporting bilingual language delays have used item sets in which target words occurred only once (Ardal et al., 1990; Hahne, 2001; Liu & Perfetti, 2003; Moreno & Kutas, 2005; Proverbio et al., 2009). The use of a Stroop task in the current study was unique in this respect, as this paradigm necessitates the repetition of colour words. Moreover, the fact that a delay in L2 orthographic recognition occurred despite hundreds of repetitions of high-frequency colour words suggests that this delay is a fundamental effect of lower proficiency and reduced frequency of language use, which cannot be overcome in a short period of time.

5. Conclusions

In summary, the current data demonstrated that lexical processing in unbalanced bilinguals' L1 was not delayed compared to monolingual language processing. The onset of orthographic discrimination occurred at the same time in a native language, regardless of the presence of two languages and independently of language script. In contrast, the second language experienced a significant 100 ms delay in orthographic recognition compared to both the L1 and to monolinguals. This study therefore provided novel neurophysiological evidence that early orthographic processing is not delayed in a bilingual's native language, whereas a second language experiences deep-rooted, low-level delays in linguistic processing due to reduced proficiency.

How does this substantial language delay affect Stroop conflict processing in a second language? The temporal resolution of EEG may also elucidate differences in the timecourse of cognitive control between monolinguals and bilinguals. Using this same dataset, the next chapter investigates later conflict-related ERP components to identify whether monolinguals and bilinguals show electrophysiological differences in the timings and mechanisms of Stroop conflict processing.

Chapter 5: Electrophysiological Measures of the Bilingual Cognitive Advantage

The previous chapter used long-latency SOA manipulation with EEG to investigate bilingual lexical access speed in the context of automatic reading, revealing a dramatic delay in orthographic recognition in the L2. How might this significant delay affect the timecourse of conflict processing in the Stroop task, when interference relies on the semantic activation of words? This chapter uses the same dataset as Chapter 4 but focuses on conflict-related ERP components to investigate electrophysiological indices of the bilingual cognitive advantage. As long-latency SOA manipulation has never been investigated using ERP, this chapter has two main aims: first, to investigate how long-latency SOAs affect the N_{inc} and LPC components in monolinguals; and second, to investigate electrophysiological measures of executive control in bilingualism.

1. Introduction

1.1. Electrophysiological measures of conflict

As reviewed in Chapter 1 (section 3.2.2), executive control tasks generally elicit two conflict-related ERP components: an N_{inc} and an LPC. The N_{inc} is an increased negativity in the incongruent condition as compared to the congruent or control conditions. In the Stroop task, the N_{inc} occurs at approximately 300-550 ms post-stimulus over centro-parietal scalp (Appelbaum, Meyerhoff et al., 2009; Larson et al., 2009; Liotti et al., 2000; Markela-Lerenc et al., 2004; West, 2003). The N_{inc} is believed to be generally involved in conflict processes, which are more active in the incongruent condition. Although it has been localized to the ACC, suggesting its involvement in conflict detection (Badzakova-Trajkov et al., 2009; Hanslmayr et al., 2008; Liotti et al., 2000; Markela-Lerenc et al., 2004; West, 2003), the precise role of the N_{inc} in conflict detection and/or resolution is unclear.

The LPC (late positive component) is a sustained positivity in the incongruent condition, occurring in the Stroop task from approximately 600-900 ms post-stimulus over centro-parietal scalp (Appelbaum, Meyerhoff et al., 2009; Larson et al., 2009; Liotti et al., 2000; West, 2003; West & Alain, 1999). Although frequently reported in Stroop ERP studies, the underlying cognitive processes generating the LPC also remain unclear. This component has been generally implicated in conflict processing, potentially in conflict resolution or response selection (West, 2003; West et al., 2005). Alternatively, the LPC may be involved in semantic processing, specifically re-activation of the word following conflict resolution (Appelbaum, Meyerhoff et al., 2009; Liotti et al., 2000). The use of long-latency SOA manipulation in the current study may allow for the specification of these conflict components.

1.2. SOA manipulation in the Stroop task with EEG

Appelbaum and colleagues (Appelbaum et al., 2012; Appelbaum, Meyerhoff et al., 2009) have investigated short-latency SOA manipulation (±200, ±100, 0 ms) in the Stroop task, reporting that the latencies of the N_{inc} and LPC were modulated by SOA (see review in Chapter 2, section 3.2). Specifically, Appelbaum et al. (2009) have reported a linear shift in negative SOAs such that the N_{inc} and LPC were shifted forward by 100 ms in the -100 ms SOA and by 200 ms in the -200 ms SOA. However, as this study used only short-latency SOAs, it is unclear whether this linearity persists at long SOAs such as -400 ms. Appelbaum et al. also reported a backwards shift of the N_{inc} in positive SOAs, such that this component peaked 100 ms later in the +100 ms and +200 ms SOAs compared to the 0 ms SOA. However, a critical methodological point to mention is that Appelbaum et al. (2009) time-locked the ERPs to the colour stimulus in all SOAs. This is traditional in most Stroop ERP studies. However, during SOA manipulation the conflict does not occur until both colour and word appear; therefore time-locking these conflict-related ERPs to the *second* stimulus (i.e. the word, in positive SOAs) is a more accurate reflection of conflict processing. If Appelbaum et al.'s data is re-interpreted in this way, the conflict ERP components in positive SOAs and in the 0 ms SOA occur at similar latencies. Therefore based on this previous data, short-latency negative SOAs elicit a linear modulation of N_{inc} and LPC latency, but this shift disappears at positive SOAs. As Appelbaum et al. used only short-latency SOAs, it is unclear how these components are modulated by longer pre- or post-exposure, such as ±400 ms.

The first aim of this chapter was to evaluate how the N_{inc} and LPC are affected by long-latency SOA manipulation (±400, 0 ms) in monolinguals, to establish a 'baseline' against which to compare bilingual performance. An N_{inc} and LPC were expected in the 0 ms SOA at the latencies previously established in the literature, as this was analogous to a traditional Stroop task. These components were also predicted in the -400 ms SOA, although if negative SOA manipulation creates a linear shift, the N_{inc} and LPC should occur 400 ms earlier in the -400 ms SOA than in the 0 ms SOA. In the +400 ms SOA, an N_{inc} was expected to occur at a similar latency as in the 0 ms SOA. Appelbaum, Meyerhoff et al. (2009) reported an absence of the LPC in their +200 ms SOA, which they interpreted as a lack of semantic activation due to the post-exposure of the word; therefore no LPC was expected in the +400 ms SOA in the current study.

The use of long-latency SOAs may also provide a mechanism for disentangling the roles of conflict detection and resolution in generating the N_{inc}. In Chapter 3, RTs in the positive SOAs occurred at approximately 500 ms, meaning that a response was already being prepared or executed when the word appeared (400 ms after the colour). Thus, if the N_{inc} reflects conflict *resolution*, it should be absent in the +400 ms SOA, as a response is already in preparation or has been made, so no further resolution is necessary. However, if the N_{inc} reflects conflict *detection*, it may be present in the +400 ms SOA, as detection processes may be ongoing after response generation. The use of SOA manipulation thus provides a unique opportunity to clarify the function of this component.

1.3. ERP indices of conflict processing in bilinguals

In addition to investigating the electrophysiological effects of long-latency SOA manipulation in monolinguals, this chapter also evaluated how conflict-related ERP components are affected by bilingualism. As reviewed in Chapter 1 (Part 4), bilinguals show smaller interference effects on a range of cognitive control tasks compared to monolinguals. However, given the quantity of behavioural research dedicated to this bilingual cognitive advantage, few studies have investigated this advantage using EEG and even fewer using the Stroop task (see review in Chapter 1, section 4.2.1.1). Kousaie & Phillips (2012) compared monolinguals and bilinguals on Stroop, Simon, and flanker tasks with EEG. Their results, although complicated and inconsistent across paradigms, suggested reduced amplitudes of conflict components for bilinguals relative to monolinguals on the Stroop task. Unpublished data from Heidlmayr et al. (2012) corroborated this, reporting a reduced N_{inc} for bilinguals compared to monolinguals in a Stroop task. Therefore this limited literature suggests that the bilingual advantage is manifested as smaller conflict-related ERP components, which may be reflective of more efficient conflict processing (e.g. Swick & Turken, 2002).

The current study added to this sparse previous literature by explicitly investigating the BICA and BEPA hypotheses. Recall from Chapter 1 (section 4.4) that the BICA hypothesis predicts an advantage in inhibitory control, predicting better performance on incongruent trials and smaller interference effects for bilinguals. As the N_{inc} is defined by the behaviour of the incongruent condition, an advantage on inhibitory control should be reflected in a reduced N_{inc} amplitude, as previously demonstrated (Heidlmayr et al., 2012; Kousaie & Phillips, 2012). This bilingual interference effect was expected to be most pronounced in situations of maximal conflict which, in the current study, was the 0 ms SOA.

In contrast, the BEPA hypothesis (Chapter 1, section 4.5) predicts a bilingual advantage in general executive processing, leading to faster RTs in all trial types (a global RT advantage). As in Chapter 3, a global RT advantage was assessed by comparing the control conditions, both in behavioural RTs and in the EEG waveforms, to eliminate extraneous influences of linguistic processing. The BEPA hypothesis predicts smaller behavioural RTs in the control condition for bilinguals; if reduced ERP amplitudes are indicative of more efficient processing, reduced amplitudes for bilingual control waveforms should occur in the EEG data. In contrast, the BICA would predict no differences between monolinguals and bilinguals on the control condition, either behaviourally or electrophysiologically, as no conflict is present.

Similar effects of SOA manipulation were expected for bilinguals and monolinguals: the ERP components should occur earlier in the -400 ms SOA than in the 0 ms or +400 ms SOAs. However, the previous chapter demonstrated dramatic delays in early L2 lexical processing. As Stroop conflict arises from semantic activation of the word, a delay in early word recognition may subsequently delay the onset of conflict processing. This would predict later onsets of these conflict-related ERP components in the L2 compared to the L1 or to monolinguals, especially in the 0 ms and +400 ms SOAs: in the -400 ms SOA the word pre-exposure may allow a head-start in lexical processing, thereby compensating for the delay. In contrast, as the L1 did not experience a delay in lexical access, the conflict-related ERP components in L1 performance should occur at the same time as those of monolinguals in all SOAs.

In sum, the current study used the same dataset as Chapter 4 to address two primary aims. The monolingual ERP data was first evaluated to investigate how long-latency SOA manipulation affects the N_{inc} and LPC. The bilingual cognitive advantage was next addressed by evaluating the effects of bilingualism on the amplitude and latencies of these components.

2. Methods

As in Chapter 4, the monolingual participants were 28 native English speakers and the bilingual participants were 19 Chinese-English bilinguals with an overall self-reported English proficiency of 7.1 out of 10 (see Chapter 4, Table 4.1). All participants performed a Stroop task with three SOAs (-400, 0, +400 ms); monolinguals were tested only in English in one session and bilinguals in both English and Chinese on consecutive days. See Chapter 4 for full details on the participants, design, procedure, data acquisition, and preprocessing.

2.1. ERP data analysis

Based on previous literature, the N_{inc} occurs from approximately 300-600 ms, and the LPC from 600-900 ms. Analyses of these components were therefore restricted to these pre-specified time windows for the 0 ms SOA. Based on the findings of Appelbaum, Meyerhoff et al. (2009), in the -400 ms SOA the analysis windows were defined as the traditional window plus a 200-ms negative shift, making an N_{inc} window from 100-600 ms and an LPC window from 400-900 ms after colour presentation. For the +400 ms SOA, the analysis window allowed for a 200-ms backwards shift, making an N_{inc} window from 300-800 ms and an LPC window from 600-1100 ms post-stimulus.

As N_{inc} and LPC effects are generally reported at centro-parietal midline electrodes (e.g. Appelbaum, Meyerhoff et al., 2009; Hanslmayr et al., 2008; Liotti et al., 2000), analyses were primarily performed at Cz and Pz.[13] (However, as in Chapter 4, topographic difference-wave maps and electrodes showing significant differences ($p < 0.05$) over the analysis windows are also presented in Figures 5.2, 5.5, and 5.6.) N_{inc} and LPC windows were defined by visual inspection of the data at Cz and Pz and based on significance using running *t*-tests (20 ms bins with 12 ms overlap; Chapter 4, section 2.3 for details) within the defined analysis windows. All graphs present significant effects ($p < 0.05$) from running *t*-tests only within the range of analysis windows (100-1100 ms after the second stimulus). In the running *t*-tests, a significant Stroop effect for the N_{inc} was identified as the incongruent waveforms more

---

[13] Results at the single electrodes are reported here; however, similar results were obtained when analyzing clusters of electrodes around Cz and Pz.

negative than the congruent waveforms; interference effects as more negative incongruent than control waveforms; and facilitation effects as more negative control than congruent waveforms. Similarly, in the LPC component, Stroop effects were identified as more positive incongruent than congruent waveforms; interference as more positive incongruent than control waveforms; and facilitation as more positive control than congruent waveforms. As the N_{inc} and LPC are conflict-related components, their presence was identified by a significant difference in the incongruent compared to either the control or congruent conditions; if no significant Stroop or interference effect occurred within a window, this was said to be a non-significant effect.

Difference waves (incongruent minus congruent, to eliminate the influence of language processing) were compared between groups using running *t*-tests to identify amplitude differences. To identify shifts in the N_{inc} and LPC latencies between SOAs, latency analyses were performed on the difference waves within the relevant windows by identifying where the peak minimum (for the N_{inc}) or maximum (for the LPC) amplitude occurred at Cz and Pz and averaging the peak latency over these electrodes. The averaged peak latencies were then subjected to a 3-way (SOA) ANOVA for each group, with paired-sample *t*-tests to identify significant effects.

3. Results

Incorrect responses (3.5% for monolinguals; 2.2% for L1; 2.1% for L2) and outliers (less than 250 ms or greater than 2000 ms[14]: 0.12% for monolinguals, 0.02% for bilingual L1, 0.1% for bilingual L2) were removed from both the behavioural and ERP data before statistical analysis. The mean number of errors per condition ranged between 0.2%-0.8% for monolinguals; 0.2%-0.4% for the bilingual L1; and 0.1%-0.5% for the bilingual L2. For all groups, behavioural analyses first performed a 3 (SOA) x 3 (congruency) repeated-measures ANOVA, with follow-up paired-sample *t*-tests to identify significant Stroop, interference, and facilitation effects. (Stroop effects (incongruent minus congruent) are reported in this chapter because the corresponding contrast is investigated in the ERP data.)

---

[14] This was a different upper threshold for outlier criteria from the studies in Chapter 3, which used a 1500 ms cutoff. However, as the outlier percentages were very low, this did not affect the main patterns of the results.

3.1. Monolingual data and preliminary discussion

To address the initial subject of interest in this chapter, the effects of long-latency SOA manipulation in monolinguals were first considered[15]. The monolingual results were then used to guide analyses of the bilingual data and the direct comparisons between the groups.

3.1.1. Monolingual behavioural data

The monolingual behavioural mean RTs are presented in Figure 5.1. A 3 (SOA) x 3 (congruency) ANOVA showed significant main effects of SOA ($F(2,54) = 9.58$, $p < 0.001$) and congruency ($F(2,54) = 64.00$, $p < 0.0001$) and an interaction ($F(4,108) = 27.45$, $p < 0.0001$). Significant Stroop and interference effects occurred at the -400 ms and 0 ms SOAs (Table 5.1), with a trend of a significant interference effect at the +400 ms SOA. Significant facilitation occurred at the -400 ms SOA only.

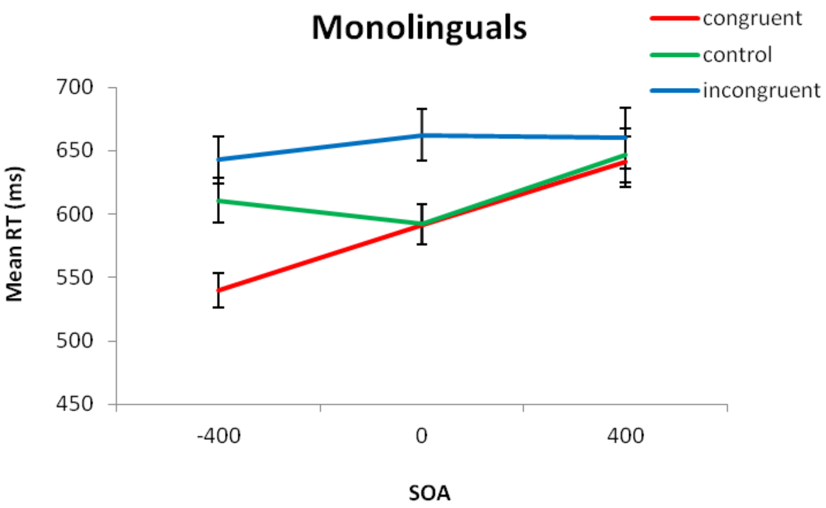
---

[15] This monolingual data has been published in *Brain Research* (Coderre et al., 2011; see Declaration). However, the analyses in this chapter differ slightly: two participants were removed from the original dataset ($n = 31$) who were proficient in other languages besides English and the comparison of N_{inc} and LPC latencies was performed differently. The overall data pattern remained the same as that reported in Coderre et al., 2011).

Table 5.1: Statistical comparisons of Stroop, interference, and facilitation effects for each group and language; n.s. = not significant ($p > 0.10$).

Group	Language	SOA	Stroop			Interference			Facilitation		
			t-value	*df*	*p*-value	*t*-value	*df*	*p*-value	*t*-value	*df*	*p*-value
Monolinguals	--	-400 ms	9.80	27	<0.0001	4.06	27	<0.001	9.30	27	<0.0001
		0 ms	8.00	27	<0.0001	6.32	27	<0.0001	0.06	27	n.s.
		+400 ms	2.60	27	0.01	1.91	27	0.07	0.95	27	n.s.
Chinese-English bilinguals	L1	-400 ms	12.20	18	<0.0001	4.63	18	<0.001	10.70	18	<0.0001
		0 ms	5.05	18	<0.001	3.93	18	<0.001	0.23	18	n.s.
		+400 ms	1.91	18	0.07	0.11	18	n.s.	2.47	18	0.02
	L2	-400 ms	9.97	18	<0.0001	5.14	18	<0.0001	7.29	18	<0.0001
		0 ms	2.90	18	0.01	2.51	18	0.02	1.82	18	0.09
		+400 ms	1.12	18	n.s.	0.33	18	n.s.	1.07	18	n.s.

Figure 5.1: Mean behavioural RTs (ms) for monolinguals.

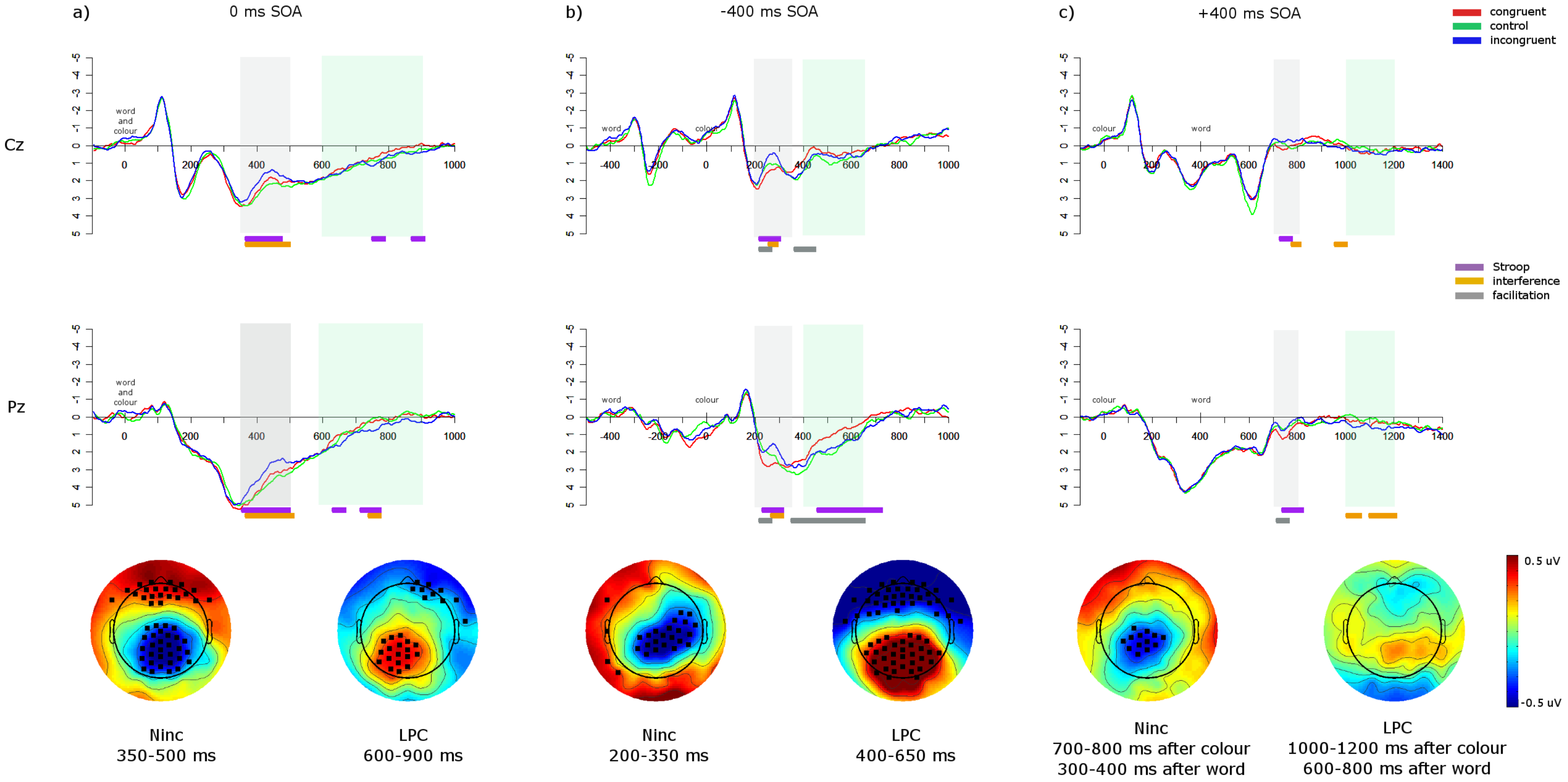


3.1.2. Monolingual ERP data

The monolingual ERP data are presented in Figure 5.2. In the 0 ms SOA (Figure 5.2a), an N_{inc} occurred from approximately 350-500 ms, showing significant Stroop and interference effects at Cz and Pz. An LPC also occurred from approximately 600-900 ms, with significant Stroop effects at Pz. As this SOA was analogous to the traditional Stroop task, this replicates previous ERP results (Appelbaum, Meyerhoff et al., 2009; Badzakova-Trajkov et al., 2009; Hanslmayr et al., 2008; Larson et al., 2009; Liotti et al., 2000; Markela-Lerenc et al., 2004; West & Alain, 1999). In the -400 ms SOA (Figure 5.2b), an N_{inc} occurred from approximately 200-350 ms after colour presentation, with significant Stroop and interference effects at Cz and Pz. An LPC also appeared from approximately 400-650 ms, with significant Stroop effects at Cz and Pz and interference at Pz. In the +400 ms SOA (Figure 5.2c), latency analyses considered the ERPs as time-locked to the word rather than the target (colour) stimulus, as discussed in section 1.2. An N_{inc} occurred from approximately 300-400 ms after word onset (700-800 ms after colour onset), with significant Stroop effects at Cz and Pz and interference at Cz. Contrary to predictions, an LPC appeared from approximately 600-800 ms (1000-1200 ms after colour onset), showing interference effects at Cz and Pz.

Component latencies were compared between SOAs using a 3-way (SOA) ANOVA. The N_{inc} latencies showed a main effect of SOA ($F(2,54) = 136.13$, $p < 0.0001$), with significant differences between all SOAs (all *p*'s < 0.0001) such that the N_{inc} occurred earliest for the -400 ms SOA (258 ms), followed by the +400 ms SOA (350 ms after colour presentation, 750 ms after word presentation), and the 0 ms SOA (434 ms; see Table 5.2 on page 135). The LPC also showed a main effect of SOA ($F(2,54) = 74.04$, $p < 0.0001$), with significant differences between all SOAs (all *p*'s < 0.05) such that the LPC occurred earliest in the -400 ms SOA (502 ms), followed by the +400 ms SOA (705 ms) and then the 0 ms SOA (762 ms).

Figure 5.2: Monolingual ERP waveforms at Cz and Pz for the a) 0 ms SOA; b) -400 ms SOA; and c) +400 ms SOA. Significant effects from the running *t*-tests, within the N_{inc} (grey shaded area) and LPC (green shaded area) windows, are indicated in bars underneath. Topographic maps show the N_{inc} and LPC components (incongruent vs. congruent), with black dots indicating electrodes that show significant differences ($p < 0.05$) between the average amplitudes of the incongruent and congruent conditions across the specified window.

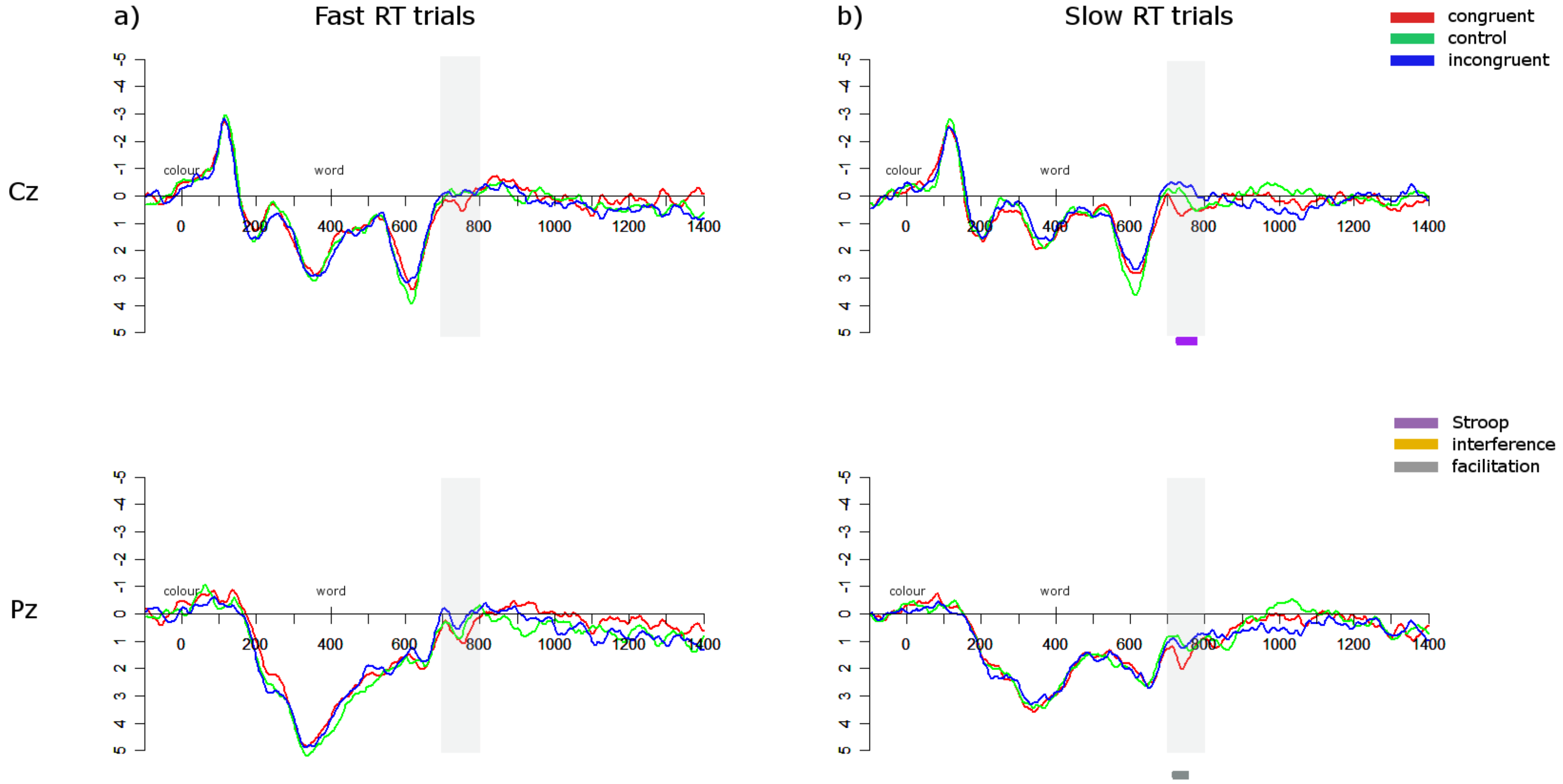


3.1.3. The cognitive generator of the N_{inc}

As proposed in the Introduction, long-latency SOA manipulation may help to clarify the currently ambiguous cognitive functions underlying the N_{inc} and LPC components. Specifically, the presence or absence of an N_{inc} in the +400 ms SOA, in which a response is in preparation or has been executed when the word appears, may indicate whether this component reflects conflict detection or resolution. In the current monolingual data, in the +400 ms SOA (Figure 5.2c) the N_{inc} appeared from 700-850 ms after colour presentation, but the median RT across all congruencies in this SOA was 601 ms. Therefore when the N_{inc} appeared at 700 ms, a response had generally already been made. This suggests that the N_{inc} was not reflective of conflict resolution, as resolution had already occurred to make a correct response, but was instead indicative of conflict detection processes.

To confirm this interpretation, the +400 ms SOA data were divided into fast- and slow-RT trials using a median split (601 ms). If an N_{inc} occurred at the same latency in the fast-RT trials, after all responses had been completed, this would further implicate the N_{inc} in conflict detection processes. In both fast and slow trials (Figure 5.3), the incongruent condition was more negative than the congruent condition at Cz and Pz from approximately 700-800 ms. Statistical analyses compared the average amplitude of conditions over the entire window (700-800 ms): the fast-RT trials showed a trend of a difference between incongruent and congruent conditions at Pz ($t(27) = 1.91$, $p = 0.07$; no significant differences at Cz: all p's > 0.28). In the slow-RT trials, a significant difference between the incongruent and congruent conditions also occurred at Cz ($t(27) = 2.32$, $p < 0.05$), but not at Pz (all p's > 0.15). The running t-tests also showed a significant Stroop effect in the slow-RT trials from approximately 700-800 ms at Cz. Therefore although the statistical significance of these effects was limited due to the reduced power resulting from splitting the data, overall an N_{inc} occurred in both the fast- and slow-RT trials. (The topographical differences between trial types are likely also an effect of reduced power.) Importantly, in the fast-RT trials all behavioural responses were completed by 600 ms and yet an N_{inc} appeared at approximately 700 ms. This suggests that the N_{inc} is not related to conflict resolution but rather is reflective of conflict detection processes (Hanslmayr et al., 2008; West, 2003) which are ongoing and continue after response generation.

Figure 5.3: Fast- and slow-RT waveforms in the monolingual +400 ms SOA at Cz and Pz, with bars indicating significant effects from running *t*-tests within an N_{inc} window of 700-800 ms (shaded region).



To explicate this conflict detection mechanism in the +400 ms SOA, when the colour is pre-exposed a response can be selected and prepared without interference. When the word appears 400 ms later a response is already in preparation, but the presence of an incongruent word still triggers a 'mismatch' response in the brain, initiating conflict detection processes and generating an N_{inc}. Other ERP literature has also reported continuous conflict detection processes. For example, the error-related negativity (ERN) appears shortly after an incorrect response has been made (e.g. Falkenstein et al., 2001; Ullsperger & von Cramon, 2006) and is thought to reflect a signalling of conflict between the executed and correct response (Yeung, Botvinick, & Cohen, 2004); it is therefore essentially a conflict detection component. Thus conflict monitoring can occur after response generation, in line with the current findings.

It is possible in the +400 ms SOA that the N_{inc} reflects additional regulatory aspects of conflict processing beyond conflict detection. For example, an incongruent word may trigger not just conflict detection but also regulatory processes like response inhibition (West & Alain, 2000) or selective enhancement of the goal concept (Roelofs et al., 2006). While these processes may be initiated upon presentation of an irrelevant word, they are likely not carried out to full completion since the goal maintenance system should realize that, because the target has been identified and a response has been made, regulatory processes are no longer needed. While it is possible that the N_{inc} in the +400 ms SOA also reflects aspects of conflict resolution, the most parsimonious interpretation is that the N_{inc} reflects conflict detection processes which are ongoing and continue after response selection. Additionally, rather than being conflict-specific, the N_{inc} could reflect a more general 'mismatch' detection: because the control condition is not a part of the response set, a '%%%%' stimulus may trigger the same type of non-match response as the conflicting incongruent stimulus. However, the 0 ms SOA showed significant Stroop and interference effects at the N_{inc} window but not facilitation, indicating that the congruent and control conditions were behaving similarly while the incongruent condition differed. This suggests that the N_{inc} in fact reflects conflict detection due to the semantic incongruency between the word and colour, rather than detection of response set mismatch in both the incongruent and control conditions.

The interpretation of the N_{inc} as reflective of conflict detection supports the proposal that the N_{inc} arises from the ACC (Badzakova-Trajkov et al., 2009; Hanslmayr et al., 2008; Liotti et al., 2000; Markela-Lerenc et al., 2004; West, 2003). Recall from Chapter 1 (section 3.2.1) that, according to the conflict monitoring hypothesis (Botvinick et al., 2001, 2004), the ACC monitors for and assesses the degree of incoming conflict, then signals other regulative areas such as the DLPFC to resolve the conflict. However, other theories of ACC function exist. For example, the regulative hypothesis suggests that the ACC exerts top-down regulation of response selection processes, potentially by enhancing the activation of the goal concept until a selection threshold is exceeded (Roelofs et al., 2006); this view therefore implicates the ACC in conflict resolution. These theories are difficult to reconcile in light of the current data. Simulations of the conflict monitoring hypothesis predict increased ACC activity for the incongruent condition but an equal amount of activation for neutral and congruent trials, which contain no conflict to detect (Botvinick et al., 2001; Roelofs et al., 2006). This is in line with the observed data in the 0 ms SOA, in which the control and congruent waveforms behaved similarly within the N_{inc} window. In contrast, the regulative hypothesis predicts that less regulation of control, and therefore less ACC activity, is needed for congruent than for control trials, since the correct response has already been activated by the word. This was supported by the -400 ms SOA, in which the incongruent condition was the most negative at the N_{inc} window followed by the control and congruent conditions, respectively. However, in the +400 ms SOA the incongruent and control condition behaved similarly at the N_{inc} (generating both Stroop and facilitation effects), which contradicts both hypotheses.

It may be that the N_{inc} reflects slightly different conflict processes at each SOA. For example, the N_{inc} could be generated by both conflict detection and resolution processes in the -400 ms and 0 ms SOAs, but only by detection in the +400 ms SOA. Alternatively, due to the poor spatial resolution of EEG, activity from different regions of the prefrontal control network, or even different parts of the ACC, could be generating the N_{inc} component in each SOA. Neuroimaging research has shown that different ACC sub-regions perform different functions (e.g. Peterson et al., 1999; van Veen & Carter, 2005) and even respond to different types of conflict (Kim, Kroger, & Kim, 2011). Moreover, conflict monitoring involves not just the detection of mismatching stimuli but additional processes such as maintenance of task goals (e.g. Dosenbach et al., 2007; Roelofs, 2003). If the N_{inc} arises from ACC activation during conflict monitoring, it could also reflect additional working memory and goal maintenance processes (e.g. remembering which stimulus to respond to). It is evident that the ACC is a complex structure, therefore concrete conclusions on its role in the SOA-modulated Stroop task, and on the ERP components that may arise from its activation, require further neuroimaging evidence. In sum, based on the current data it is proposed that the N_{inc} reflects conflict detection rather than conflict resolution, although more research is needed to support this conjecture and to specify the precise cognitive and structural generators of this component.

3.1.4. The cognitive generator of the LPC

The monolingual data also demonstrated an LPC in all SOAs, which is contrary to the initial predictions based on the data of Appelbaum, Meyerhoff et al. (2009). Appelbaum et al. (2009) did not observe an LPC in their +200 ms SOA, which they interpreted as an indication that conflict resolution was not engaged in positive SOAs due to the post-exposure of the word. However, the fact that an LPC occurred in the +400 ms SOA in the current data suggests that this component does not directly index conflict resolution. Furthermore, in the 0 ms and +400 ms SOAs the LPC arose after a response had been made, confirming that it cannot directly reflect conflict resolution. Instead, as proposed by previous literature, the LPC may reflect post-resolution conflict processing such as re-activation of the semantic information that was initially suppressed to overcome conflict (Appelbaum, Meyerhoff et al., 2009; Liotti et al., 2000) and/or a general lifting of other cognitive control mechanisms (Larson et al., 2009). However, in the -400 ms SOA, the LPC occurred during the average response time (median RT across all -400 ms SOA trials = 593 ms), suggesting that this component may also reflect the implementation of conflict resolution processes.

One interpretation of the current data is that the LPC reflects conflict resolution. In the -400 ms SOA at Pz, the incongruent and control conditions behaved similarly in the LPC window, as reflected in the significant Stroop and facilitation but not interference effects (see Figure 5.2). Pre-exposure of the word in this SOA may lead to activation of a ‘concept node’ (see WEAVER++ model, Roelofs, 2003; Chapter 2, section 3.1) related to the semantics of the word; when the colour (i.e. target stimulus) is subsequently presented, a new concept node must be activated. Conflict resolution processes may subsequently enhance attention to the target stimulus (Egner & Hirsch, 2005a) in order to activate the correct concept node; therefore conflict resolution (in the form of attentional control processes) may be required in both the incongruent and control conditions. In the congruent condition, the word has pre-activated the relevant concept node, requiring no conflict resolution. Thus, if the LPC does reflect conflict resolution processes, this may explain why in the -400 ms SOA the incongruent and control conditions differed from the congruent conditions and the LPC showed significant Stroop and interference effects but not facilitation effects. Although a tentative explanation, this would suggest that the LPC is an index of conflict resolution rather than post-resolution processes, but could not explain why an LPC was also observed after response generation in the other SOAs. In sum, the precise interpretation of this component remains unclear: the LPC appears to index conflict resolution processes, but whether it is a direct reflection of resolution, or signals a post-resolution effect, requires further research.

3.1.5. SOA shifts

As predicted, the N_{inc} and LPC were shifted forward in the -400 ms SOA compared to the 0 ms SOA. However, the forward shift was only approximately 200 ms, a similar offset to that of the -200 ms SOA in Appelbaum, Meyerhoff et al. (2009). This does not support Appelbaum et al.’s conclusion of a linear shift in negative SOAs (as a linear offset in a -400 ms SOA would predict a forward shift of 400 ms). This non-linearity beyond 200 ms could reflect a ceiling effect of lexical access speed: full semantic activation generally occurs within 200 ms (Dell’Acqua et al., 2007; Pulvermüller et al., 2001), so any pre-exposure of the word longer than this may have no additional effect on subsequent conflict processing. This would explain why behavioural SOA studies (Glaser & Glaser, 1982) and simulations of the SOA Stroop task (Roelofs, 2003) show relatively stable amounts of interference beyond -200 ms: after the word is fully activated, any additional pre-exposure results in a plateau of priming effects.

The earlier N_{inc} onset latencies in the -400 ms and +400 ms SOAs compared to the 0 ms SOA suggest that SOA manipulation creates a semantic priming effect (see Chapter 7 for discussions of response priming in negative SOAs). For instance, in the -400 ms SOA, word pre-exposure primes lexical and semantic activation, giving conflict detection processes a head-start when the colour stimulus is subsequently presented: the meaning of the word has already been accessed, so evaluation of conflict can occur more quickly. This explains the earlier N_{inc} in the -400 ms SOA. In congruent conditions specifically, pre-activation of the word also creates a semantic priming effect such that the concept of the colour is already activated when the colour appears: response selection processes can occur more quickly, explaining the faster behavioural congruent RTs and increased facilitation effects. In the simultaneous presentation of the 0 ms SOA, the lexical properties of the word must be accessed before conflict processes can be initiated, leading to relatively slower conflict processing (Dell'Acqua et al., 2007; Pulvermüller et al., 2001). In the +400 ms SOA the colour is primed, meaning full semantic activation of the colour information has been achieved when the word appears. Therefore conflict processing must wait only for word activation, creating an earlier N_{inc} in the +400 ms SOA (when time-locked to the second stimulus) than in the 0 ms SOA. Semantic priming can also explain why a larger forward N_{inc} shift occurred in the -400 ms SOA than the +400 ms SOA. Word activation, being a more complex process, takes longer than colour activation (e.g. Brown, 2011). In the -400 ms SOA, when conflict processing is limited only by colour activation because full semantic access has already occurred, an earlier conflict component occurs than in the +400 ms SOA, when conflict detection is limited by the word processing speed. Therefore these results suggest that SOA manipulation creates a semantic priming effect and highlights the fact that conflict processing speed is limited by the relative timecourses of both stimuli.

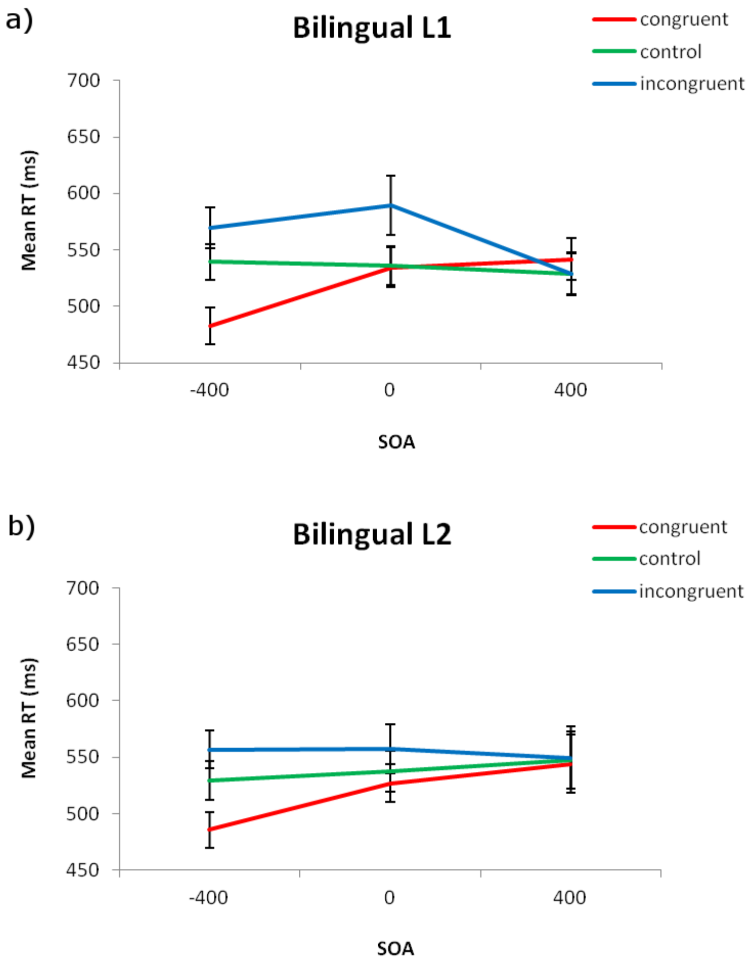
In sum, the monolingual data has replicated the findings of Appelbaum, Meyerhoff et al. (2009) in demonstrating that N_{inc} and LPC component latencies are modulated by SOA manipulation; this modulation is limited by lexical access speed and does not occur linearly. The use of long-latency SOAs has also suggested that the N_{inc} component reflects conflict detection processes, although the precise role of the LPC remains ambiguous. Analyses next turn to the effects of bilingualism on long-latency SOA manipulation in the Stroop task. Because of the indistinct function of the LPC, this component was not investigated in the bilingual ERP data. Instead, analyses focused only on the N_{inc} component which, based on previous data, was predicted to show reduced amplitude in bilinguals. Additionally, as conflict detection processes are limited by lexical access speed, delays in bilingual language processing may delay the onset of the N_{inc}.

3.2. Bilingual data

3.2.1. Bilingual behavioural data

The mean behavioural RTs for the bilinguals are presented in Figure 5.4. In the bilingual L1 (Figure 5.4a), a 3 (SOA) x 3 (congruency) ANOVA showed main effects of congruency ($F(2,36) = 38.44$, $p < 0.0001$) and SOA ($F(2,36) = 3.86$, $p < 0.05$) and an interaction ($F(4,72) = 27.23$, $p < 0.0001$). Significant Stroop and interference effects occurred at -400 ms and 0 ms SOAs (see Table 5.1), with a trend of a significant Stroop effect at +400 ms SOA. Significant facilitation occurred at -400 ms and +400 ms SOAs. The mean RTs in the bilingual L2 (Figure 5.4b) showed a main effect of congruency ($F(2,36) = 32.53$, $p < 0.0001$) but not of SOA ($F(2,36) = 1.90$, $p = 0.16$), and an interaction of congruency and SOA ($F(4,72) = 16.09$, $p < 0.0001$). Significant Stroop and interference effects occurred at -400 ms and 0 ms SOAs, and significant facilitation occurred at -400 ms with a trend at 0 ms (Table 5.1). No effects occurred at the +400 ms SOA.

Figure 5.4: Mean behavioural RTs (ms) for a) bilingual L1 (Chinese) and b) bilingual L2 (English).



3.2.2. Bilingual ERP data

In the bilingual L1 (Chinese) 0 ms SOA (Figure 5.5a), an N_{inc} occurred from approximately 350-550 ms, showing significant interference at Cz. In the -400 ms SOA (Figure 5.5b), an N_{inc} appeared from approximately 200-350 ms after colour presentation, showing interference at Cz and Stroop effects at Pz. In the +400 ms SOA (Figure 5.5c), latency analyses again considered the ERPs as being time-locked to the word. An N_{inc} appeared from approximately 350-450 ms after word onset (750-850 ms after colour onset), with significant Stroop effects at Cz and Pz and interference at Cz. Comparing component latencies with a 3-way (SOA) ANOVA, the N_{inc} showed a significant main effect of SOA ($F(2,36) = 51.55$, $p < 0.0001$), with significant differences between all SOAs (all p's < 0.01) such that the N_{inc} occurred earliest for the -400 ms SOA (294 ms), followed by the +400 ms SOA (398 ms after colour presentation, 798 ms after word presentation), and the 0 ms SOA (464 ms; Table 5.2).

In the bilingual L2 (English) 0 ms SOA (Figure 5.6a), an N_{inc} occurred from approximately 400-600 ms, with significant Stroop and interference effects at Cz and Pz. In the -400 ms

SOA (Figure 5.6b), an N_{inc} occurred from 200-350 ms after colour presentation, with significant Stroop effects at Cz and Pz. In the +400 ms SOA (Figure 5.6c), no significant N_{inc} occurred: although significant interference and facilitation effects occurred at Cz and Pz, the incongruent condition was more positive than the control condition, which is not a typical N_{inc} component. Comparing the latencies between SOAs, the N_{inc} occurred earlier in the -400 ms SOA (286 ms) than the 0 ms SOA (528 ms; $t(18) = 12.70$, $p < 0.0001$; Table 5.2).

Figure 5.5: Bilingual L1 Chinese waveforms at Cz and Pz for the a) 0 ms SOA; b) -400 ms SOA; and c) +400 ms SOA. Significant effects from the running *t*-tests, within the N_{inc} windows (grey shaded area), are indicated in bars underneath. Topographic maps show the N_{inc} components, plus electrodes showing significant differences ($p < 0.05$) between the incongruent and congruent conditions across the specified window.

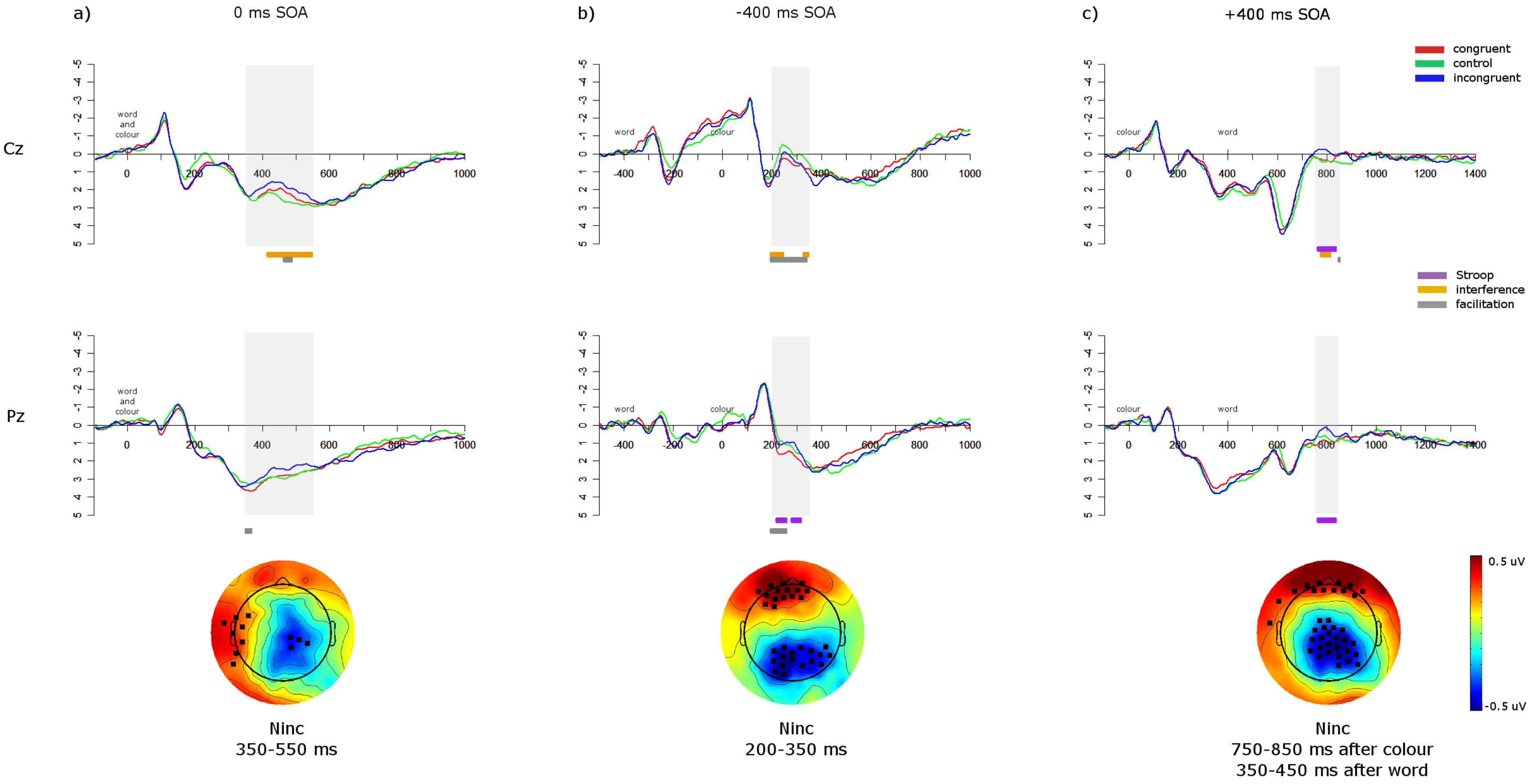
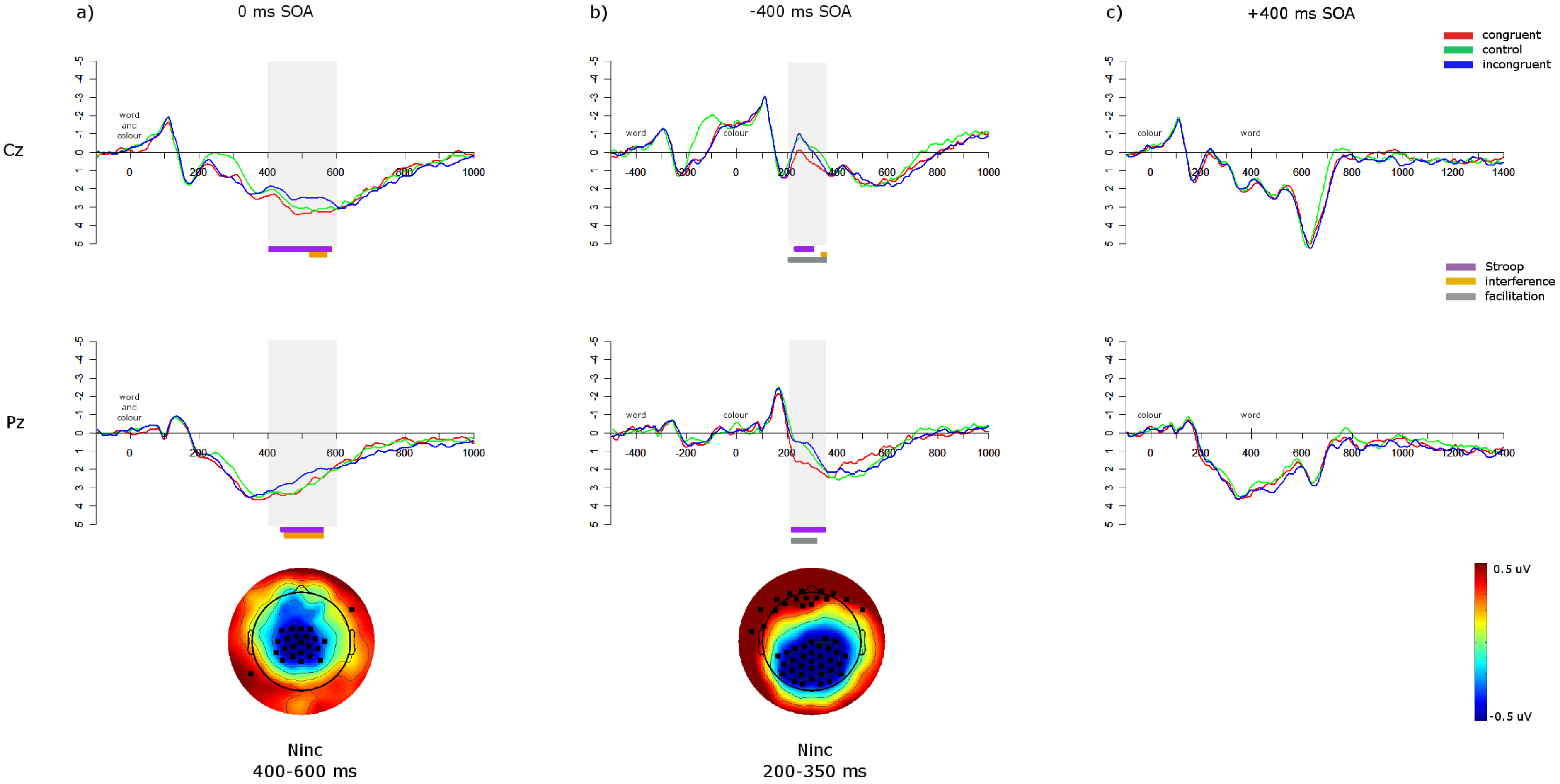


Figure 5.6: Bilingual L2 English waveforms at Cz and Pz for the a) 0 ms SOA; b) -400 ms SOA; and c) +400 ms SOA. Significant effects from the running *t*-tests, within the N_{inc} windows (grey shaded area), are indicated in bars underneath. Topographic maps show the N_{inc} components, plus electrodes showing significant differences ($p < 0.05$) between the incongruent and congruent conditions across the specified window.



3.3. Comparison of monolinguals and bilinguals

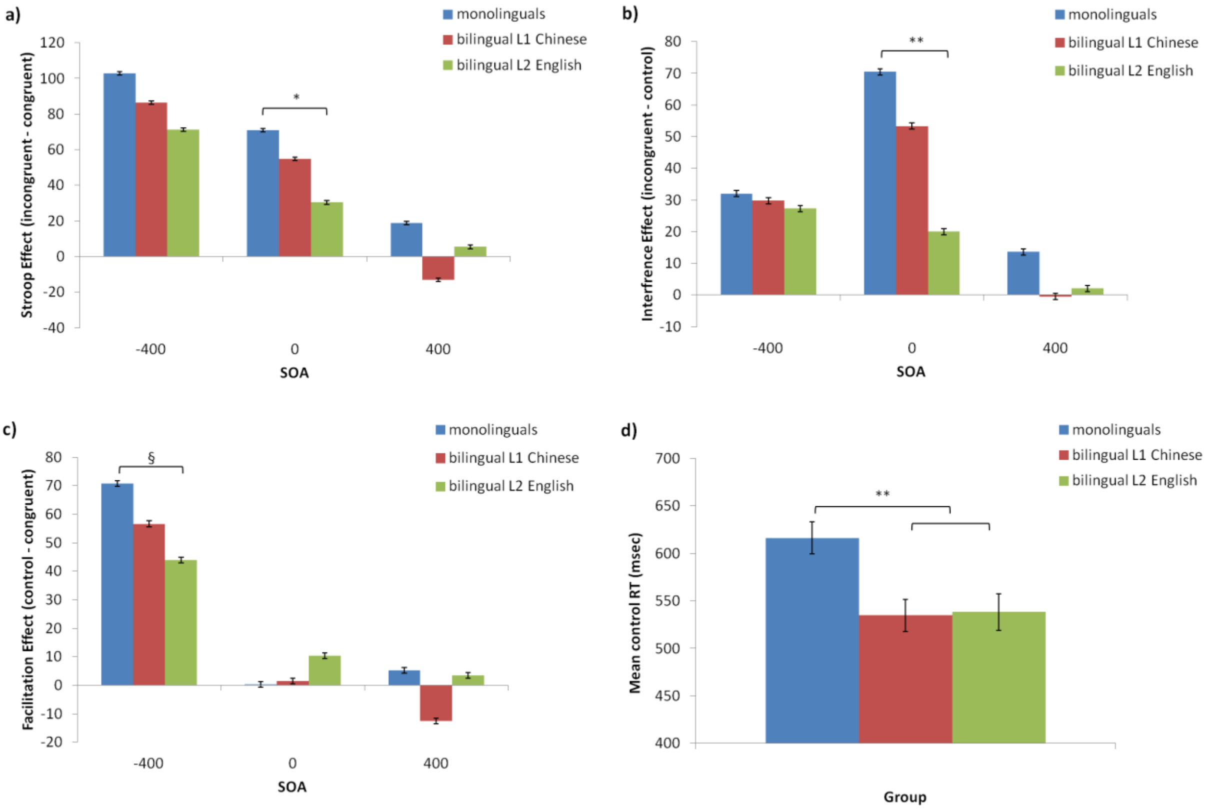
Monolinguals and bilinguals were directly compared to evaluate the bilingual cognitive advantage. Specifically, the BICA hypothesis was assessed by comparing the magnitudes of behavioural Stroop and interference effects and the amplitudes of the N_{inc} in the incongruent-congruent difference waves. The BEPA hypothesis was evaluated by comparing the control conditions across groups, both behaviourally and electrophysiologically.

3.3.1. Behavioural comparisons

The magnitudes of Stroop, interference and facilitation effects were compared between groups using *t*-tests with Bonferroni corrections (Figure 5.7, panels a-c). Only significant effects or trends after corrections are reported. Monolinguals experienced a significantly larger Stroop effect at the 0 ms SOA (71 ms, *SE* = 11 ms) than the bilingual L2 (30 ms, *SE* = 10 ms; $t(39.5) = 2.95$, $p < 0.05$) and a larger Stroop effect at the +400 ms SOA (19 ms, *SE* = 7 ms) compared to the L1 (-13 ms, *SE* = 7 ms; $t(44.0) = 3.20$, $p < 0.05$). Monolinguals also showed larger interference effects at the 0 ms SOA (70 ms, *SE* = 11 ms) compared to the L2 (20 ms, *SE* = 8 ms; $t(44.3) = 3.68$, $p < 0.01$) and a trend of larger facilitation effects in the -400 ms SOA (71 ms, *SE* = 8 ms) than the L2 (44 ms, *SE* = 6 ms; $t(45.0) = 2.77$, $p = 0.07$).

To identify a global RT advantage, the mean RTs for the control condition, collapsed over all SOAs for each subject, were compared between groups using *t*-tests (Figure 5.7d). Monolinguals showed significantly longer control RTs (616 ms, *SE* = 17 ms) than both the bilingual L1 (535 ms, *SE* = 17 ms; $t(43.2) = 3.41$, $p < 0.01$) and the bilingual L2 (538 ms, *SE* = 19 ms; $t(40.5) = 3.06$, $p < 0.01$), but there was no difference between bilinguals' L1 and L2 ($p = 0.68$).

Figure 5.7: Behavioural a) Stroop; b) interference; and c) facilitation effects; and d) the overall RTs for the control condition, averaged over SOAs, for the monolinguals, bilingual L1 and bilingual L2. Significant differences between the groups are marked with asterisks (§ = trend, $p < 0.10$; * = $p < 0.05$; ** = $p < 0.01$).



3.3.2. ERP comparisons

3.3.2.1. Bilingual conflict processing advantage

In the ERP data, group differences in conflict processing were evaluated by computing incongruent-minus-congruent difference waves. As observed in the previous chapter, language-related activity was observable in comparisons with the control condition, so contrasting the two word congruencies eliminated linguistic influences and provided a better estimate of conflict-related processing. The amplitude of the incongruent-congruent difference waves were compared between groups using running *t*-tests (Figure 5.8). More efficient conflict processing in bilinguals (as predicted by the BICA hypothesis) should result in reduced N_{inc} amplitudes (Heidlmayr et al., 2012; Kousaie & Phillips, 2012), and subsequently smaller negative peaks in the difference waves, for bilinguals than monolinguals.

In the 0 ms SOA (Figure 5.8a), the N_{inc} was more sustained for the bilingual L2, with a significant amplitude difference between the monolinguals and L2 from approximately 450-600 ms. However, the negativity onset occurred for all groups at approximately 400 ms. In the -400 ms SOA (Figure 5.8b), the bilingual L1 showed a reduced N_{inc} amplitude compared to the monolinguals and L2, but this was not statistically significant. The bilingual L2 was significantly more negative than the L1 from approximately 350-400 ms at Cz, which may again reflect a more sustained N_{inc}. In the +400 ms SOA (Figure 5.8c) at the N_{inc} window, the lack of an N_{inc} component in the L2 +400 ms SOA data led to significantly reduced difference-wave amplitudes compared to monolinguals from approximately 700-800 ms at Pz and from 700-750 at Cz. Therefore a more sustained N_{inc} component occurred for the bilingual L2 in the 0 ms and -400 ms SOAs.

To investigate differences in N_{inc} peak latency between the groups, latency analyses were performed on the difference waves for each SOA using the SOA- and group-specific N_{inc} windows (Table 5.2). In the 0 ms SOA, the bilingual L2 N_{inc} peak (528 ms) occurred significantly later than both the L1 (464 ms) and monolinguals (434 ms; all p's < 0.01), but monolinguals and the L1 did not differ ($p = 0.13$). This later peak in the bilingual L2 arose from the more sustained N_{inc} component. In the -400 ms SOA, the N_{inc} occurred slightly earlier for monolinguals (258 ms) than for the bilingual L1 (294 ms; $t(39.4) = 2.25$, $p < 0.05$) but no differences occurred between monolinguals and L2 (286 ms; $p = 0.10$) or between L1 and L2 ($p = 0.63$). In the +400 ms SOA, no N_{inc} occurred in the bilingual L2, but the L1 N_{inc} peak (398 ms) occurred significantly later than the monolingual peak (350 ms; $t(32.6) = 4.28$, $p < 0.001$). Therefore the N_{inc} in both the -400 ms and +400 ms SOAs peaked later for bilinguals than monolinguals.

Figure 5.8: Difference waves (incongruent minus congruent) at Cz and Pz for each group in the a) 0 ms; b) -400 ms; and c) +400 ms SOAs. Significant differences between the groups, as evaluated by running *t*-tests, are plotted in bars below. Shaded regions show the approximate N_{inc} windows for each SOA.

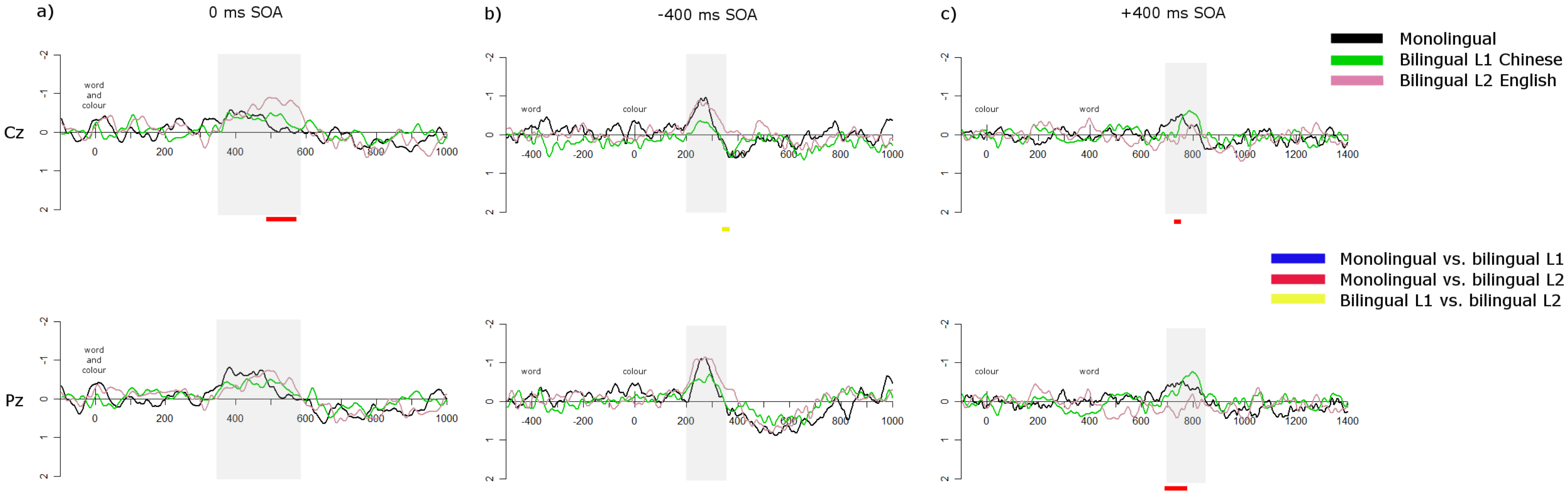


Table 5.2: Summary of the N_{inc} windows and peak N_{inc} latencies in the difference waves (averaged over Cz and Pz) for each group and SOA.

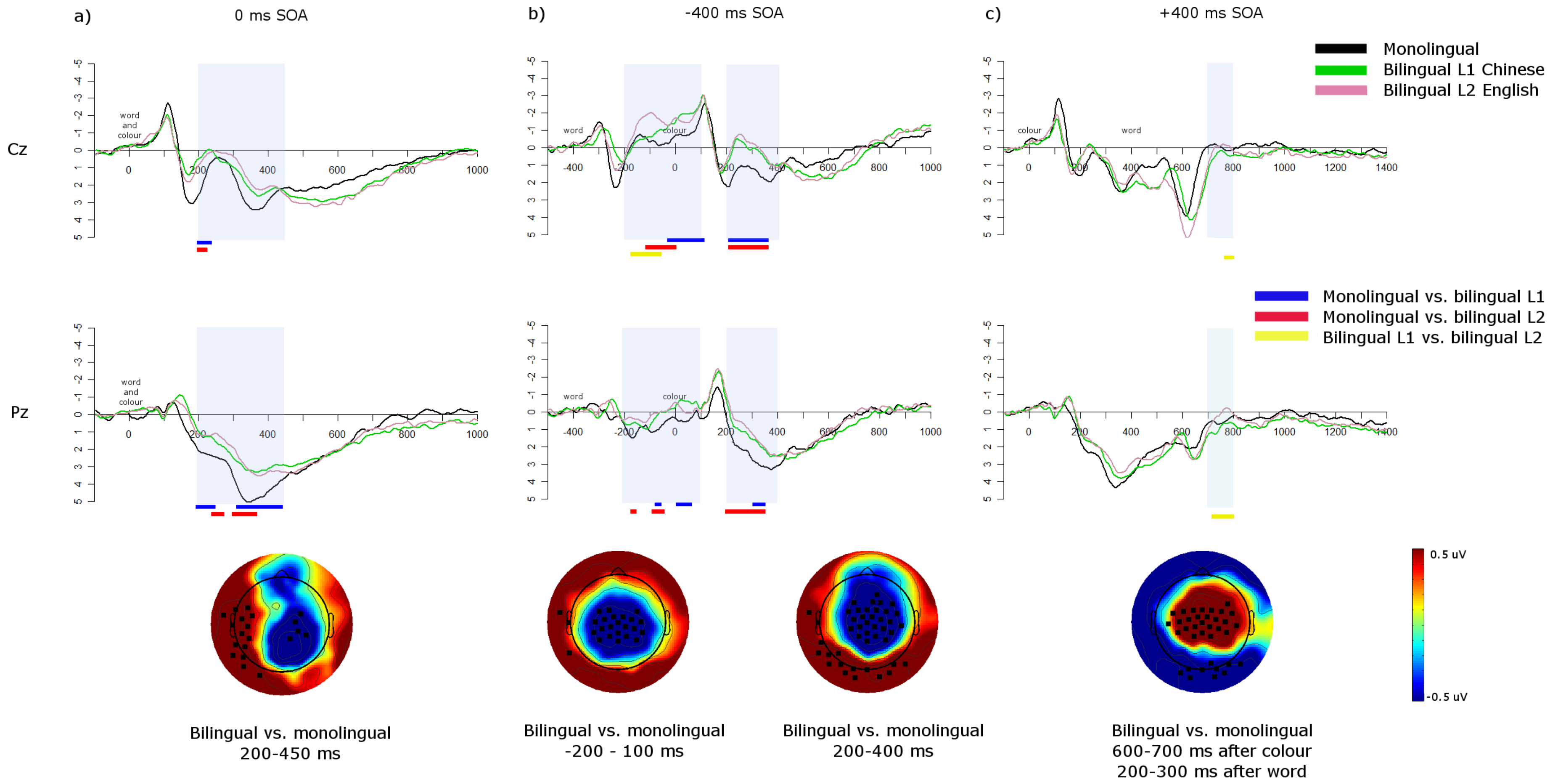
SOA	**Group**	**N_{inc} window**	**N_{inc} peak**
0 ms SOA	Monolinguals	350-500	434
	Bilingual L1	350-550	464
	Bilingual L2	400-600	528
-400 ms SOA	Monolinguals	200-350	258
	Bilingual L1	200-350	294
	Bilingual L2	200-350	286
+400 ms SOA	Monolinguals	300-400	350
	Bilingual L1	350-450	398
	Bilingual L2	None	--

Because running *t*-tests compare the amplitude at each time point, they do not account for temporal shifts; therefore the groups were also compared on the peak difference wave amplitude (averaged over Cz and Pz) within the specific N_{inc} windows for each group/language (Table 5.2). In the 0 ms SOA there was a marginally more negative N_{inc} for the bilingual L1 (-0.9 uV, *SE* = 0.2) compared to monolinguals (-0.5 uV, *SE* = 0.1; $t(39.4) = 1.75$, $p = 0.09$), but no other differences between the groups (all *p*’s > 0.15).

3.3.2.2. Bilingual global RT advantage

As in the behavioural data, the control conditions were compared in the ERP data to evaluate a bilingual global RT advantage. In the 0 ms SOA (Figure 5.9a), monolingual waveforms were significantly more positive than both the L1 and L2 from approximately 200-450 ms at Cz and Pz. As the N_{inc} in this SOA extended from 300-500 ms, this suggests differences at the N_{inc} component as well as before the onset of conflict detection. In the -400 ms SOA (Figure 5.9b), monolinguals were again more positive than both L1 and L2 in the N_{inc} window (200-400 ms), as well as in an earlier window from approximately -200 to 100 ms (200-500 ms after word presentation). The +400 ms SOA (Figure 5.9c) showed a different pattern such that monolingual waveforms were more negative than the bilingual L1 or L2 from 600-700 ms after colour presentation (200-300 ms after word presentation).

Figure 5.9: Waveforms of the control condition at Cz and Pz for each group in the a) 0 ms SOA; b) -400 ms SOA; and c) +400 ms SOA. Significant differences between the groups, based on running *t*-tests, are indicated in bars underneath. Shaded regions highlight the windows where significant differences occurred between groups. Topographic maps show the bilingual – monolingual differences (bilinguals averaged over L1 and L2), plus electrodes showing significant differences ($p < 0.05$) between the bilinguals and monolinguals across the specified window.



Bilingual vs. monolingual
200-450 ms

Bilingual vs. monolingual
-200 - 100 ms

Bilingual vs. monolingual
200-400 ms

Bilingual vs. monolingual
600-700 ms after colour
200-300 ms after word

4. Discussion

The current chapter investigated the effects of long-latency SOA manipulation on conflict-related ERP components in monolinguals and bilinguals. There were two aims to these analyses: first, to identify how the N_{inc} and LPC conflict components were affected by long-latency SOA manipulation in monolinguals; and second, to identify the effects of bilingualism on the amplitude and latency of the N_{inc} component.

4.1. Effects of SOA manipulation in monolinguals

As already discussed in section 3.1, in monolinguals the behavioural results replicated previous Stroop SOA studies (Glaser & Glaser, 1982) and the electrophysiological results replicated previous studies in reporting an N_{inc} and an LPC in the 0 ms SOA (Appelbaum, Meyerhoff et al., 2009; Badzakova-Trajkov et al., 2009; Hanslmayr et al., 2008; Liotti et al., 2000; Markela-Lerenc et al., 2004; West & Alain, 1999). The N_{inc} and LPC were modulated by SOA manipulation, as predicted (Appelbaum, Meyerhoff et al., 2009); however, the results also demonstrated that the temporal modulation does not linearly increase with increasing word pre-exposure but is instead reliant on lexical access speed. The N_{inc} was interpreted as reflecting conflict detection rather than resolution, whereas the precise function generating the LPC was unclear, as the data suggested that the LPC may reflect both active conflict resolution as well as more general post-resolution processes. In sum, these explorations with long-latency SOAs in monolinguals have built on previous research (Appelbaum, Meyerhoff et al., 2009) and have clarified the cognitive mechanisms that give rise to SOA modulations of conflict and to the N_{inc} component.

4.2. Executive control in bilinguals

The current chapter also investigated the effects of bilingualism on the amplitude and latency of the N_{inc} component. It was predicted that a bilingual advantage in conflict processing (BICA hypothesis) would generate smaller behavioural interference effects and smaller N_{inc} amplitudes (Heidlmayr et al., 2012; Kousaie & Phillips, 2012) for bilinguals. A bilingual advantage in domain-general executive control (BEPA hypothesis) was investigated by comparing control trials in both the behavioural and ERP data. In light of the delayed L2 lexical access documented in Chapter 4, N_{inc} onset latency was also evaluated to compare the timecourse of conflict detection in each group.

4.2.1. Bilingual conflict processing

Behaviourally, bilinguals showed decreased Stroop and interference effects compared to monolinguals at the 0 ms SOA, but this was only significant in the L2. This does not support the BICA hypothesis, as an inhibitory control advantage should be present in both languages (see Chapter 3, section 6.2). Reduced interference effects in the L2 could be a result of enhanced executive control abilities, but in light of the delayed lexical access documented in the previous chapter and the lack of a significant advantage in the L1, it is more likely that reduced proficiency in the L2 led to less interference from the word stimuli (see Chapter 2, section 2.1).

In the ERP data, conflict processing was evaluated via the N_{inc} conflict-related ERP component. Previous research has documented reduced N_{inc} amplitudes for bilinguals (Heidlmayr et al., 2012; Kousaie & Phillips, 2012) but this was not supported by the current data, as the bilingual L1 actually showed a larger N_{inc} amplitude than monolinguals in the 0 ms SOA (although this was only a statistical trend). As mentioned in Chapter 1 (section 4.2.1.1), poorer cognitive control has also been associated with a smaller N_{inc} (Holmes & Pizzagalli, 2008; West & Alain, 2000), so this result could indicate enhanced executive control for bilinguals. However, because this effect was only a statistical trend and contradicts previous results in bilinguals, this is a tentative explanation and requires further corroboration. Overall, there was no strong evidence for group differences in N_{inc} amplitude, in contradiction to the predictions of the BICA hypothesis.

The bilingual L2 showed a more sustained N_{inc} in the 0 ms SOA compared to the L1 and monolinguals, which could suggest difficulties in evaluating the presence of conflict due to more effortful language processing. An N_{inc} was absent in the L2 +400 ms SOA, which may also indicate processing difficulties. If in the +400 ms SOA an N_{inc} is indicative of conflict detection after a response has been made, as concluded from the monolingual data, then the lack of an N_{inc} in the L2 may indicate that conflict processes are not engaged as strongly. For instance, if lexico-semantic links are weaker in the L2 and language requires more processing to become engaged, the post-exposure of the word in the +400 ms SOA may disengage active conflict detection, leading to an absent N_{inc}. In other words, the active monitoring of conflict, as reflected by the N_{inc}, may have been relaxed in the L2 in the +400 ms SOA due to the more effortful and unnecessary activation of the word. In sum, the data did not support the predictions of smaller N_{inc} components in bilinguals, but other disparities in the L2 data suggested differences in linguistic conflict processing in the non-native language.

4.2.2. Timecourse of bilingual conflict processing

SOA manipulation exerted a similar modulation of the N_{inc} in bilinguals as in monolinguals: all groups demonstrated the earliest N_{inc} latency in the -400 ms, followed by the +400 ms and 0 ms SOAs. However, when comparing between groups the bilingual L2 showed a significantly delayed N_{inc} peak in the 0 ms SOA compared to the L1 and to monolinguals due to the sustained N_{inc} component. Interestingly, despite the sustained N_{inc} in the L2, all groups showed a similar N_{inc} onset in the difference waves, indicating that conflict detection was initiated at the same latency in all groups and languages. This suggests that, despite the significant delays in lexical access speed documented in Chapter 4, conflict processing was not delayed in the L2. As discussed, Stroop conflict is heavily dependent on the speed of lexical access; the fact that conflict detection mechanisms experienced similar onset latencies in all groups suggests that early linguistic processing delays do not persist throughout all subsequent processing, but may catch up at some point along the way. There are likely a number of other cognitive functions occurring between lexical access and conflict detection which may have contributed to this alleged compensation in the L2 processing delay, so further research is required to determine precisely where this compensation occurs.

As Chapter 4 documented no delays in L1 lexical processing, no differences in N_{inc} latency were predicted between the bilingual L1 and monolinguals. However, the L1 experienced a significantly later N_{inc} in the -400 ms and +400 ms SOAs compared to monolinguals. This may suggest that L1 lexical processing delays occur not at early stages of orthographic recognition but during later semantic or conflict processing. Alternatively, the delayed N_{inc} onset in the L1 could be indicative of enhanced inhibitory control over the stronger L1: as language was blocked in this paradigm, bilinguals may have exerted more inhibitory control throughout the entire block to avoid interference from the L1 words. This could have slowed conflict detection processes and led to later N_{inc} components. Alternatively, in the 0 ms SOA, being the more cognitively demanding condition, cognitive control may have been heightened in monolinguals, creating a similar effect and equalizing conflict processing speed between groups, which would explain the lack of group differences in N_{inc} latencies at this SOA. These are all tentative interpretations, as no differences occurred in behavioural interference effects or N_{inc} amplitudes; nevertheless, these bilingual differences in N_{inc} onset at long-latency SOAs may be an interesting way of assessing language control.

4.2.3. Bilingual domain-general executive processing

Bilinguals experienced a significant behavioural global RT effect in both languages, demonstrating faster RTs on the control condition than monolinguals. In the ERP data, comparisons of the control condition across groups also yielded significant differences in all SOAs. Specifically, bilinguals showed more negative waveforms within the N_{inc} windows, in both languages, than monolinguals. This enhanced negativity in the non-linguistic, non-conflict control condition contradicts the BICA hypothesis, which predicted no differences between groups in the absence of conflict, and instead suggests more efficient monitoring processes in bilinguals as predicted by the BEPA hypothesis. Importantly, in the -400 ms SOA the increased negativity for bilinguals occurred not only at the N_{inc} window but also before the colour had been presented, from -200 to 100 ms (200-500 ms after word/control stimulus presentation). These early differences suggest that the bilingual executive processing advantage arose not from more efficient conflict monitoring (Costa et al., 2009), as no conflict had occurred yet, but from domain-general monitoring processes. Furthermore, bilinguals may have more efficiently engaged an alternative control mechanism such as ignoring or suppressing irrelevant information; this possibility will be explored in later interpretations of the bilingual executive processing advantage, presented in the General Discussion (Chapter 9).

5. Conclusions

In sum, the current chapter investigated electrophysiological indices of SOA manipulation and of the bilingual cognitive advantage in the Stroop task. The data presented here demonstrated that the N_{inc} component was indicative of conflict detection processes, rather than conflict resolution. SOA manipulation affected the onset latency of the N_{inc} in positive and negative SOAs by creating a semantic priming effect which accelerated conflict detection. Interestingly, despite the large delay in early lexical processing demonstrated in the previous chapter, there were no delays in the onset of L2 conflict detection, although the L2 data suggested more effortful conflict processing in the weaker second language. There was no evidence for a bilingual advantage in conflict processing, but a significant global RT advantage occurred for bilinguals. Furthermore, the ERP data suggested that bilinguals may exhibit more efficient mechanisms of monitoring or managing irrelevant information, regardless of the presence of conflict or semantic information.

This data therefore supported the BEPA but not the BICA hypothesis. However, as discussed in Chapter 2 (section 3.4), a manual Stroop task elicits the peak interference effect at the -200 ms SOA, which was not included in the current paradigm. Therefore the lack of a significant bilingual interference advantage may merely indicate that conflict processing demands were not high enough to elicit group differences. The next chapter therefore employs a similar paradigm using negative SOAs only (-400 ms, -200 ms, and 0 ms) to more effectively isolate the differences in executive processing between bilinguals and monolinguals.

Chapter 6: The Effect of Script Similarity on the Bilingual Advantage

Using long-latency SOAs, the previous chapter documented evidence for the BEPA hypothesis (a bilingual global RT advantage) but not for the BICA hypothesis (no group differences in interference effects). However, the Stroop SOA experiment in the previous chapter did not include a -200 ms SOA, which as demonstrated in Chapter 2 is the most cognitively demanding SOA in a manual Stroop task and may elicit a stronger bilingual advantage. The current chapter therefore assesses the bilingual cognitive advantage only at negative SOAs (-400, -200, 0 ms). Moreover, special consideration is given to how the bilingual advantage is modulated by individual differences. As described in Chapter 1 (section 4.3), bilingual executive control abilities can be affected by language proficiency and the frequency of language switching. The current chapter explicitly considers how an additional individual difference, that of the orthographic similarity of a bilingual's two languages, might modulate the bilingual cognitive advantage.

1. Introduction

A language's specific characteristics of orthography and phonology can influence language processing at various cognitive and linguistic levels. For example, as discussed in Chapter 3 (section 6.3), the role of phonology in visual word recognition, and whether its influence is consistent across writing systems[16], is strongly debated (e.g. Perfetti et al., 2005; Saalbach & Stern, 2004). Language processing mechanisms also differ between shallow orthographies (which have consistent grapheme-phoneme conversion rules, such as Italian and Finnish) and deep orthographies (which contain common irregularities, such as English, French and Arabic), as demonstrated by neural and electrophysiological data (e.g. Bar-Kochva, 2011; Meschyan & Hernandez, 2006). For example, Bar-Kochva (2011) demonstrated that shallow orthographies generated larger N170 effects than deep orthographies. Language organization in the brain is also influenced by writing system (e.g. Bick, Goelman, & Frost, 2011; Bolger et al., 2005; Coderre, Filippi, Newhouse, & Dumas, 2008; Nelson et al., 2009; Perfetti et al., 2007; Sakurai et al., 2000; Tan et al., 2001; Tan, Spinks, Eden, Perfetti, & Siok, 2005): Chinese, which places more emphasis on spatial representations, typically activates a bilateral language network, whereas alphabetic languages activate a left-lateralized network (see Bolger et al., 2005 and Tan, Laird et al., 2005 for meta-analyses). Picture naming times also

---

[16] The term 'writing system' refers here to the genre of a language's symbolic system, such as alphabetic (in which each symbol represents a letter, as in English), syllabic (in which each symbol represents a syllable, as in Japanese kana), or logographic (in which each symbol represents an entire word or concept, as in Chinese). 'Script' refers to the specific symbols within a language; for example, Japanese has two scripts: the syllabic kana and the logographic kanji. 'Orthography' refers to the standardized rules and conventions of the language, such as spelling and pronunciation.

differ between languages according to various factors like the degree of word order flexibility (Bates et al., 2003), indicating differences at the level of production.

Despite these variations in linguistic processing characteristics, cross-linguistic activation still occurs for different-script languages (Hoshino & Kroll, 2008; Sumiya & Healy, 2004; Zhang et al., 2011). For example, Hoshino & Kroll (2008) observed cross-linguistic phonological effects during picture naming in Japanese-English bilinguals, indicating that the non-target language was active despite having a completely different writing system. Importantly however, the magnitude of cross-linguistic activation may be modulated by orthographic similarity. The BIA+ model (which is based on alphabetic word recognition and codes letter positions) proposes that cross-linguistic bottom-up activation is dependent on the degree of orthographic overlap (Dijkstra & van Heuven, 2002):

> "The larger the overlap between the input string and a representation in the mental lexicon, the more the internal representation is activated...if the two languages differ with respect to their input codes (e.g. letter sets), the activated set of [orthographic] neighbors [sic] may become much smaller" (Dijkstra & van Heuven, 2002, pg. 182-183).

Therefore according to the BIA+ model, languages with more orthographic overlap (i.e. overlapping letters) generate more cross-linguistic influence. Furthermore, same-script languages also contain orthographic neighbours (words that differ by only one letter, maintaining word length and letter positions) and homographs (words that are spelled the same between languages), which may exaggerate cross-linguistic influences during comprehension. Similarly, during production, although cross-linguistic phonological activation occurs in all scripts (Hoshino & Kroll, 2008; Wu & Thierry, 2010), increased phonological similarity between languages could create more co-activation when selecting a word for speech.

1.1. The effect of script on the bilingual advantage

The BIA+ model therefore predicts that bilinguals who use two very similar languages (e.g. German and English) experience more cross-linguistic activation on a daily basis than bilinguals who use two very different languages (e.g. Chinese and English). According to the BICA hypothesis (Chapter 1, section 4.4), bilinguals recruit inhibitory control mechanisms to manage cross-linguistic influences, generating a bilingual advantage in interference effects. If same-script bilinguals experience more cross-linguistic activation on a daily basis than different-script bilinguals, the BICA hypothesis would predict that these individuals have superior inhibitory control abilities and should therefore show larger interference advantages. In contrast, the BEPA hypothesis (Chapter 1, section 4.5) proposes that bilinguals have superior domain-general executive processing abilities arising from the need to monitor the environment for language membership and select the target language. This leads to an advantage in general executive processing and a subsequent global RT advantage. If same-script bilinguals experience more cross-linguistic activation, they may also be more experienced in monitoring for and selecting the target language; thus the BEPA hypothesis would predict enhanced executive processing abilities for same-script bilinguals. Script similarity is therefore an important factor which could potentially affect the magnitude of the bilingual cognitive advantage. However, this variable is rarely considered in bilingualism research.

1.1.1. Bilingual populations in previous literature

Many studies investigating the bilingual advantage have tested bilinguals from a wide variety of L1 backgrounds (Bartolotti et al., 2010; Bialystok, Craik, & Ruocco, 2006; Bialystok, Craik, & Ryan, 2006; Bialystok et al., 2008; Bialystok & Feng, 2009; Bialystok & Shapero, 2005; Luk et al., 2010). For example, Bialystok et al. (2008) included a bilingual population from 24 different native languages, including Spanish, German, Cantonese, Greek, Arabic, Korean, Hebrew, Tamil, and Latvian; yet the researchers collapsed across these widely disparate languages to report a bilingual executive processing advantage.

Studies testing heterogeneous bilingual populations have reported evidence for a bilingual advantage (Bialystok et al., 2008; Bialystok & Shapero, 2005) as well as against (Bialystok, Craik, & Ryan, 2006; Luk et al., 2010). Similarly, studies using homogeneous populations have documented evidence for a bilingual advantage (Bialystok, 1999; Bialystok et al., 2004; Blumenfeld & Marian, 2011; Carlson & Meltzoff, 2008; Costa et al., 2008, 2009; Garbin et al., 2010; Kuo & Anderson, 2012; Poulin-Dubois, Blaye, Coutya, & Bialystok, 2011) as well as against (Heidlmayr et al., 2012; Kousaie & Phillips, 2012; Morton & Harper, 2007). The evidence is therefore mixed: evidence for and against a bilingual advantage has been found in both heterogeneous and homogeneous populations. However, there is a dearth of studies employing a systematic manipulation of this factor to determine whether and how it affects the bilingual cognitive advantage.

1.1.2. Previous research on the effect of script in bilingual cognitive control

Only two studies have explicitly investigated the factor of script in bilingual cognitive control (Bialystok, Craik, et al., 2005; Linck et al., 2008). Bialystok et al. (2005) tested two groups of bilinguals on the Simon task, one French-English and one Cantonese-English (although they did not explain why they tested two different groups, nor why those particular languages were chosen). Behaviourally, the monolinguals and French-English bilinguals did not differ but the Cantonese-English bilinguals demonstrated a global RT advantage, indicating that different-script bilinguals outperformed same-script bilinguals. However, Bialystok et al. did not interpret this difference between bilingual groups beyond attributing it to sampling variability due to the small number of participants.

Linck et al. (2008) hypothesized that different-script bilinguals are able to use script as a cue to restrict lexical selection (Guo et al., 2005; Hoshino & Kroll, 2008), whereas same-script bilinguals cannot use this strategy and must rely on executive control to manage linguistic competition. They therefore predicted greater inhibitory control abilities for same-script bilinguals. Testing Japanese-English and Spanish-English bilinguals on a Simon task, Linck et al. (2008) found no overall differences in Simon effects between the groups. However, when analyzing only the bilinguals tested in an L2 context, different-script bilinguals showed greater inhibitory control abilities. As reported in Bialystok, Craik et al. (2005), this again suggests that different-script bilinguals experience superior executive control. Linck et al. proposed that this effect was due to code-switching frequency: as Japanese-English bilinguals code-switch less often, they demonstrated greater language control, whereas Spanish-English bilinguals, who code-switch more frequently, have less experience in language inhibition. Therefore this limited research suggests that cognitive control abilities may *increase* with decreasing orthographic similarity, in contrast to the predictions of the BIA+ model.

1.2. The current study

The current study investigated the effect of script similarity on the bilingual cognitive advantage by testing three groups of bilinguals from language backgrounds of differing script overlap: German-English (highly similar in both orthography and phonology), Polish-English (same writing system but less orthographic and phonological overlap), and Arabic-English (both alphabetic writing systems but no orthographic or phonological overlap); a control group of English monolinguals was also included. Participants performed the Stroop task with three SOAs chosen to maximize interference (-200 ms and 0 ms) and facilitation (-400 ms) effects. Once again the Stroop task employed a manual response, so SOA manipulation was expected to yield the largest interference effects at the -200 ms SOA followed by the 0 ms SOA and the largest facilitation effects at the -400 ms SOA. A non-linguistic Simon task was also included to assess executive control abilities independently of script influences.

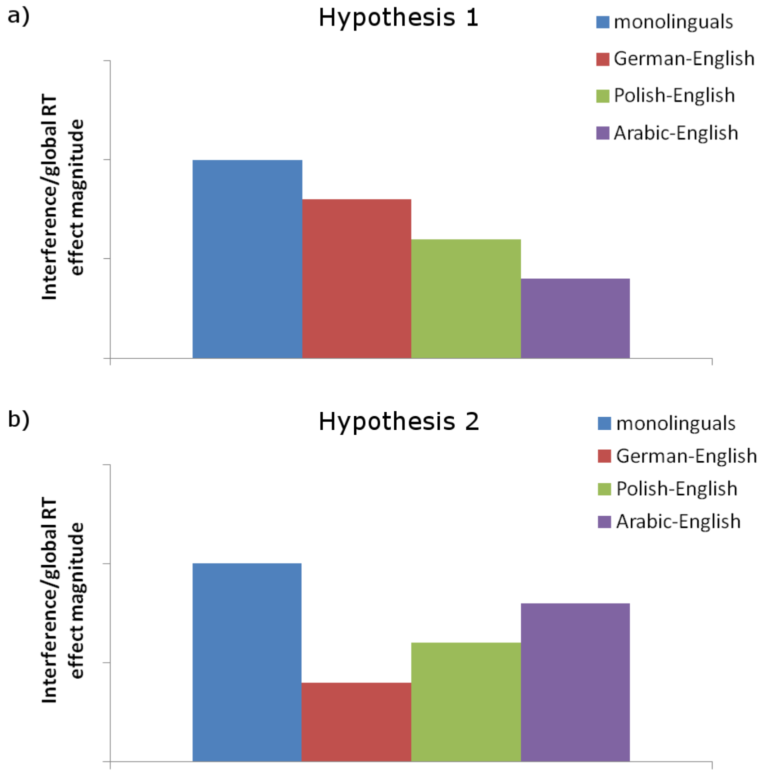
1.2.1. Predictions for bilingual cognitive control

As demonstrated by the results of Bialystok, Craik, et al. (2005) and Linck et al. (2008), one possibility is that different-script bilinguals experience superior cognitive control than same-script bilinguals (Hypothesis 1). As proposed by Linck et al. (2008), this pattern may arise from the more frequent occurrence of code-switching in similar-script languages. Based on this previous literature, Hypothesis 1 therefore proposed a *negative* relationship between script similarity and cognitive control abilities, predicting superior cognitive control (i.e. smaller interference/global RT effects) for Arabic-English bilinguals, followed by Polish-English, German-English, and monolinguals (see Figure 6.1a).

Alternatively, as proposed in section 1.1, similar-script bilinguals may show enhanced executive control abilities compared to different-script bilinguals. Because similar-script language pairs such as English and German have a high amount of phonological and orthographic overlap, more cross-linguistic activation occurs, requiring more cognitive control on a daily basis and enhancing control abilities. In contrast, different-script language pairs like Arabic and English create less cross-linguistic activation, requiring less cognitive control which results in under-developed executive processing abilities (compared to same-script bilinguals). Therefore Hypothesis 2 proposed a *positive* relationship between cognitive abilities and script similarity, predicting superior cognitive control (smaller interference/global RT effects) for German-English bilinguals, followed by Polish-English, Arabic-English, and monolinguals (see Figure 6.1b).

Bilingual executive control was again assessed in light of the BICA and BEPA hypotheses: the BICA would predict group differences in interference effects, whereas the BEPA would predict differences in global RT effects. For both hypotheses, the Polish-English bilingual performance was expected to fall between German-English and Arabic-English bilinguals and monolinguals were expected to show the worst cognitive control (Figure 6.1). These patterns were expected for the global RT effects and for interference effects in the Simon task. However, because of the explicit presentation of language in the Stroop task (which was performed in both languages for bilinguals), a different set of predictions was proposed. For example, the bilingual Stroop task (with a vocal response) demonstrates increasing Stroop interference with increasing language similarity (see Chapter 2, section 2; Brauer, 1998; van Heuven et al., 2011). This would predict the largest Stroop interference for German-English bilinguals, in contrast to Hypothesis 1 but in line with Hypothesis 2. The inclusion of the non-linguistic Simon task in this study was therefore imperative, as it delineated the effects of cross-linguistic interference from executive control ability.

Figure 6.1: Predictions of the current experiment: a) Hypothesis 1 proposed a negative relationship between cognitive control abilities and script similarity, predicting better cognitive control abilities, i.e. smaller interference and global RT effects, with decreasing script similarity (German to Arabic); b) Hypothesis 2 proposed a positive relationship between cognitive control and script similarity, predicting better cognitive control abilities with increasing script similarity. Note that monolinguals were expected to perform worst in both cases.



2. Methods

2.1. Participants

All participants were right-handed and reported no colour-blindness. Demographic information is presented in Table 6.1. Three groups of bilinguals were recruited: German-English (n = 19), Polish-English (n = 22), and Arabic-English (n = 17). All bilinguals considered English to be their second language and all lived in England at the time of testing. All participants completed a language background questionnaire prior to testing and two vocabulary assessments (X-Lex and Y-Lex; see Procedure, section 2.3). The bilingual participants did not differ statistically on their self-rated proficiency (all p's > 0.21), English AoA (all p's > 0.17), or years of English experience (all p's > 0.47). However, Arabic bilinguals showed significantly lower scores on the English vocabulary measures compared to the German and Polish bilinguals (all *p*’s < 0.05). The monolingual participants were 18 native English speakers (Table 6.1). Some (*n* = 9) reported learning other languages, but none considered themselves fluent in anything but English.

2.2. Materials and Design

2.2.1. <u>The Stroop task</u>

As in all previous chapters, word stimuli for the English Stroop task consisted of the words ‘red’, ‘green’, and ‘blue’ in lowercase letters printed in white ink on a black background. Corresponding word stimuli for the L1 task were: German words ‘rot’, ‘grün’, ‘blau’; Polish words ‘czerwony’, ‘zielony’, ‘niebieski’; and Arabic words ‘أحمر’ ‘أخضر’ ‘أزرق’. All stimuli were printed in white ink on a black background. A symbol string control condition (‘%%%%’) was also printed in white ink on a black background. The design was otherwise identical to that of Chapters 4 and 5 (see Chapter 4 for full details on the participants, design, procedure, and data acquisition.)

2.2.2. <u>The Simon task</u>

Stimuli in the Simon task consisted of blue and red squares (60 x 60 pixels) on a white background, presented either in the centre or slightly to the left (42% of horizontal) or right (58% of horizontal) of centre. Participants responded to the colour of the square with a keyboard button response (left index finger for blue, right index finger for red).

2.3. Procedure

Before testing, participants completed an online language background questionnaire, a short colour-blind test, and two vocabulary tests estimating high-frequency (1K-5K: X-Lex: Meara, 2005) and low-frequency (5K-10K: Y-Lex: Meara & Miralpeix, 2006) word knowledge. Bilingual participants performed two experimental sessions on consecutive days; each session consisted of the Simon task and the Stroop task in one language. The order of task and of Stroop language administration was counterbalanced across participants. In the second session, bilinguals performed a picture-naming task in both of their languages (data not presented here). Monolingual participants performed one session, consisting of the English Stroop task and the Simon task.

Three SOAs (-400 ms, -200 ms, 0 ms) were used in the Stroop task. The procedure was identical to that of Chapters 4 and 5, with the exception that the +400 ms SOA was substituted with the -200 ms SOA, in which the interval between word and colour presentation was 200 ms.

The Simon task was presented in E-Prime. A brief practice session of 24 stimuli was first administered, followed by the experimental blocks. Each experimental block was approximately 2 minutes long: bilinguals performed 3 blocks in each session and monolinguals performed 6 blocks during their single session. Each block consisted of 42 randomly presented trials (14 each of congruent, control, and incongruent), creating 252 total trials for each participant. In each trial, a fixation cross was presented for 350 ms, followed by a blank screen for 150 ms, then the coloured square for 750 ms. A blank screen was then presented with an inter-trial interval of 850 ms.

2.4. Data acquisition

The behavioural data was collected during an EEG session; high-density ERPs were also collected at 250 Hz using an EGI Hydrocel 128-channel sensor net and NetStation version 4.3. The EEG data is not reported here due to space restrictions.

Table 6.1: Demographic and proficiency information for all participants (F = female, M = male). X-Lex and Y-Lex scores range from 0-5000 in 100-point increments. The adjusted score accounts for false alarms.

Group	***n***	**Age**	**Gender**	**X-Lex score**		**Y-Lex score**		**Age of first L2 contact**	**Years experience**	**Self-rated L2 proficiency**				
				raw	**adjusted**	**raw**	**adjusted**			**speaking**	**listening**	**reading**	**writing**	**overall**
German-English	19	26 (6)	11 F, 8 M	4875 (170)	4514 (402)	3672 (961)	3353 (934)	9.6 (2.3)	14.4 (5.8)	8.7 (1.1)	8.9 (1.2)	8.9 (1.2)	8.3 (1.4)	8.7 (1.1)
Polish-English	22	25 (5)	13 F, 9 M	4891 (128)	4436 (369)	3684 (561)	2905 (808)	8.9 (3.1)	13.4 (5.0)	8.7 (1.2)	8.8 (1.3)	9.1 (1.1)	8.5 (1.1)	8.8 (1.0)
Arabic-English	17	26 (4)	9 F, 8M	4671 (289)	3626 (833)	2926 (1054)	2000 (868)	7.9 (4.5)	12.9 (5.9)	8.2 (1.3)	8.7 (1.0)	8.6 (0.9)	8.1 (1.3)	8.4 (1.0)
Monolingual	18	21 (2)	9 F, 9 M	4976 (31)	4550 (511)	4406 (396)	3706 (912)	--	--	--	--	--	--	--

Table 6.2: Percentages of errors, range of errors across conditions, and outliers for each group and language.

%	**German-English**			**Polish-English**			**Arabic-English**			**Monolinguals**	
	Stroop		**Simon**	**Stroop**		**Simon**	**Stroop**		**Simon**	**Stroop**	**Simon**
	L1	**L2**		**L1**	**L2**		**L1**	**L2**			
Errors	3.6	3.6	6.8	5.0	5.0	6.2	6.4	7.0	7.2	3.8	7.1
Errors per condition (range)	0.2-0.8	0.3-0.5	2.0-2.9	0.4-0.8	0.4-0.8	1.4-3.1	0.5-0.9	0.6-1.1	2.0-3.2	0.3-0.5	1.6-3.6
Outliers	0.4	0.1	0.2	0.1	0.1	0.6	0.02	0.04	0.2	0.04	0.2

3. Results

Incorrect responses and outliers (RTs less than 250 ms or greater than 2000 ms; Table 6.2) were removed before statistical analyses. As in the previous behavioural study (Chapter 3), Stroop/Simon effects (incongruent vs. congruent) are not reported for this dataset because these effects consist of both interference and facilitation influences.

3.1. Stroop task

For each group and language, a 3 (congruency) x 3 (SOA) repeated-measures ANOVA was performed on the mean RTs (Figure 6.2), with paired-sample *t*-tests to identify interference and facilitation effects at each SOA (full results presented in Table 6.3). All groups showed a main effect of congruency (all p's < 0.0001) and interactions of congruency and SOA (all p's < 0.05) in both L1 and L2. A main effect of SOA also occurred in both languages of German-English bilinguals ($p < 0.05$), but not in any other groups (all p's > 0.19). All groups and languages showed significant interference effects at all SOAs (all p's < 0.05) and significant facilitation at -400 ms and -200 ms SOAs (all p's < 0.05; Table 6.4).

Figure 6.2: Mean RTs (ms) in the Stroop task for each group and language.

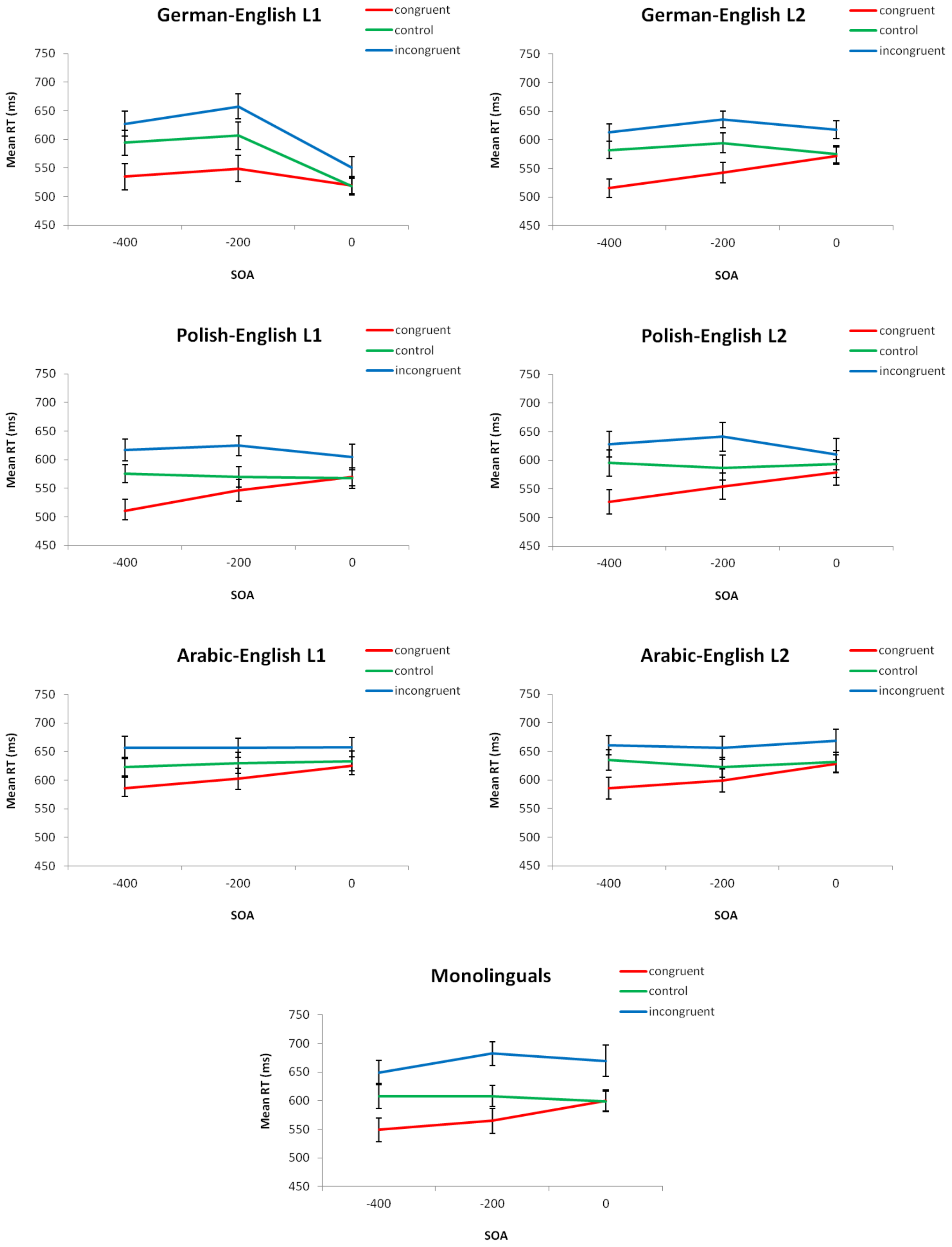


Table 6.3: Results of the 3 (congruency) x 3 (SOA) repeated-measures ANOVAs for each group and language in the Stroop task (n.s. = not significant, *p* > 0.10).

Group	**Language**	**Congruency**			**SOA**			**Congruency x SOA**		
		df	***F*-value**	***p*-value**	***df***	***F*-value**	***p*-value**	***df***	***F*-value**	***p*-value**
German-English	L1	2,36	103.82	<0.0001	2,36	28.47	<0.0001	4,72	15.08	<0.0001
	L2	2,36	89.16	<0.0001	2,36	5.00	0.012	4,72	12.62	<0.0001
Polish-English	L1	2,42	113.44	<0.0001	2,42	0.79	n.s.	4,84	15.67	<0.0001
	L2	2,42	47.11	<0.0001	2,42	1.73	n.s.	4,84	10.59	<0.0001
Arabic-English	L1	2,32	49.15	<0.0001	2,32	2.04	n.s.	4,64	3.53	0.01
	L2	2,32	43.62	<0.0001	2,32	2.15	n.s.	4,64	7.41	<0.0001
Monolinguals	--	2,34	150.21	<0.0001	2,34	0.98	n.s.	4,68	8.65	<0.0001

Table 6.4: Statistical comparisons of interference and facilitation effects for each group and language in the Stroop task (n.s. = not significant, $p > 0.10$).

Group	**Language**	**SOA**	**Interference**			**Facilitation**		
			***t*-value**	***df***	***p*-value**	***t*-value**	***df***	***p*-value**
German-English	L1	-400 ms	4.78	18	<0.001	6.24	18	<0.0001
		-200 ms	4.73	18	<0.001	7.85	18	<0.0001
		0 ms	4.61	18	<0.001	-0.32	18	n.s.
	L2	-400 ms	4.44	18	<0.001	8.55	18	<0.0001
		-200 ms	4.32	18	<0.001	7.39	18	<0.0001
		0 ms	4.70	18	<0.001	0.44	18	n.s.
Polish-English	L1	-400 ms	5.10	21	<0.0001	11.66	21	<0.0001
		-200 ms	9.45	21	<0.0001	3.93	21	<0.001
		0 ms	5.13	21	<0.0001	0.92	21	n.s.
	L2	-400 ms	3.16	21	<0.01	6.51	21	<0.0001
		-200 ms	4.31	21	<0.001	5.09	21	<0.0001
		0 ms	2.54	21	0.02	3.35	21	<0.01
Arabic-English	L1	-400 ms	5.13	16	<0.001	4.68	16	<0.001
		-200 ms	3.39	16	<0.01	6.15	16	<0.0001
		0 ms	2.53	16	0.02	1.33	16	n.s.
	L2	-400 ms	3.89	16	<0.01	7.55	16	<0.0001
		-200 ms	5.40	16	<0.0001	2.45	16	0.03
		0 ms	5.14	16	<0.0001	0.57	16	n.s.
Monolinguals	--	-400 ms	5.72	17	<0.0001	6.45	17	<0.0001
		-200 ms	10.39	17	<0.0001	6.81	17	<0.0001
		0 ms	5.25	17	<0.0001	-0.10	17	n.s.

3.1.1. Stroop interference and facilitation comparisons

To compare the magnitude of interference and facilitation effects (presented in Figure 6.3) between groups, two types of ANOVAs were run for each effect and language. First, to identify differences associated with bilingualism, the bilingual data was collapsed over German, Polish, and Arabic groups and a 2 (group: monolingual, bilingual) x 3 (SOA) ANOVA was performed for each effect (interference and facilitation) in each language (i.e. monolinguals vs. L1 and monolinguals vs. L2). Next, to identify script-driven differences within the bilingual groups, the monolinguals were taken out of the analyses and a 3 (language group: German, Polish, Arabic) x 3 (SOA) ANOVA was performed for each effect (interference and facilitation) and language (L1 and L2; see Table 6.5 and Table 6.6 for full results). These analyses were performed for each language individually to investigate differences explicitly related to orthography (i.e. between different L1s) compared to differences within English (i.e. L2).

The interference magnitudes (Figure 6.3a) showed a main effect of group (monolingual/bilingual) and SOA in both languages (all *p*'s < 0.05; Table 6.5). There was also a trend of an interaction between group and SOA in the L1 ($p = 0.07$), which was investigated with a 2-way (group) ANOVA for each SOA. The -400 ms SOA showed no main effect of group ($p = 0.51$), but there was a significant group effect in the -200 ms SOA ($F(1,74) = 7.19$, $p < 0.01$) such that monolinguals showed larger interference effects (72 ms, *SE* = 7 ms) than bilinguals (collapsed over language group: 46 ms, *SE* = 5 ms). To investigate this effect further, the monolinguals were compared to each bilingual group individually: at the L1 -200 ms SOA, Arabic bilinguals showed significantly smaller interference effects (25 ms, *SE* = 7 ms) than monolinguals (72 ms, *SE* = 7 ms; $t(32.7) = 4.64$, $p < 0.0001$). The 2-way (group) ANOVA in the 0 ms SOA also showed a main effect of group on the L1 interference effects ($F(1,74) = 11.50$, $p < 0.01$) such that again monolinguals showed larger interference effects (67 ms, *SE* = 13 ms) than bilinguals (31 ms, *SE* = 4 ms). Comparing against each bilingual group, monolinguals showed significantly larger interference effects (67 ms, *SE* = 13 ms), than German (33 ms, *SE* = 7 ms; $t(26.7) = 2.34$, $p < 0.05$), Polish (36 ms, *SE* = 7 ms; $t(26.7) = 2.15$, $p < 0.05$), and Arabic bilinguals (23 ms, *SE* = 9 ms; $t(30.4) = 2.79$, $p < 0.01$).

Figure 6.3: a) Interference effects; b) facilitation effects; and c) average control RTs (collapsed over SOA) for each group and language in the Stroop task (the same monolingual data was compared against each language).

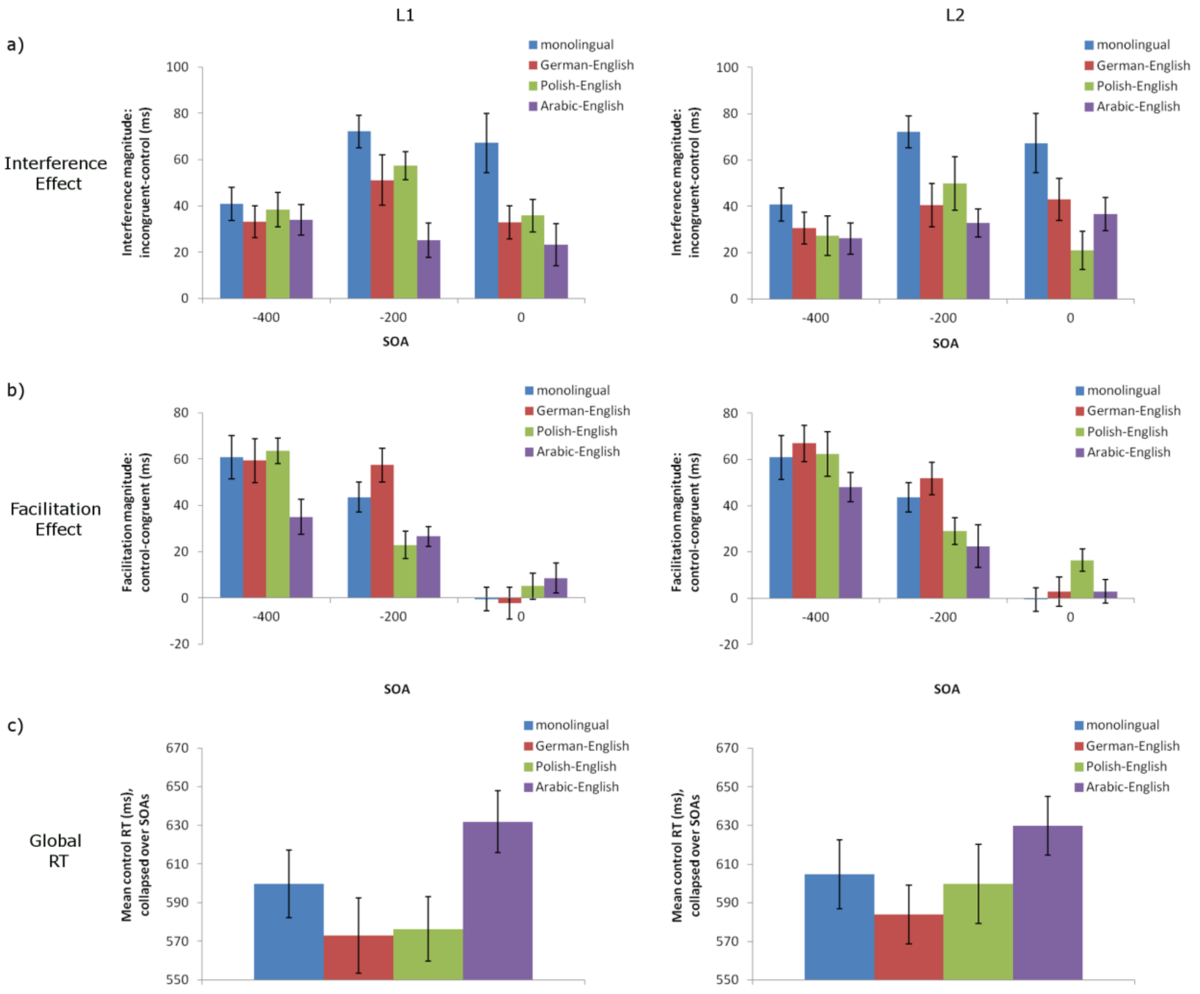


Table 6.5: Results of the 2 (group: monolingual/bilingual) x 2 (SOA) repeated-measures ANOVAs for interference and facilitation effects in the Stroop task (n.s. = not significant, *p* > 0.10).

Effect	**L1/L2**	**Group (monolingual/bilingual)**			**SOA**			**Group x SOA**		
		df	***F*-value**	***p*-value**	***df***	***F*-value**	***p*-value**	***df***	***F*-value**	***p*-value**
Interference	L1	1,222	16.50	<0.0001	2,222	3.97	0.02	2,222	2.63	0.07
	L2	1,222	18.68	<0.0001	2,222	4.15	0.02	2,222	1.23	n.s.
Facilitation	L1	1,222	0.58	n.s.	2,222	57.07	<0.0001	2,222	0.69	n.s.
	L2	1,222	0.01	n.s.	2,222	55.15	<0.0001	2,222	1.06	n.s.

Table 6.6: Results of the 3 (bilingual group: German/Polish/Arabic) x 3 (SOA) ANOVAs for interference and facilitation effects in the Stroop task (n.s. = not significant, *p* > 0.10).

Effect	**L1/L2**	**Bilingual group (German/Polish/Arabic)**			**SOA**			**Bilingual group x SOA**		
		df	***F*-value**	***p*-value**	***df***	***F*-value**	***p*-value**	***df***	***F*-value**	***p*-value**
Interference	L1	2,165	3.46	0.03	2,165	2.89	0.06	4,165	1.03	n.s.
	L2	2,165	0.45	n.s.	2,165	1.97	n.s.	4.165	1.23	n.s.
Facilitation	L1	2,165	3.45	0.03	2,165	43.53	<0.0001	4,165	5.20	<0.001
	L2	2,165	3.70	0.03	2,165	39.48	<0.0001	4,165	1.91	n.s.

The interference effects were next compared within bilinguals with a 3 (language group) x 3 (SOA) ANOVA for each language (Table 6.6, Figure 6.3a). The L1 showed a main effect of language group ($p < 0.05$) and a trend of SOA ($p = 0.06$), but no interaction ($p = 0.40$); there were no main effects or interactions in the L2 (all p's > 0.30). However, the largest Stroop interference effects were expected at the -200 ms SOA, so subtle differences between bilingual groups may have been obscured by evaluating main effects of SOA. Therefore the interference effects were compared between bilingual groups for each language at the -200 ms SOA only. At the -200 ms SOA in the L1, a 3-way (language group) ANOVA (with follow-up independent-sample *t*-tests) showed a significant main effect of language group ($F(2,55) = 4.11$, $p < 0.05$) such that Arabic bilinguals experienced significantly smaller interference effects (25 ms, $SE = 7$ ms) than Polish bilinguals (57 ms, $SE = 6$ ms; $t(33.3) = 3.37$, $p < 0.01$) and marginally smaller interference than German bilinguals (51 ms, $SE = 11$ ms; $t(31.1) = 1.99$, $p = 0.06$). In contrast, the L2 showed no main effect of language group at the -200 ms SOA ($p = 0.46$). Therefore within the bilinguals at the most cognitively-demanding SOA, the Arabic bilinguals showed the smallest interference effects.

Turning to the facilitation effects (Figure 6.3b), the preliminary 2 (group: monolingual/bilingual) x 3 (SOA) ANOVAs (Table 6.5) showed no effects of group in either language (all p's > 0.45); there were significant effects of SOA (all p's < 0.0001), but no interactions (all p's > 0.35), therefore no follow-up analyses were performed. Comparing within bilinguals, the 3 (language group: German, Polish, Arabic) x 3 (SOA) ANOVAs (Table 6.6) showed main effects of language group and SOA in both languages (all p's < 0.05), but an interaction of group and SOA in the L1 only ($p < 0.001$). This interaction was investigated with 3-way (language group) ANOVAs for each SOA. The -400 ms SOA showed a main effect of group ($F(2,55) = 3.96$, $p < 0.05$), such that Arabic bilinguals experienced smaller facilitation effects (35 ms, $SE = 7$ ms) than Polish bilinguals (64 ms, $SE = 5$ ms; $t(30.8) = 3.07$, $p < 0.01$) and marginally smaller facilitation than German bilinguals (59 ms, $SE = 10$ ms; $t(33.0) = 2.01$, $p = 0.05$). The 3-way ANOVA in the -200 ms SOA also showed a main effect of language group on facilitation effects ($F(2,55) = 9.80$, $p < 0.001$), such that German bilinguals showed larger facilitation (57 ms, $SE = 7$ ms) than Polish (23 ms, $SE = 6$ ms; $t(35.8) = 3.68$, $p < 0.001$) and Arabic bilinguals (27 ms, $SE = 4$ ms; $t(28.8) = 3.63$, $p < 0.01$). The 0 ms SOA showed no main effect of language group ($p = 0.49$).

3.1.2. Stroop global RT comparisons

As in previous chapters, the global RT effects (Figure 6.3c) were assessed by comparing the control condition RTs between groups, collapsed over SOA. Analyses first collapsed the bilinguals over language group and performed a 2-way (group: monolingual/bilingual) ANOVA for each language. There was no effect of group in either the L1 or L2 (all p's > 0.70).

The control RTs in bilinguals were next compared using a 3 (language group: German/Polish/Arabic) x 2 (language context: L1/L2) ANOVA. Language context was investigated as a factor in this analysis because global executive processing effects should be independent of language context. There was a main effect of language group ($F(2,110) = 4.61$, $p < 0.05$), but not of language context ($p = 0.41$) and no interaction ($p = 0.77$). Because there was no effect of language context, the bilingual data was collapsed over L1 and L2 and the groups were compared with independent-sample *t*-tests. Arabic bilinguals showed significantly longer control RTs (631 ms, $SE = 15$ ms) compared to German (578 ms, $SE = 17$ ms; $t(69.7) = 3.20$, $p < 0.01$) and Polish bilinguals (588 ms, $SE = 19$ ms; $t(75.7) = 2.52$, $p < 0.05$); German and Polish bilinguals did not differ ($p = 0.60$).

3.2. Simon task

In the Simon data, a 3-way (congruency) ANOVA on the mean RTs (Figure 6.4a) showed a significant main effect of congruency in all groups (German: $F(2,36) = 105.17$, $p < 0.0001$; Polish: $F(2,42) = 90.31$, $p < 0.0001$; Arabic: $F(2,32) = 29.46$, $p < 0.0001$; monolinguals: $F(2,34) = 56.27$, $p < 0.0001$). Significant interference effects (all p's < 0.0001) and significant facilitation effects (all p's < 0.0001) occurred for all groups except Arabic bilinguals in facilitation ($p = 0.06$; Table 6.7).

Table 6.7: Statistical comparisons of interference and facilitation effects for each group in the Simon task.

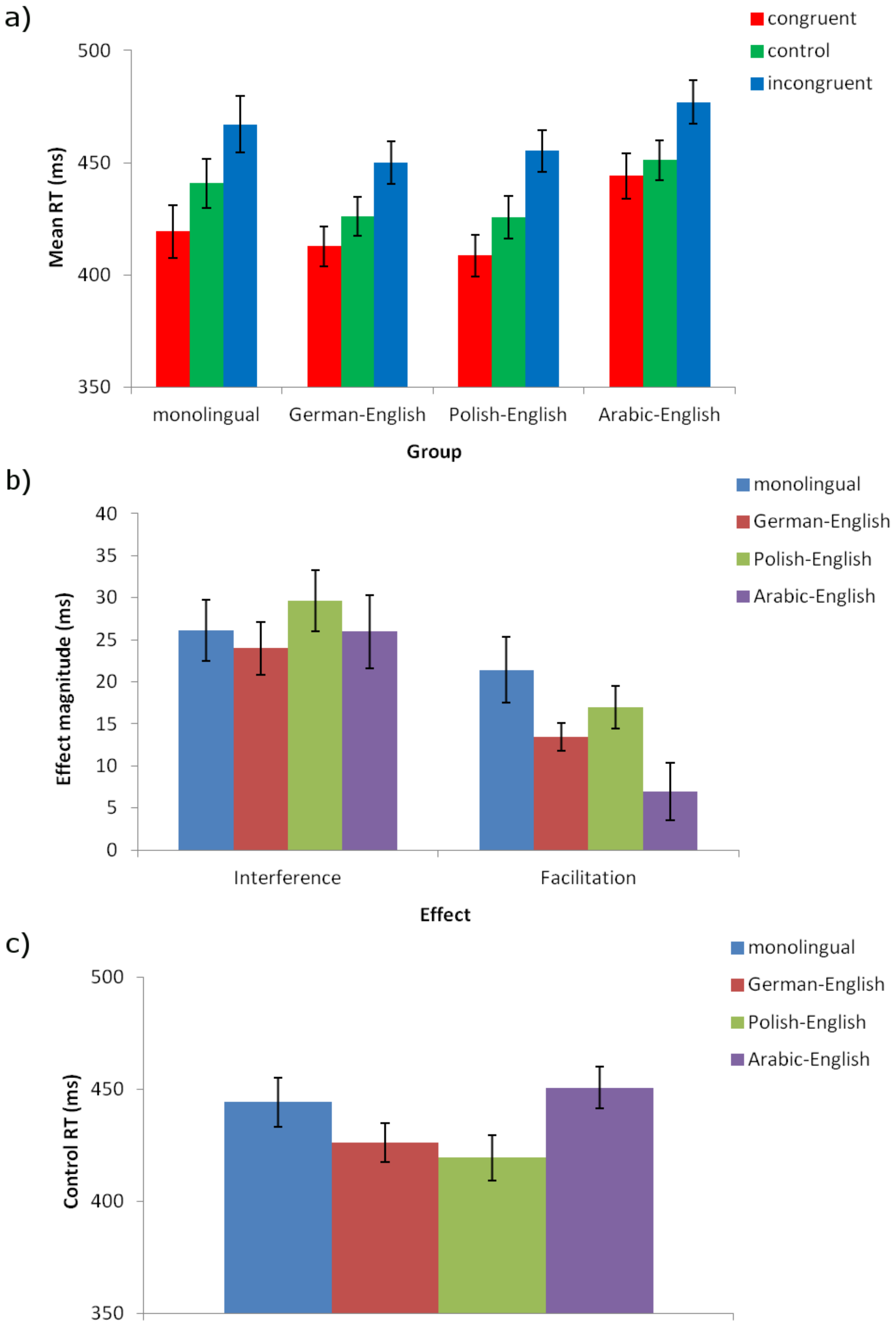
Group	**Interference**			**Facilitation**		
	***t*-value**	***df***	***p*-value**	***t*-value**	***df***	***p*-value**
German-English	7.59	18	<0.0001	8.15	18	<0.0001
Polish-English	8.09	21	<0.0001	6.77	21	<0.0001
Arabic-English	5.95	16	<0.0001	2.05	16	0.06
Monolinguals	7.26	17	<0.0001	5.44	17	<0.0001

To compare interference and facilitation magnitudes in the Simon task (Figure 6.4b) between groups, a 2-way (group: monolingual/bilingual) ANOVA was first performed to compare monolinguals and bilinguals. The interference magnitudes showed no effect of group ($p = 0.90$). However, in the facilitation effects there was a main effect ($F(1,74) = 5.84$, $p < 0.05$) such that monolinguals experienced larger facilitation effects (21 ms, $SE = 4$ ms) than bilinguals (13 ms, $SE = 5$ ms). To further investigate this group effect, monolinguals were compared against each of the bilingual groups using independent-sample *t*-tests. Monolinguals showed marginally larger facilitation effects (21 ms, $SE = 4$ ms) than German bilinguals (13 ms, $SE = 2$ ms; $t(22.8) = 1.88$, $p = 0.07$) and significantly larger effects than Arabic bilinguals (7 ms, $SE = 3$ ms; $t(32.6) = 2.77$, $p < 0.01$).

Next, Simon interference and facilitation magnitudes were compared between bilinguals using a 3-way (language group: German/Polish/Arabic) ANOVA. There was no main effect of language group on interference effects (all $p = 0.54$), but facilitation effects showed a main effect ($F(2,55) = 3.77$, $p < 0.05$) such that Polish bilinguals showed significantly larger facilitation (17 ms, *SE* = 3 ms) than Arabic bilinguals (7 ms, *SE* = 3 ms; *t*(31.0) = 2.35, $p < 0.05$).

Finally, for the Simon global RT analyses, performed on the control RTs (Figure 6.4c), a 2-way (group: monolingual/bilingual) ANOVA showed no effect of group (*F*(2,55) = 2.41, $p = 0.51$). However, the 3-way (language group: German, Polish, Arabic) ANOVA showed a weak trend of an effect of language group (*F*(2,55) = 2.41, $p = 0.10$). There were trends of longer RTs for Arabic bilinguals (451 ms, *SE* = 9 ms) compared to both German (426 ms, *SE* = 9 ms; *t*(33.8) = 2.02, $p = 0.05$) and Polish bilinguals (426 ms, *SE* = 9 ms; *t*(36.8) = 1.98, $p = 0.05$). As these effects were trends they should be interpreted cautiously; however, overall Arabic bilinguals experienced longer global RTs.

Figure 6.4: Simon task data: a) Mean RTs for each group and congruency; b) Interference and facilitation effects; c) Global RT effects (control condition RTs).



4. Discussion

The current study investigated bilingual cognitive control with specific regards to the effects of script similarity. Two hypotheses were proposed regarding the potential patterns of results. Hypothesis 1, based on the findings of previous research investigating script differences in cognitive control, predicted superior executive control (i.e. smaller interference and/or global RT effects) with decreasing language similarity, whereas Hypothesis 2 predicted superior control abilities with increasing language similarity. To investigate these effects, bilinguals of three native languages with varying script similarity to English (German, Polish, and Arabic) performed a Stroop task with negative SOAs and a non-linguistic Simon task. The groups were compared on the magnitude of interference and control condition RTs to evaluate the BICA and BEPA hypotheses, respectively.

In the Stroop task, a bilingual interference advantage was observed in the L1: monolinguals showed larger interference effects than bilinguals at the most cognitively-demanding -200 ms and 0 ms SOAs, which supports the BICA hypothesis. When comparing between bilingual groups, Arabic-English bilinguals experienced the smallest Stroop interference effects in the L1, which suggests enhanced cognitive control for different-script bilinguals and supports Hypothesis 1. In contrast, no differences in Simon interference effects occurred between any groups, contradictory to the BICA predictions and to previous studies reporting a bilingual advantage on this task (Bialystok, 2006; Bialystok et al., 2004, 2008; Bialystok, Martin, et al., 2005; Martin-Rhee & Bialystok, 2008).

In the global RT effects, there were no differences in control RTs between monolinguals and any of the bilingual groups on either the Stroop or Simon task. However, when comparing global RTs among the bilingual groups, in both tasks Arabic-English bilinguals showed slower RTs overall compared to German- and Polish-English bilinguals. This pattern suggests that different-script bilinguals have poorer executive processing abilities than same-script bilinguals, as predicted by Hypothesis 2.

Taken together, this data therefore revealed discordant results: the Stroop interference effects suggested enhanced cognitive control for Arabic-English bilinguals, as predicted by Hypothesis 1, whereas the global RT patterns for both tasks suggested the poorest cognitive control for Arabic-English bilinguals, as predicted by Hypothesis 2. These contradictory results most likely occurred because the Stroop interference effects were driven by script similarity. In a Stroop task, bilinguals must resolve not just the semantic and response conflict between the word and the colour, but also the additional cross-linguistic conflict that arises from reading the word. (As the Simon task is non-linguistic and does not require explicit language processing, cross-linguistic effects should be minimal.) As this cross-linguistic interference was stronger in same-script bilinguals, they experienced larger interference effects compared to different-script bilinguals. This pattern replicates previous literature on the bilingual Stroop task, reviewed in Chapter 2 (section 2; Brauer, 1998; van Heuven et al., 2011).

Interestingly, the significant group effects in the Stroop task all emerged in the L1, in which different orthographies were compared; no differences occurred in the L2, which was performed in English for all groups (although similar patterns were elicited, as can be seen in Figure 6.3). In word reading, theoretically the amount of cross-linguistic activation should be similar regardless of whether the input is in the L1 or L2. The different amounts of interference may therefore suggest an effect of proficiency. Specifically, because the L1 was the stronger language it may have generated stronger Stroop conflict, whereas the L2 may have experienced reduced interference due to weaker language ties and slower lexical access (see Chapter 2, section 2.1, and Chapter 9, section 2.2.1). The smaller interference effects in the L2 for all bilinguals could have consequently eliminated the significant group differences.

In sum, the interference magnitudes in the Stroop task supported previous research regarding the effects of script in the Stroop task (Brauer, 1998; van Heuven et al., 2011), but confounded interpretations of executive control abilities between bilingual groups. For this reason, the Simon task was included to assess bilingual cognitive abilities using a non-linguistic comparison of executive control. Although Simon interference effect magnitudes did not differ between groups, there were differences in Simon facilitation: all bilinguals showed generally smaller effects than monolinguals, with the largest reduction in facilitation for the Arabic bilinguals. As mentioned in Chapter 2 (section 3.5.2), some researchers have suggested that poorer cognitive control generates not only larger interference effects, but also larger facilitation effects (e.g. Zelazo et al., 2004), which in this case would suggest superior cognitive control for different-script bilinguals, supporting Hypothesis 1. However, as can be seen in Figure 6.4, the smaller facilitation effects in Arabic bilinguals resulted from the overall longer RTs in all conditions, suggesting that facilitation effects were mediated by these differences in processing speed (see Chapter 9 section 3.4.1 for further discussion of facilitation effects).

Corroborating this, global RT comparisons demonstrated longer control RTs in both the Stroop and the Simon task for Arabic-English bilinguals compared to German-English and Polish-English bilinguals. This suggests that different-script bilinguals have poorer executive processing abilities than same-script bilinguals, as predicted by Hypothesis 2. Importantly, these global RT patterns were consistent across both the Stroop and Simon tasks, although the effects were only statistical trends in the Simon data: this may have occurred because the overall Simon RTs were faster for all groups due to the simpler nature of the Simon task. Furthermore, these consistent patterns occurred in the absence of linguistic stimuli or conflicting/facilitating information, indicating that these effects were not driven by explicit orthographic differences between the languages (as in the Stroop interference effects), but arose as a result of cross-linguistic overlap. More work is needed to replicate these patterns; nevertheless, it is concluded that different-script bilinguals experience poorer cognitive control due to the reduced cross-linguistic activation from their languages.

This conclusion contradicts the findings of Bialystok, Craik, et al. (2005) and Linck et al. (2008), who reported superior cognitive control in different-script bilinguals. However, as mentioned, Bialystok et al. (2005) did not interpret this effect beyond attributing it to variations in sampling size. Linck et al. (2008) ascribed this pattern to differences in language-switching frequency, although they had initially predicted that same-script bilinguals would experience superior cognitive control, as concluded here. One reason for these disparate results may be differences in writing systems between the bilingual groups. Bialystok et al. (2005) contrasted Cantonese-English bilinguals (a logographic and alphabetic writing system, respectively) with French-English bilinguals (both alphabetic); similarly, Linck et al. (2008) contrasted Japanese-English bilinguals (Japanese contains scripts in both logographic and syllabic writing systems) with Spanish-English bilinguals (both alphabetic). It may be that logographic writing systems confer unique effects on executive control abilities. This could explain the inconsistent effects between the previous literature, which included logographic languages, and the current data, in which all were alphabetic languages. Similarly, note that no differences in interference or global RT effects occurred between German and Polish bilinguals in the global RT advantages, despite the larger overlap of German and English compared to Polish and English. This could indicate that the specific writing system that a language belongs to is the more influential factor in cross-linguistic influences: because Polish and English are both alphabetic writing systems, they may create similar cross-linguistic effects as German and English. Other linguistic factors, such as orthographic depth and the visuospatial properties of script (e.g. Arabic is read right-to-left), may have also affected linguistic access and cross-language activation (Bar-Kochva, 2011; Taha, Ibrahim, & Khateb, 2012; see Chapter 3 section 6.3 and Chapter 9 section 3.6 for further discussion of script effects). As this is the first study to systematically manipulate script overlap, more research investigating these patterns, especially the role of writing system, is warranted.

Overall, this data suggested that script similarity does affect bilingual cognitive control abilities, with bilinguals of similar languages experiencing an additional benefit in executive control. Importantly, this conclusion was based on global RT effects, indicating that larger script overlap does not benefit just inhibitory control abilities but confers a more general executive processing advantage. These findings hold important implications for research investigating the bilingual advantage, as combining same-script and different-script bilinguals within the same participant sample could obscure significant effects. Alternatively, these results suggest that bilingual cognitive control abilities could be maximized by testing bilinguals of similar scripts. Significant bilingual advantages have been reported for language pairs of varying similarity, such as Chinese-English (Bialystok, 1999; Kuo & Anderson, 2012), Spanish-Catalan (Costa et al., 2009, 2008; Garbin et al., 2010), and French-English (Poulin-Dubois et al., 2011) although, as documented in section 1.1.1, studies testing these populations have also found evidence against an advantage (e.g. Kousaie & Phillips, 2011). Thus although bilingual advantages may still be seen in different-script bilinguals, the evidence that script modulates cognitive control abilities warrants a more thorough consideration of this factor in bilingualism research.

5. Conclusions

In summary, the current data demonstrated significant effects of script on both Stroop interference effects and on domain-general cognitive control abilities, suggesting that individual differences, such as the similarity of a bilingual’s languages, can affect executive control abilities. The chapters presented thus far have demonstrated significant evidence that bilinguals experience enhanced executive control compared to monolinguals. However, the neural mechanism(s) underlying these effects remain unclear. Neuroimaging methods with precise spatial resolution, such as fMRI, may illuminate how monolinguals and bilinguals differ in executive processing performance. The next two chapters switch to the fMRI method to investigate the neural signatures of the bilingual advantage.

Chapter 7: Neural Effects of Stroop SOA Manipulation on Executive Control: an fMRI Study in Monolinguals

The previous chapters, using behavioural and electrophysiological methods, have yielded valuable information about how SOA manipulation in an SOA Stroop task modulates the magnitude and timecourse of conflict effects. However, these methodologies provide limited information about the underlying neural mechanisms at play. This chapter moves away from the question of lexical access speed and the timing of cognitive processing, employing fMRI to specify the neural underpinnings of SOA effects in a Stroop task. This paradigm has never before been performed with fMRI, so the study reported in this chapter tested monolinguals first to establish the impact of SOA manipulation on the neural mechanisms of executive control. The next chapter, which directly compares cognitive control in monolinguals and bilinguals using fMRI, originally intended to use this same paradigm in bilinguals; however, the task was changed during paradigm development, as will be explained. The current chapter therefore deviates slightly from the theme of this thesis, exploring the SOA Stroop task with fMRI only in monolinguals, but nevertheless provides important insight into the neural effects of SOA manipulation.

1. Introduction

1.1. The executive control network in the brain

As discussed in Chapter 1 (section 3.2.1), the executive control system consists of a network of regions across the prefrontal and parietal cortices that participate in a range of cognitive functions. To review the specific areas that will be of interest for this chapter, the rostral cingulate zone (RCZ; located along the borders of BAs 6, 8, 32 and 24 in the medial frontal cortex) is involved in performance monitoring (Ridderinkhof, Ullsperger et al., 2004; see Figure 1.11 in Chapter 1). A subset of this region, the anterior cingulate cortex (ACC: Brodmann areas (BAs) 24/32), is thought to perform conflict monitoring, whereas middle and inferior frontal gyri including the dorsolateral prefrontal cortex (DLPFC; BAs 9/46) are involved in conflict resolution (Botvinick et al., 2001, 2004; van Veen & Carter, 2002). The left inferior frontal gyrus (LIFG) is believed to implement cognitive control via suppression of irrelevant semantic information (Novick et al., 2005, 2009; Thompson-Schill, Kurtz, & Gabrieli, 1998; Ye & Zhou, 2009), while the right inferior frontal gyrus (RIFG) is involved in inhibitory control, specifically response inhibition (Aron, Robbins, & Poldrack, 2004; Garavan, Ross, & Stein, 1999; Hampshire, Chamberlain, & Monti, 2010; Levy & Wagner, 2011). The inferior (BAs 39/40) and superior (BA 7) parietal lobes perform top-down visuospatial control of attention towards the task-relevant target or attribute (Corbetta et al., 1993; Culham & Kanwisher, 2001; Milham et al., 2003; Rushworth et al., 2001). Other areas of the prefrontal cortex such as the premotor (BA 6) and frontopolar (BA 10) cortices are also involved in cognitive control, as are subcortical structures like the thalamus and caudate (e.g.

Ridderinkhof, Ullsperger, et al., 2004; Ridderinkhof, van den Wildenberg, Segalowitz, & Carter, 2004; Seeley et al., 2007; see Nee et al., 2007 and Niendam et al., 2012 for meta-analyses).

These areas are reliably activated for a spectrum of executive control functions, including working memory, cognitive flexibility, vigilance or sustained attention, and – importantly for this study – inhibition of prepotent behaviours and the management of cognitive conflict (Niendam et al., 2012). The activation and recruitment of this executive control system is also affected by various task parameters, such as the context, magnitude, and nature of cognitive conflict (e.g. Barch, Braver, Sabb, & Noll, 2000; Carter et al., 2000; Milham et al., 2003; van Heuven et al., 2008). This malleability of the executive control network highlights its dynamic, moment-to-moment recruitment of different conflict processing strategies. The current study specifically explored how this network is modulated by SOA manipulation in the Stroop task.

1.2. The SOA Stroop task in the brain

The Stroop task recruits the canonical executive control network, generating stronger activation in these areas for incongruent trials than congruent or control trials (e.g. Fan, Flombaum et al., 2003; Liu et al., 2004; Nee et al., 2007; Peterson et al., 1999, 2002). Many variations of the Stroop task have been employed with fMRI to investigate the precise function of executive control structures (e.g. Barch et al., 2001; Kim et al., 2010; Milham et al., 2003). However, the current study was the first to explore the effects of Stroop SOA manipulation (specifically negative SOAs: -400 ms, -200 ms, and 0 ms) on the activation and recruitment of the executive control network in the brain. Based on prior research, this study addressed three specific cognitive aspects of SOA manipulation.

1.2.1. SOA modulation of neural interference and facilitation effects

First, the current chapter explored how the executive control network in the brain is modulated by conflict and facilitation effects in each SOA. Behaviourally, each SOA generates different magnitudes of interference and facilitation, with maximal interference at simultaneous presentation or short word pre-exposure (i.e. 0 ms or -200 ms) and increasing facilitation with longer word pre-exposure (Chapters 3 and 6; (Appelbaum, Meyerhoff, et al., 2009; Glaser & Glaser, 1982). Furthermore, the N_{inc} and LPC ERP components are sensitive to conflict across a variety of task designs and conflict demands (Appelbaum et al., 2012; Appelbaum, Meyerhoff et al., 2009; Chapter 5). This modulation of conflict and facilitation effects suggests the participation of different cognitive control mechanisms for each SOA. The primary aim of the current study was therefore to explore how these ‘trial-specific’ effects of SOA affected the activation of the executive control network.

Overall, typical executive control areas of the prefrontal cortex were expected to be elicited by incongruency in the 0 ms SOA (as this was analogous to a traditional Stroop task), such as the RCZ, left middle/medial frontal gyrus (LMFG), and LIFG (e.g. Botvinick et al., 2001;

Niendam et al., 2012; Ridderinkhof, Ullsperger, et al., 2004; Ridderinkhof, van den Wildenberg, et al., 2004; Seeley et al., 2007; Ye & Zhou, 2009), as well as parietal regions such as the left angular gyrus (Bunge, Hazeltine et al., 2002; Fan, Flombaum, et al., 2003; Schroeder et al., 2002; Ye & Zhou, 2009) and the inferior/superior parietal lobe (Corbetta et al., 1993; Culham & Kanwisher, 2001; Milham et al., 2003; Rushworth et al., 2001). Activation in these areas was also expected for the -400 ms and -200 ms SOAs, although with potentially different extents and/or strengths of activation compared to the 0 ms SOA. For example, the executive control network has demonstrated stronger activation in the presence of more conflict (e.g. Barch et al., 2000), so increased behavioural interference in the -200 ms SOA may be reflected in stronger neural recruitment of these areas.

1.2.2. Response priming effects in negative SOAs

The second topic addressed in the current study regarded the effects of response priming in negative SOAs. Appelbaum, Meyerhoff et al. (2009) have proposed that in negative SOAs, word pre-exposure creates a priming effect by pre-activating response selection. In congruent conditions this accelerates processing time because the subsequently-presented colour matches the pre-activated information, leading to larger behavioural facilitation effects. In contrast, incongruent conditions require more conflict control to overcome or inhibit the primed response, increasing behavioural RTs and interference effects. Increased interference and facilitation effects have been previously documented at the -200 ms SOA, in line with this proposal of response priming effects (Chapter 3 and 6; Appelbaum, Meyerhoff et al., 2009). The current study sought to establish the neural correlates of response priming effects in negative SOAs.

Response priming effects were expected in executive control areas linked to response preparation, such as the DLPFC (Badre & Wagner, 2004) or supplementary and cingulate motor areas (Cunnington, Windischberger, Deecke, & Moser, 2003). This activation was predicted to be stronger in the -200 ms SOA, and potentially also -400 ms SOA, compared to the 0 ms SOA. Furthermore, if the increased behavioural interference in the -200 ms SOA arises from the need to overcome the primed response in incongruent conditions, evidence of response priming may also be observed in areas linked to response inhibition, such as the RIFG (Aron et al., 2004; Garavan et al., 1999; Hampshire et al., 2010; Levy & Wagner, 2011).

1.2.3. Effects of blocked SOAs on strategic orientation of attention

Finally, the third aspect of SOA manipulation investigated in this chapter concerned the effects of blocked SOA presentation. As reviewed in Chapter 2 (section 3.3), Appelbaum et al. (2012) have observed different patterns of interference for blocked and mixed SOA presentation. Specifically, temporally-predictable SOAs, as in blocked presentations, may lead to a strategic orientation of attention which could modulate the amount of conflict experienced. In their EEG data, Appelbaum et al. (2012) demonstrated that although the N_{inc} tracked the onset of conflict across SOA manipulation, a larger N_{inc} component occurred in the 0 ms SOA when SOAs were blocked, whereas when SOAs were randomized a larger N_{inc} occurred in the -200 ms SOA. In blocks of negative SOAs, the pre-exposed word may have acted as an alerting cue for the upcoming target information, prompting participants to use this cue to strategically orient their attention towards the target stimulus. In contrast, in the 0 ms SOA this strategy could not be used, leading to larger interference effects. Therefore Appelbaum et al. (2012) proposed that the temporal predictability of blocked SOAs encourages an attentional orientation strategy. On the other hand, Roelofs (2010a) has also investigated this issue of blocked versus mixed SOA presentation using a behavioural paradigm and reported that, although overall RTs were affected, no difference in interference patterns occurred between SOA presentation methods. This argues against such a temporal predictability effect, but it may be that the electrophysiological technique used in Appelbaum et al. (2012) was more sensitive to strategic attentional effects. The current study sought to establish the underlying neural effects of strategic orientation resulting from blocked SOA presentation.

If blocked SOA presentation engages strategic attentional processes, such block-wide SOA effects should be observable in all congruency conditions. The current study investigated these ‘global’ (i.e. block-wide and conflict-independent) effects of strategic attentional control by first collapsing over congruencies and comparing SOAs, as well as comparing congruency conditions across SOAs (e.g. -400 ms control vs. 0 ms control). Global SOA effects on attentional orientation were expected in areas involved in top-down attentional control such as the right parietal lobe, specifically the angular gyrus (BA 40) and superior parietal lobe (BA 7; Corbetta et al., 1993; Culham & Kanwisher, 2001; Milham et al., 2003; Rushworth et al., 2001). Specifically, if subjects use the pre-exposed word in negative SOAs as a temporal cue, activation in these attentional control areas should be enhanced in the -200 ms and -400 ms SOAs compared to the 0 ms SOA.

In summary, the current study employed a Stroop task with negative SOA modulation in fMRI to explore how SOA affects the recruitment and performance of the executive control network.[17] Of specific interest were 1) the effects of SOA on Stroop, interference, and facilitation effects in the brain; 2) response priming effects in negative SOAs; and 3) strategic orientation of attention with blocked SOA presentation.

2. Methods

2.1. Participants

Fourteen right-handed participants (10 males) with no history of neurological disorder, no colour-blindness, and normal or corrected-to-normal vision, were recruited from the University of Nottingham community. Their mean age was 25 years (*SD* = 4.2) and all were

---

[17] In addition to the Stroop task, a flanker task (without SOA manipulation) was also performed; however, this is not reported here due to space restrictions.

native English speakers. Although some (*n* = 10) had learned other languages, none considered themselves fluent in anything but English (average self-reported proficiency in other languages = 2.5, *SD* = 1.2).

2.2. Materials and Design

The design was identical to the English Stroop task of Chapter 6. Participants responded to the colour of the rectangle by pressing a button on an MRI-compatible button box (right index finger for red, right middle finger for green, right ring finger for blue).

2.3. Procedure

All participants gave informed written consent according to the ethics guidelines of the University of Nottingham Medical Ethics Committee. All subjects completed a safety screening questionnaire ensuring their eligibility for MRI. Participants were offered an inconvenience allowance for their participation. The scanning session was approximately 1 hour including set-up, structural image acquisition, and experimental testing. Stimuli were presented using E-Prime. The experimental session consisted of four runs (one for each SOA, with an additional flanker task) of approximately 7 minutes each. Task order (Stroop or flanker) was counterbalanced between participants. SOAs were blocked and their order of presentation was also counterbalanced. Within each task block, conditions were presented in an event-related fashion.

The procedure was similar to that of Chapter 6. Three SOAs were used (-400 ms, -200 ms, 0 ms), each consisting of 120 trials (30 each of congruent, control, incongruent and null-event trials). In null-event trials, a non-bold fixation cross remained on the screen for 750 ms. Each trial was followed by an ISI fixation screen with a non-bold fixation cross, varying from 1500-2900 ms in 200-ms intervals (average 2200 ms). The trial order was pseudo-randomly presented such that each trial type (congruent, control, incongruent) was followed equally often by a null-event trial and there were no occurrences of the same trial type occurring more than twice in a row throughout a block.

2.4. fMRI scan procedure and pre-processing

Structural and functional MRI scans were acquired using a Philips Achieva 3.0 Tesla scanner at the Sir Peter Mansfield Magnetic Resonance Centre at the University of Nottingham. A sagittal T1-weighted volumetric sequence (TR 7600 ms, TE 2.3 ms, flip angle 8 degrees, NSA 1.0, FOV 256 mm, 256 x 256 matrix, 1.0 mm slice thickness, no gap, 184 slices) was acquired as a structural reference scan. fMRI was collected using gradient-echo EPI BOLD (echoplanar blood oxygenation level dependent) pulse sequences (TR 2500 ms, TE 40 ms, flip angle 90 degrees, 1 NSA, SENSE factor 2.3, resolution 3 x 3 x 3 mm, 38 slices of 3mm thickness, no gap, FOV 240 mm, matrix size 80 x 80).

All pre-processing and data analyses were performed using SPM8 (Wellcome Trust Centre for Neuroimaging, “Statistical Parametrical Mapping, SPM8”, http://www.fil.ion.ucl.ac.uk/spm/). For each subject, functional images were spatially realigned to the first volume of the first run to account for motion during the scan. The anatomical scan was then co-registered to a mean EPI image of the realigned functional scans. The original anatomical scan was segmented using DARTEL (Ashburner, 2007) into grey matter (GM), white matter (WM) and cerebro-spinal fluid (CSF) in order to create a template of transformation parameters for normalizing the anatomical image to an MNI template brain. Functional and structural images were then normalized using these parameters. The normalized functional images were spatially smoothed using an 8 mm FWHM isotropic Gaussian kernel.

2.5. fMRI analyses

Vectors of stimuli onsets were created for each trial type; onsets were defined as the onset time of the first stimulus presented (i.e. in negative Stroop SOAs, onset of the word stimulus). Behavioural errors and outliers were included as additional conditions in the model specification. Six realignment parameters from the realignment step of pre-processing were also included as covariates. The stimuli onset vectors were convolved using a canonical HRF plus the temporal derivative. Statistical analyses based on general linear modelling (GLM) were then performed by multiple linear regression of the signal time course in each voxel. The three Stroop runs (0 ms, -200 ms, and -400 ms SOAs) were modelled together in the same design matrix. Three directional contrasts of interest were performed for each SOA (Stroop: incongruent > congruent; interference: incongruent > control; facilitation: congruent > control[18]). Percent signal change was calculated using Marsbar (Brett, Anton, Valabregue, & Poline, 2002) and significant regions were labelled using the WFU PickAtlas package (Maldjian, Laurienti, Kraft, & Burdette, 2003). In identifying significant areas of activation in all analyses, an uncorrected *p*-value of $p < 0.001$ for the height (intensity) threshold of each activated voxel was used, with an extent threshold (cluster size) of 30 voxels.

3. Results

3.1. Behavioural data

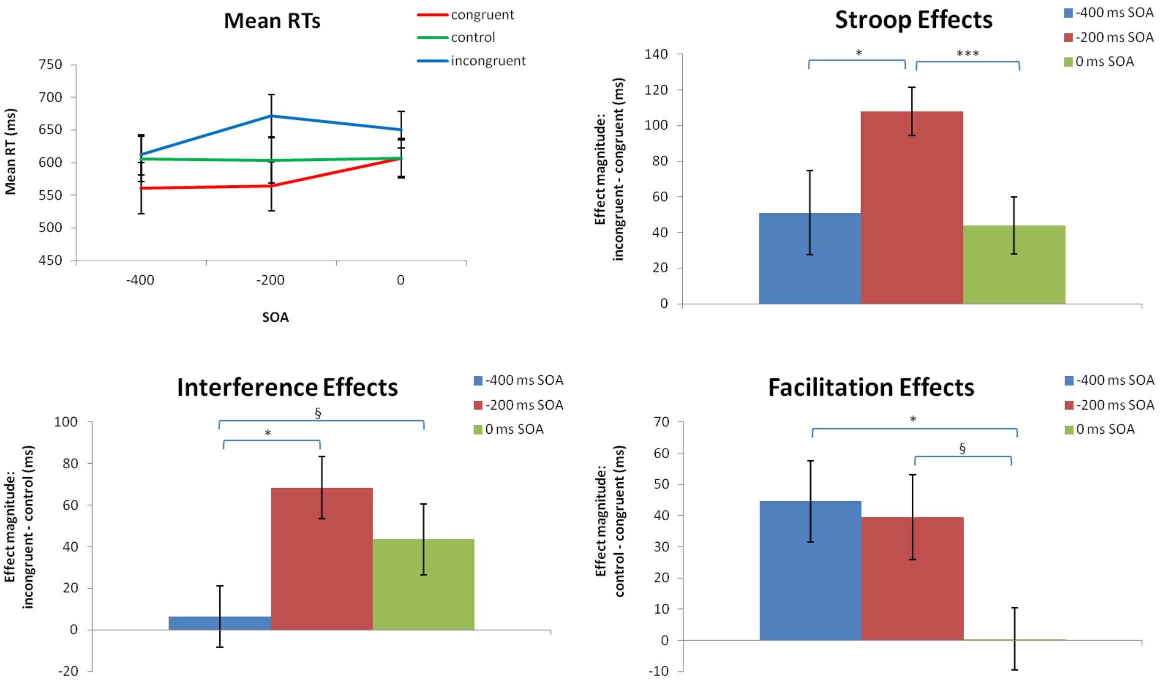
Incorrect responses (5.9%) and outliers (RTs of less than 250 or greater than 2000 ms: 0.3%) were removed before analyses. The mean RTs and magnitudes of Stroop, interference, and facilitation effects are presented in Figure 7.1. (As in Chapter 5, Stroop effects are reported

---

[18] In behavioural RT analyses, facilitation effects were calculated as control minus congruent, as is typical. However, in neuroimaging data a Stroop congruent condition generates brain activation associated with linguistic processing, but the control condition, which lacks linguistic information, should elicit relatively less activation. Facilitation effects in the neural data were therefore examined using a congruent > control contrast.

here because the corresponding effects are investigated in the neuroimaging data.) A 3 (congruency) x 3 (SOA) ANOVA showed a main effect of congruency ($F(2,26) = 20.27$, $p < 0.0001$) but not of SOA ($F(2,26) = 1.75$, $p = 0.19$), and an interaction ($F(4,52) = 4.86$, $p < 0.01$). To investigate this interaction, paired-sample *t*-tests were performed between congruencies. Significant Stroop effects occurred in the -400 ms ($t(13) = 2.17$, $p < 0.05$), -200 ms ($t(13) = 8.06$, $p < 0.0001$) and 0 ms SOAs ($t(13) = 2.76$, $p < 0.05$). Significant interference occurred in the -200 ms ($t(13) = 4.60$, $p < 0.001$) and 0 ms SOAs ($t(13) = 2.56$, $p < 0.05$) and significant facilitation in the -400 ms ($t(13) = 3.42$, $p < 0.01$) and -200 ms SOAs ($t(13) = 2.91$, $p < 0.05$). The -200 ms SOA generated the largest Stroop (108 ms, *SE* = 13 ms; Figure 7.1b) and interference (68 ms, *SE* = 15; Figure 7.1c) effects. The largest facilitation occurred at the -400 ms SOA (45 ms, *SE* = 13 ms) followed closely by the -200 ms SOA (39 ms, *SE* = 14 ms; Figure 7.1d).

Figure 7.1: a) Mean RTs for each congruency and SOA; b) Stroop; c) interference; and d) facilitation effects, with significant differences between SOAs, as determined by paired-sample *t*-tests, indicated with asterisks (§ = trend, $p < 0.1$; * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$).



3.2. fMRI data

3.2.1. Trial-specific effects of SOA

As outlined in the Introduction (section 1.2.1), this study first investigated how SOA affected the neural representations of conflict and facilitation effects. Before comparing SOAs to address this question, the contrasts of interest (Stroop, interference, and facilitation) were investigated for each SOA individually using one-sample *t*-tests (Table 7.1).

3.2.1.1. Stroop 0 ms SOA

In the 0 ms SOA (shown in red in Figures 7.2, 7.3, and 7.4), the Stroop contrast revealed activation in areas of the prefrontal and parietal cortices such as the LMFG (BAs 6/10), bilateral superior parietal lobes/angular gyri (BAs 7/40), LIFG (BA 46), posterior cingulate (BA 23) and ACC/RCZ (BAs 6/8/32), as well as subcortical activation in the left thalamus and right caudate nucleus (Table 7.1 and Figure 7.2). Similar areas were activated in the interference contrast (Figure 7.3): the bilateral superior parietal lobes/angular gyri (BA 40), LMFG (BAs 6/9), LIFG (BA 46), left ACC/RCZ (BA 8/32), and right caudate. The facilitation contrast (Figure 7.4) showed no significant areas of activation for the 0 ms SOA.

3.2.1.2. Stroop -200 ms SOA

In the -200 ms SOA (shown in green in Figures 7.2, 7.3, and 7.4), the Stroop contrast revealed activation in similar areas as the 0 ms SOA, although the extent of activation was notably smaller: the bilateral insula/IFG (BAs 13/47), LIFG/LMFG (BAs 44/6/9), and the ACC/RCZ (BAs 6/32; Table 7.1 and Figure 7.2). In the interference contrast (Figure 7.3), significant clusters of activation were observed in the bilateral IFG (BAs 46/47), LMFG (BAs 8/9), and right superior parietal lobule (BA7). The facilitation contrast (Figure 7.4) showed clusters in the left superior parietal lobe (BAs 7/40) and the LIFG (BA 46).

3.2.1.3. Stroop -400 ms SOA

In the -400 ms SOA (shown in blue in Figures 7.2, 7.3, and 7.4), no clusters survived statistical thresholding in the Stroop or facilitation contrasts (Table 7.1, Figure 7.2 and Figure 7.4). However, the interference contrast (Figure 7.3) revealed one significant cluster of activation in the right IFG (BA 47).

Table 7.1: Main effects of interest (clusters > 30 voxels) for each SOA. Brodmann areas (BA) for the entire cluster are listed; for large clusters that extend into multiple areas, regions/BAs are listed in order of their activation extent. Cluster size reported is number of voxels. Z-score and MNI coordinates are taken from the peak of the cluster.

SOA	**Contrast**	**Region**	**BA(s)**	**MNI coordinates**			**Cluster size**	**Peak Z-score**
				x	**y**	**z**		
0 ms SOA	Stroop effect	L precentral gyrus/postcentral gyrus	6/44	-56	-4	44	613	4.70
		Medial frontal gyrus/ACC/RCZ	6/8/32	4	26	46	209	3.88
		L inferior/superior parietal lobule/angular gyrus	40/7	-34	-50	46	185	4.07
		L angular gyrus/superior parietal lobule	7/19	-36	-72	26	171	4.08
		L middle/inferior frontal gyrus	46/10	-40	38	22	159	4.90
		L supramarginal gyrus	40/22	-58	-36	22	117	4.40
		R superior parietal lobule	7	12	-70	44	90	3.85
		R superior temporal gyrus	13	48	-38	14	60	4.03
		L precentral gyrus/medial frontal gyrus	6	-6	-30	60	54	3.67
		R superior temporal gyrus/supramarginal gyrus	40	66	-40	22	49	4.24
		Posterior cingulate	23	-2	-40	18	48	3.81
		R lateral occipitotemporal gyrus	37	50	-54	-14	47	3.62
		R superior parietal lobule/angular gyrus	40	32	-54	38	45	3.59
		L thalamus	--	-10	-20	12	41	3.68
		R caudate nucleus	--	16	2	10	30	3.73
	Interference	L superior parietal lobule/angular gyrus	40/7	-12	-60	54	1082	4.75
		L middle frontal gyrus	9	-50	18	38	267	4.00
		L middle/inferior frontal gyrus	46	-50	30	16	198	4.12
		L medial frontal gyrus/ACC/RCZ	8/32	-4	28	40	173	4.13
		R precentral/postcentral gyrus	5/6	12	-38	52	100	3.76
		L medial frontal gyrus	6/31	-16	-20	44	83	3.71
		R superior parietal lobule	7	18	-74	46	81	3.67

		L middle frontal gyrus	6	-40	2	52	67	4.11
		L lateral occipitotemporal gyrus	19	-44	-50	-14	66	3.79
		L middle temporal gyrus	39	-56	-62	18	44	3.99
		R caudate nucleus	--	14	6	18	43	4.11
		R angular gyrus	40	58	-46	24	43	3.74
		L middle occipital gyrus	39	-52	-72	22	36	4.55
	Facilitation	No voxels surviving thresholding	--	--	--	--	--	--
-200 ms SOA	Stroop effect	R insula/inferior frontal gyrus	13/47	34	24	6	274	3.77
		L precentral gyrus/inferior frontal gyrus	44/9/6	-44	0	32	126	4.37
		L insula/inferior frontal gyrus	13/47	-30	28	4	74	3.68
		L medial frontal gyrus /ACC/RCZ	32/6	-6	14	48	44	3.94
	Interference	L middle/inferior frontal gyrus	46/9	-48	16	24	126	3.77
		L medial frontal gyrus	8	-8	14	50	63	4.37
		R inferior frontal gyrus	47	50	16	-8	52	3.68
		R superior parietal lobule	7	8	-64	38	32	3.94
	Facilitation	L superior parietal lobule	40/7	-38	-56	40	84	4.82
		L inferior frontal gyrus	46	-42	16	20	30	3.80
-400 ms SOA	Stroop effect	No voxels surviving thresholding	--	--	--	--	--	--
	Interference	R inferior frontal gyrus	47	50	20	-4	98	4.16
	Facilitation	No voxels surviving thresholding	--	--	--	--	--	--

Figure 7.2: Overlaid contrasts for the Stroop comparison (incongruent > congruent) for all SOAs, with clusters of interest labelled. Axial slices are shown from z = -25 to z = 70. In neurological convention, the left hemisphere is presented on the left.

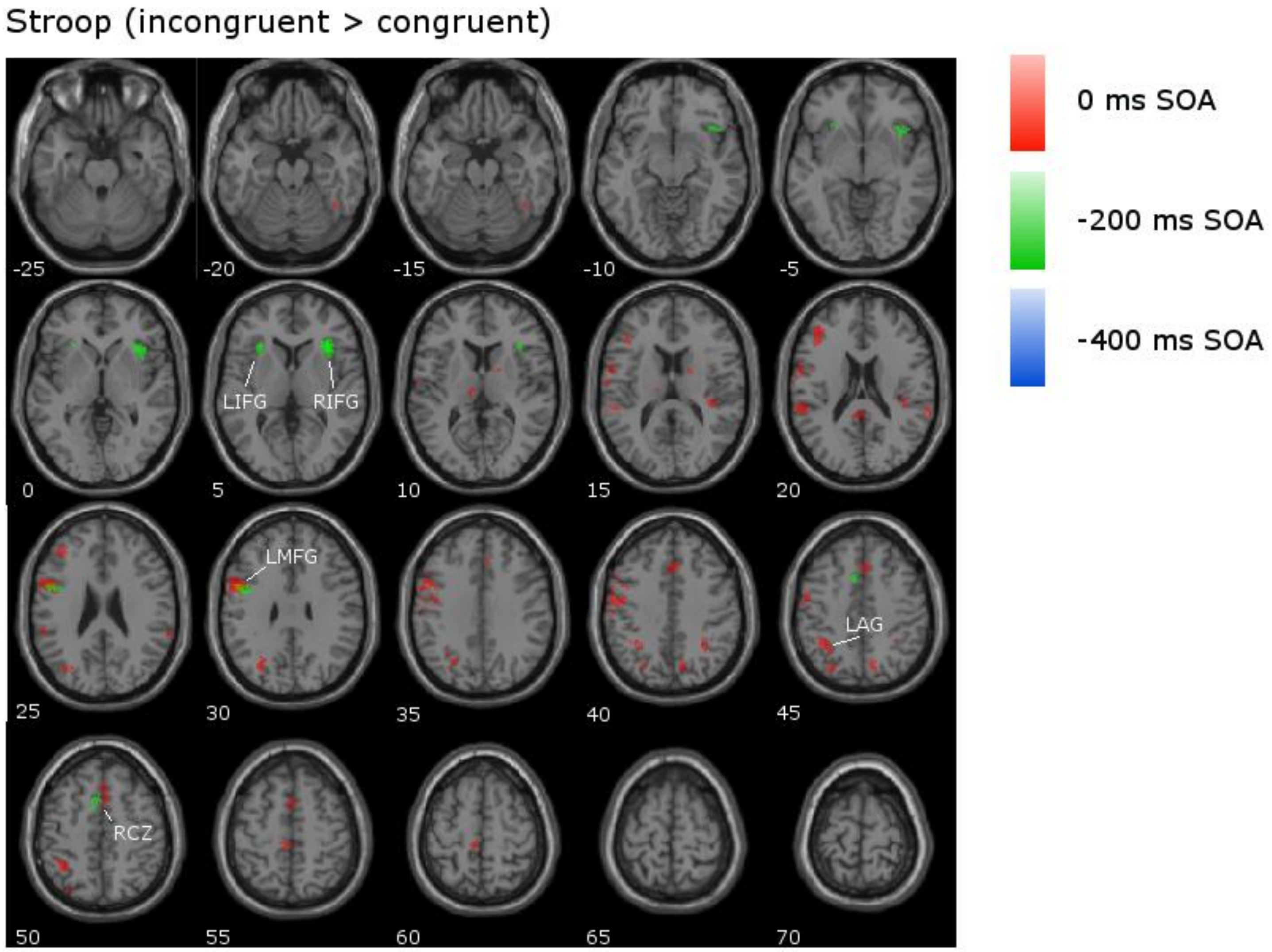


Figure 7.3: Overlaid contrasts for the interference comparison (incongruent > control) for all SOAs, with clusters of interest labelled (LAG = left angular gyrus; RSPL = right superior parietal lobe).

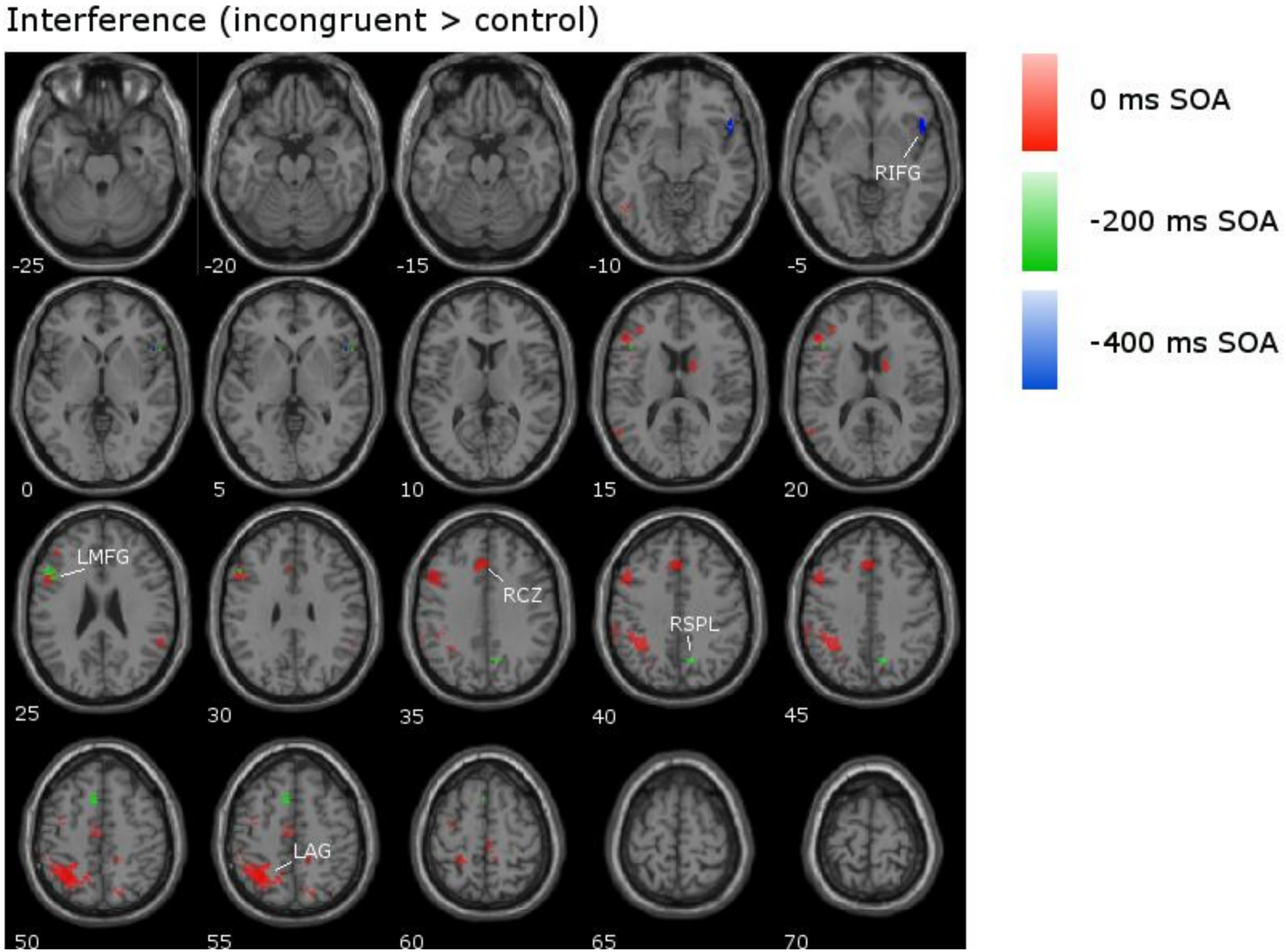
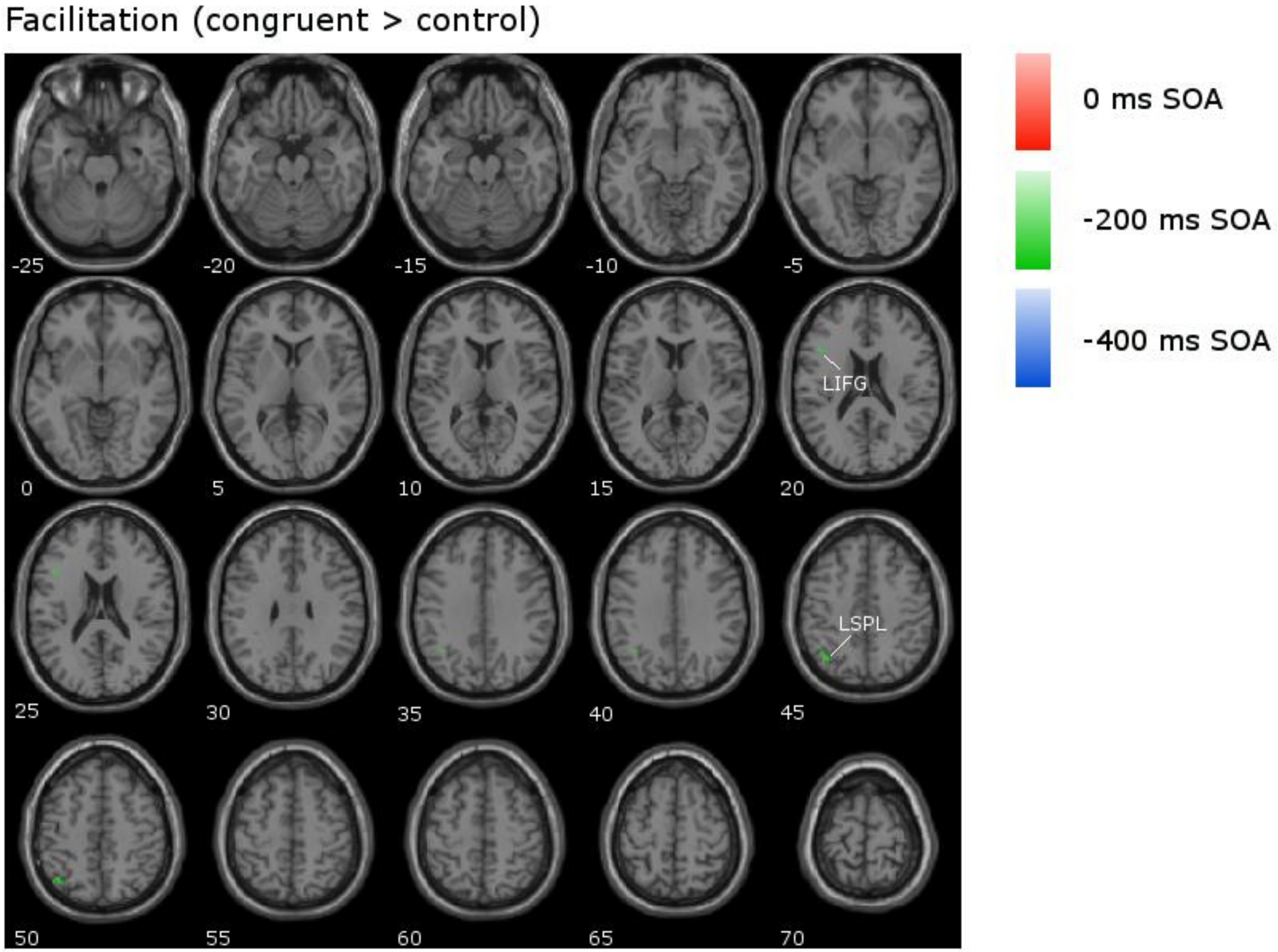


Figure 7.4: Overlaid contrasts for the facilitation comparison for all SOAs, with clusters of interest labelled (LSPL = left superior parietal lobe).



3.2.1.4. SOA modulation of neural interference and facilitation effects

To next investigate trial-specific effects of SOA on conflict and facilitation, three second-level ANOVAs were performed (for the Stroop, interference, and facilitation effects, respectively) by entering the first-level effect contrasts for each SOA into a 3-way (SOA) ANOVA (Figure 7.5, Table 7.2).

The Stroop and facilitation ANOVAs revealed no significant clusters of activation. However, the interference effects elicited a main effect of SOA in four areas of the control network: the RCZ (BA 8), right superior frontal gyrus (BA 9), LMFG (BA 6), and right superior parietal lobule (BA 7), as well as a cluster in the occipital lobe. To further investigate how SOA modulated interference effects in these regions, the percent signal change for each condition was extracted from these four ROIs. The percent signal change interference effects (i.e. incongruent signal change minus control signal change; Figure 7.5b) demonstrated the largest neural interference effects in these areas in the 0 ms SOA.

Figure 7.5: a) Results of the 3-way ANOVA identifying significant interactions of interference magnitude with SOA, with ROIs indicated; b) the percent signal change effect (incongruent signal change minus control signal change) for each ROI and SOA.

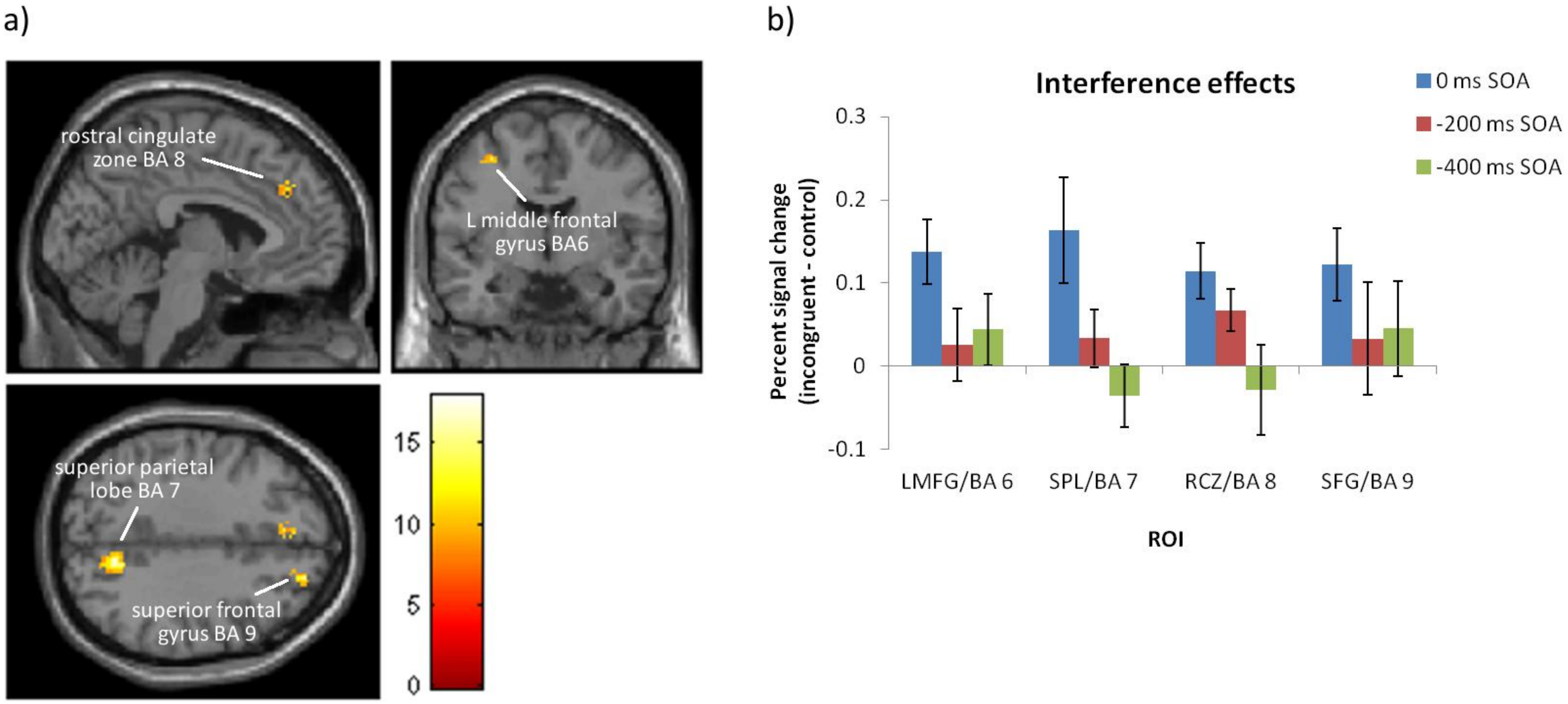


Table 7.2: Results of the 3-way (SOA) ANOVAs identifying local effects of SOA on Stroop, interference, and facilitation effect magnitude, with a threshold of $p < 0.001$ and clusters > 30 voxels.

Contrast	**Region**	**BA**	**MNI coordinates**			**Cluster size**	**Peak Z-score**
			x	**y**	**z**		
Stroop	No voxels surviving thresholding	--	--	--	--	--	--
Interference	R precuneus/superior parietal lobe	7	18	-70	42	285	4.54
	L medial frontal gyrus/RCZ	8	-6	36	36	53	4.00
	R superior frontal gyrus	9	22	48	36	45	4.14
	L middle frontal gyrus	6	-30	0	54	32	4.12
	L superior occipital gyrus	19	-34	-70	22	31	3.93
Facilitation	No voxels surviving thresholding	--	--	--	--	--	--

Table 7.3: Results of the 3-way ANOVA identifying global effects of SOA manipulation by collapsing across congruency in each SOA block, with a threshold of $p < 0.001$ and clusters > 30 voxels.

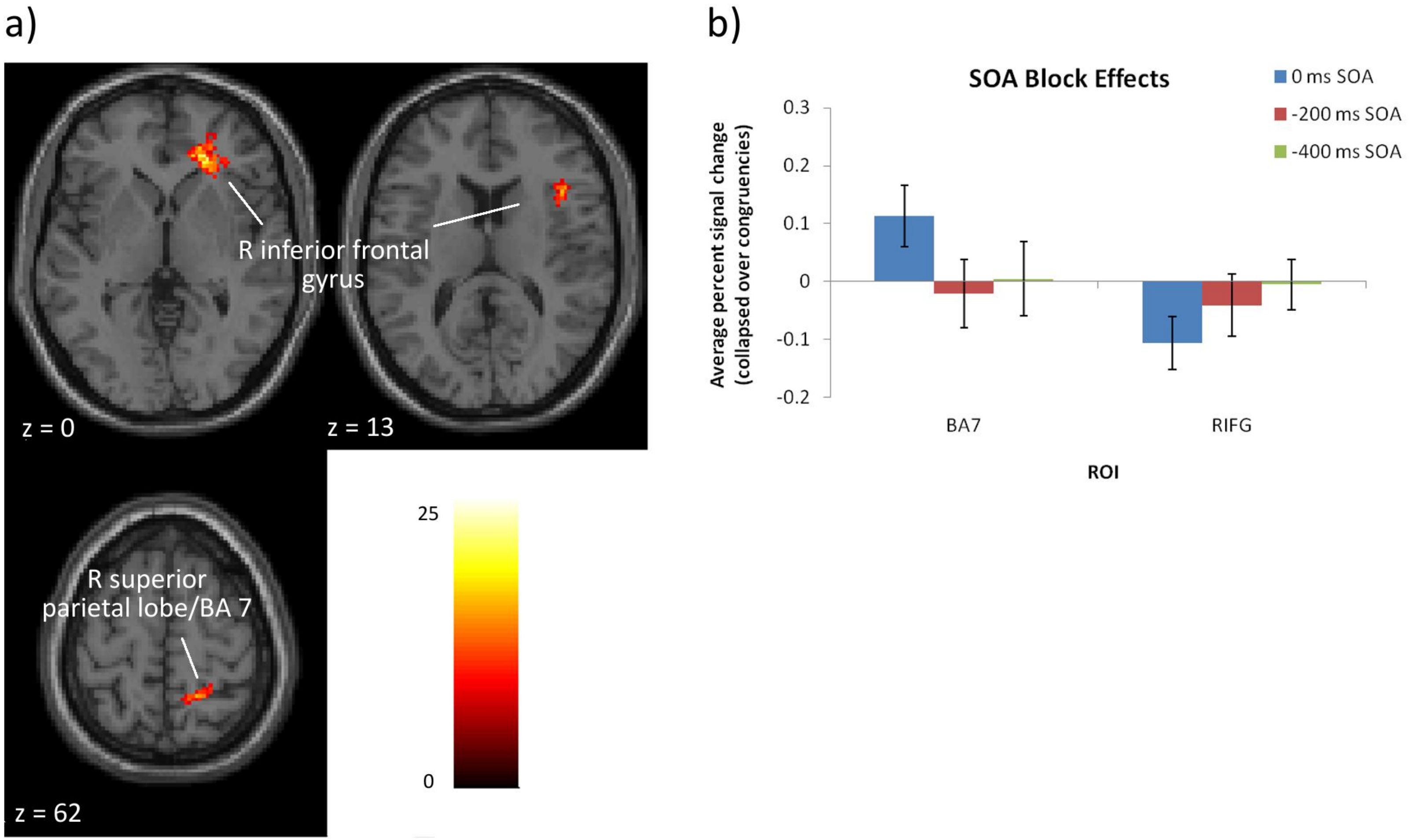
Contrast	**Region**	**BA(s)**	**MNI coordinates**			**Cluster size**	**Peak Z-score**
			x	**y**	**z**		
Block-wide SOA effect	R inferior frontal gyrus/ACC	47/32	16	38	0	310	5.32
	R inferior frontal gyrus	45	42	20	10	104	4.38
	R superior parietal lobe	7	18	-48	62	75	4.41

3.2.2. Global (block-wide) effects of SOA

As discussed in the Introduction (sections 1.2.2 and 1.2.3), SOA was predicted to create global (i.e. block-wide or conflict-independent) effects of response priming in negative SOAs (Appelbaum, Meyerhoff et al., 2009) and of strategic attentional orienting due to blocked SOA presentation (Appelbaum et al., 2012). These effects of SOA were expected when evaluating block-wide SOA effects (collapsing over congruencies), as well as when directly comparing congruencies between SOAs. For example, block-wide attentional orientation should be present in all congruencies, leading to differences even when comparing control conditions between SOAs.

To investigate block-wide SOA effects, each SOA was first collapsed over congruencies (contrasted with null-event trials: (incongruent, control, congruent) > null) and entered into a 3-way (SOA) ANOVA. Two main regions emerged that were sensitive to global SOA effects: the RIFG (BAs 45/47; part of a RIFG cluster also extended into the ACC/BA 32) and the right superior parietal lobe (BA 7; see Figure 7.6 and Table 7.3). The percent signal change for each SOA was also extracted from these two regions, which revealed larger overall effects for the 0 ms SOA (when collapsed across congruencies: Figure 7.6b). A block effect of SOA was confirmed by the presence of differences in the overall level of activation in each SOA.

Figure 7.6: Results of the 3-way ANOVA collapsing across congruency to investigate global (i.e. block-wide) SOA effects. a) Axial slices presented at three z-coordinates to illustrate two distinct clusters in the right inferior frontal gyrus, as well as a cluster in the superior parietal lobe. b) The percent signal change for each ROI and SOA, collapsed over congruency (the RIFG percent signal change was extracted from the larger cluster at z = 0).



To further investigate global effects of SOA, each congruency was compared between SOAs using two-sample *t*-tests (e.g. -400 ms congruent > 0 ms congruent; Table 7.4). Due to the pre-exposure of the word in negative SOAs, visual activation was expected in these conditions compared to the 0 ms SOA. The data confirmed this prediction: the -400 ms SOA showed more activation across all congruencies in medial, lateral, and inferior areas of the occipitotemporal gyrus (BAs 17/18/19) and the -200 ms SOA incongruent condition activated the lateral occipitotemporal gyrus (BA 36) compared to the 0 ms SOA. All subsequent analyses focused on activation outside of the occipital cortex. Of particular interest were SOA effects in the congruent and control conditions, which would suggest a conflict-independent effect of SOA on response priming and/or strategic attention.

The full results are presented in Table 7.4. To summarize the most important effects, which will be further interpreted with specific regards to response priming effects and strategic attentional control in the Discussion, the -200 ms SOA elicited stronger activation for the congruent and control conditions in the left superior/middle frontal gyrus (BA 9) compared to the 0 ms SOA. The -400 ms SOA control condition activated the RIFG to a greater extent than the 0 ms SOA. The -200 ms SOA incongruent and control conditions activated the posterior cingulate more than the other SOAs. The 0 ms SOA congruent and incongruent conditions showed enhanced right superior parietal lobe (BA 7) and posterior cingulate activation compared to the -400 ms SOA. Finally, the -400 ms SOA congruent and control conditions, and the -200 ms SOA congruent condition, activated the LIFG to a greater extent than the 0 ms SOA.

Table 7.4: Between-condition comparisons across SOAs of the Stroop task (clusters > 30 voxels) for each congruency condition.

Congruency condition	**Contrast**	**Region**	**BA(s)**	**MNI coordinates**			**Cluster size**	**Peak Z-score**
				x	**y**	**z**		
congruent	0 ms > -200 ms	No voxels surviving thresholding	--	--	--	--	--	--
	-200 ms > 0 ms	L insula	13	-40	4	-8	85	3.76
		L postcentral gyrus/insula	13/45	-42	-12	20	45	3.98
		L middle frontal gyrus	9	-14	50	22	44	3.76
		L inferior frontal gyrus	13/45/47	-48	16	4	43	3.91
	0 ms > -400 ms	R superior parietal lobule/postcentral gyrus	7	22	-46	62	46	3.78
		L postcentral gyrus	40	-40	-36	60	39	3.77
	-400 ms > 0 ms	L inferior frontal gyrus/precentral gyrus	13/38	-46	12	2	105	3.91
		L medial/inferior occipital gyrus	18	-26	-84	-2	75	3.85
	-200 ms > -400 ms	No voxels surviving thresholding	--	--	--	--	--	--
	-400 ms > -200 ms	No voxels surviving thresholding	--	--	--	--	--	--
control	0 ms > -200 ms	No voxels surviving thresholding	--	--	--	--	--	--
	-200 ms > 0 ms	L parahippocampal gyrus	--	-32	-24	-14	77	4.22
		L superior frontal gyrus	9	-14	46	22	45	4.77
		L ACC	32	-14	22	18	34	4.21
		L insula/postcentral gyrus	13	-40	-10	22	34	4.04
	0 ms > -400 ms	No voxels surviving thresholding	--	--	--	--	--	--
	-400 ms > 0 ms	L lingual gyrus/medial occipitotemporal gyrus	17/18	-26	-84	-2	452	4.71
		R lateral occipitotemporal gyrus	18	22	-76	-2	92	4.14
		R insula/inferior frontal gyrus	45/47	44	16	-8	87	3.91
		L insula/superior temporal gyrus	38/47	-40	14	-12	51	3.89
		R lateral occipitotemporal gyrus	19	38	-68	-8	46	3.86
		L inferior frontal gyrus	47	-32	36	8	43	4.19
		R medial occipitotemporal gyrus	19	26	-54	-2	33	3.77

	-200 ms > -400 ms	R posterior cingulate	23/29	4	-36	18	89	4.12
		R angular gyrus/posterior cingulate gyrus	31	24	-44	38	82	4.88
	-400 ms > -200 ms	No voxels surviving thresholding	--	--	--	--	--	--
incongruent	0 ms > -200 ms	No voxels surviving thresholding	--	--	--	--	--	--
	-200 ms > 0 ms	L posterior cingulate gyrus	31	-18	-40	34	73	4.54
		L lateral occipitotemporal gyrus	36	-30	-32	-10	69	4.36
	0 ms > -400 ms	R posterior cingulate gyrus	31	24	-44	38	40	4.27
		L superior occipital gyrus	18/19	-4	-88	30	38	4.44
	-400 ms > 0 ms	L middle occipital gyrus	18	-26	-84	-2	35	3.74
	-200 ms > -400 ms	R posterior cingulate gyrus	31	24	-44	38	72	4.47
	-400 ms > -200 ms	R parahippocampal gyrus	28	20	-14	-22	36	4.42

4. Discussion

The current study employed fMRI to investigate for the first time how the executive control network is modulated by SOA in a Stroop task. Of particular interest were 1) the neural effects of SOA on interference and facilitation effects; 2) response priming in negative SOAs; and 3) the effects of blocked SOA presentation on strategic orientation of attention. To briefly summarize the results that will be discussed at length in the next sections, four areas in the executive control network were sensitive to trial-specific SOA effects on interference. An overall ANOVA investigating the global, congruency-independent effects of SOA demonstrated that the RIFG was sensitive to response priming effects in negative SOAs, whereas the right superior parietal lobe (BA 7) was sensitive to the attentional control effects of blocked SOA presentation.

4.1. SOA modulation of interference and facilitation effects

Previous work with SOA manipulation in the Stroop task has documented varying amounts of interference and facilitation in each SOA. Behaviourally, the current data replicated prior observations that, in a manual task, peak interference occurred at the -200 ms SOA and was also significant at the 0 ms SOA, whereas maximal facilitation occurred in the -400 ms SOA (Chapters 3 and 6; Appelbaum, Meyerhoff et al., 2009; Glaser & Glaser, 1982). Importantly, the effects of SOA on the magnitudes of interference and facilitation effects suggest differences in executive control strategies or recruitment in each SOA, which was investigated with fMRI for the first time in the current study.

Analyses indicated that areas of the brain participating in Stroop and facilitation effects were not strongly modulated by SOA. However, four areas of the cognitive control network were sensitive to the effects of SOA on interference: the right superior parietal lobe (BA 7), RCZ (BA 8), LMFG (BA 6), and superior frontal gyrus (BA 9).Percent signal change analyses indicated that these areas were more active for the 0 ms and -200 ms SOAs than the -400 ms SOA, suggesting sensitivity to the magnitude of cognitive conflict. Specifically, this indicates that areas involved in conflict monitoring (RCZ), conflict resolution (superior frontal gyrus/BA 9), and task-relevant attentional control (superior parietal lobule/BA 7) were most affected by interference during simultaneous stimuli presentation in the 0 ms SOA. As this SOA showed comparatively smaller behavioural interference effects, the stronger recruitment of these areas may reflect more efficient conflict processing. In contrast, the reduced activation in the -200 ms SOA illustrates that conflict resolution mechanisms were not engaged as efficiently, generating larger behavioural effects. In sum, this demonstrates that SOA significantly affected the recruitment of the cognitive control network during interference, as predicted.

When investigating Stroop, interference, and facilitation effects in each SOA individually, the 0 ms SOA showed a traditional recruitment of the executive control network for Stroop and interference effects, including the RCZ, LMFG, LIFG, and right superior parietal lobe, in line with previous literature (Botvinick et al., 2001; Bunge, Dudukovic, et al., 2002; Nee et al., 2007; Niendam et al., 2012; Ridderinkhof, Ullsperger, et al., 2004; Ridderinkhof, van den Wildenberg, et al., 2004; Ye & Zhou, 2009; van Veen & Carter, 2002). The -200 ms SOA activated these same areas but to a lesser extent, again indicating a less-efficient recruitment of cognitive control which generated increased behavioural interference. Therefore the two most cognitively-demanding SOAs activated a similar neural network, but the amount of activation was modulated by SOA.

Despite the relatively reduced activation in the conflict contrasts of the -200 ms SOA, when directly comparing the congruency conditions this SOA showed heightened ACC and LMFG (BA 9) activation in all congruencies, including the control condition. Previous research has reported that the ACC and prefrontal cortex are sensitive to the amount of conflict in a task (Barch et al., 2000) and that activation can be enhanced with task difficulty across the entire task rather than on a trial-by-trial basis (Barch et al., 1997). The observed ACC and LMFG activation therefore suggests that cognitive control was enhanced throughout the -200 ms SOA block and in all congruencies due to the heightened cognitive demands in this SOA.

In the -400 ms SOA, despite the large behavioural facilitation effects, the corresponding neural contrast showed no significant clusters of neural activation. This could indicate that similar brain areas were engaged to similar extents in all congruencies, such that the contrast subtractions cancelled out this activation. However, in the interference contrast, one cluster of activation was identified in the RIFG which, as discussed in the next section, may be indicative of response priming effects.

Overall, there was a disparity between the behavioural and neural effects: the 0 ms SOA elicited stronger brain activity yet experienced smaller behavioural conflict effects, while the opposite was true for the -200 ms SOA. This negative association of behavioural and neural responses has been reported previously (Booth et al., 2003; Egner & Hirsch, 2005a, 2005b; Fan, Fossella et al., 2003) and suggests that successful cognitive control requires more extensive activation of the executive control network to reduce behavioural conflict effects.

In sum, the cognitive control network was sensitive to trial-specific effects of SOA on interference. Specifically, four regions of the network were most active in the 0 ms SOA, leading to correspondingly smaller behavioural interference effects. In contrast, the -200 ms SOA experienced comparatively less neural activation, suggesting less-efficient cognitive control which led to larger behavioural interference effects. This therefore demonstrates that SOA modulates the conflict-processing demands of the executive control network and suggests that short pre-exposure of the word in the -200 ms SOA disrupts the efficient processing of this system.

4.2. Response priming effects in negative SOAs

Appelbaum, Meyerhoff et al. (2009) have suggested that negative SOAs create a response priming effect by pre-activating response selection, which generates larger behavioural interference and facilitation effects compared to the 0 ms SOA. This study explored the neural representation of these response priming effects in the -200 ms and -400 ms SOAs. The block-wide SOA analysis (presented in section 3.2.2) identified two regions that were modulated by the global effects of SOA: the RIFG and the right superior parietal lobe. As will be argued here, the RIFG was involved in response priming effects.

In the SOA-specific analyses, the Stroop and interference contrasts in the -200 ms SOA elicited RIFG activation to a greater extent than the 0 ms SOA; additionally, the -400 ms SOA activated the RIFG in the interference contrast. As mentioned in the Introduction, the RIFG has been implicated in response inhibition (i.e. inhibiting pre-potent motor responses, as in a no-go paradigm; Aron et al., 2004; Garavan et al., 1999; Hampshire et al., 2010; Levy & Wagner, 2011). The activation of this area in negative SOAs suggests its involvement in response priming effects; specifically, the fact that RIFG activation occurred in Stroop and interference contrasts in negative SOAs suggests that this area is involved in applying response inhibition after incorrectly-primed response selection in incongruent conditions.

To illustrate, in incongruent conditions the pre-exposed word primes (incorrect) response selection, which must then be overcome (via response inhibition mechanisms in the RIFG) to make a correct response to the colour. This would explain why the -200 ms SOA generates larger interference effects: the need for response inhibition in incongruent conditions leads to longer incongruent RTs and consequently larger behavioural interference effects relative to the other conditions. In congruent conditions, however, the primed response preparation leads to faster RTs and increased behavioural facilitation effects. Response priming in the RIFG can therefore explain the larger interference and facilitation effects observed in the -200 ms SOA, as observed in the current data and in previous research (Appelbaum, Meyerhoff et al., 2009; Glaser & Glaser, 1982; Chapters 2 and 6).

In contrast, the -400 ms SOA generated large behavioural facilitation effects but no interference, which contradicts the proposal that response priming increases both interference and facilitation effects. In this SOA, the long pre-exposure of the word may have allowed for response priming effects to be overcome, as suggested by the fMRI data. In direct comparisons of the individual congruencies in the neural data, the -400 ms SOA also showed more RIFG activation in the control condition compared to other SOAs. This suggests that the RIFG cannot purely reflect response inhibition in this SOA, because a response cannot be primed in the control condition as it does not contain semantic information.

Although the RIFG has been specifically implicated in response inhibition, previous investigations of the right posterior ventrolateral prefrontal cortex, which includes the RIFG, have indicated that this area is involved more generally in updating action plans, a function which includes, but is not limited to, response inhibition (Aron et al., 2004; Bunge, Hazeltine, et al., 2002; Garavan et al., 1999; Hampshire et al., 2010; Levy & Wagner, 2011; Rubia, Smith, Brammer, & Taylor, 2003; Verbruggen, Aron, Stevens, & Chambers, 2010). The current data in the -400 ms SOA support this more general role of the RIFG in action updating. To illustrate, although the pre-exposure of the word primes response selection, the long pre-exposure may allow sufficient time to fully inhibit the motor response, as the word is a non-target stimulus: this would explain the lack of behavioural interference in the -400 ms SOA. If the primed response is fully inhibited, this would also predict a reduction in facilitation effects; however, facilitation is *increased* in this SOA. Therefore in addition to response inhibition, the RIFG may also perform more general action updating, as proposed by previous literature, which readies the motor system to make a response. If response preparation mechanisms are primed in a -400 ms SOA, upon subsequent colour presentation the system benefits from the convergent information in the congruent condition (therefore generating large facilitation effects) but the incongruent condition does not cause any additional conflict (resulting in little or no interference). In both congruencies, similar brain regions are active, which may explain the lack of neural differences between these conditions in the current -400 ms SOA data.

Thus, the current data can be explained by assuming that in the -200 ms SOA the RIFG is engaged primarily for response inhibition in incongruent conditions, as a result of the response priming effect, whereas in the -400 ms SOA the RIFG is involved in more general action updating. Importantly, in the -200 ms SOA the increased interference occurs because the response priming effect does not have enough time to be resolved. Lexical access occurs approximately 200 ms after word onset (e.g. Dell'Acqua et al., 2007; Pulvermüller et al., 2001), meaning that the colour appears at the same approximate time that semantic activation occurs in this SOA, leaving little extra time for stimulus suppression before conflict arrives. As a result, there is not enough time to overcome the response priming in the incongruent condition before the colour arrives, creating conflict and requiring the RIFG to perform response inhibition. In contrast, in the -400 ms SOA there is ample time for both semantic activation of the word and subsequent suppression of the primed response (via the RIFG), which explains the lack of behavioural interference. As well as inhibiting the primed response, the RIFG also performs a more general function of action updating, priming the system to make a motor response. Therefore the current data supported Appelbaum, Meyerhoff et al. (2009)'s proposal of response priming with word pre-exposure and also provided additional knowledge of how this mechanism functions in each SOA.

4.3. Effects of blocked SOAs on strategic orientation of attention

The current chapter additionally investigated whether blocked SOA presentation would create a strategy of attentional orientation such that the temporal predictability could be used to direct attention to the upcoming target stimulus (Appelbaum et al., 2012; Roelofs, 2010a). Such strategic effects should be apparent across the entire block. As mentioned, the global (congruency-independent) analysis of SOA effects (section 3.2.2) revealed two clusters of activation: the RIFG (which has been attributed to response priming effects of response inhibition and action updating) and the right superior parietal lobe (BA7). As BA 7 is involved in top-down attentional control (Corbetta et al., 1993; Culham & Kanwisher, 2001; Milham et al., 2003; Rushworth et al., 2001) this area may have been sensitive to attentional control strategies resulting from the temporal predictability of blocked SOAs.

It was expected that strategic attentional control effects would be most prominent in negative SOAs, as the word pre-exposure might act as a temporal cue that the target colour would soon appear. However, the percent signal change analyses illustrated that BA 7 was most active for the 0 ms SOA. This could suggest that when stimuli are simultaneously presented, attention to the relevant stimulus (the colour) is enhanced in order to facilitate response selection. For example, Egner & Hirsch (2005a) have suggested that conflict resolution proceeds via amplification of task-relevant attributes; enhanced attentional control in the 0 ms SOA may therefore indicate a strategy of directed attention towards the colour in order to overcome the effects of the distracting word stimulus. In contrast, the pre-exposure of the word in the negative SOAs may disrupt this process, leading to less activation in BA 7. Interestingly, the enhanced activation of this area for the 0 ms SOA mirrors the findings of Appelbaum et al. (2012), who reported a larger N_{inc} in the 0 ms SOA with blocked SOA presentation. In general, the fact that global effects of SOA were observed in regions involved in attentional control supports the proposal of strategic orientation of attention with blocked SOA presentation.

Block-wide strategic attention effects were also identified in the direct comparisons of congruencies across SOA blocks: specifically, the -200 ms SOA showed more activation in the posterior cingulate. While being assigned to a number of cognitive roles, one function of the posterior cingulate is in anticipating the need to spatially allocate attention (Small et al., 2003). This could suggest an attentional priming effect in the -200 ms SOA such that the short pre-exposure of the word acted as a cue for attentional engagement. It is unclear why a similar effect did not occur in the -400 ms SOA; one possibility is that the longer word pre-exposure allowed ample time for the suppression of the word information, so attentional allocation was not prioritized.

In summary, the right superior parietal lobe was sensitive to the effects of blocked SOA presentation, demonstrating that attentional control was modulated by the global effects of SOA. These effects were enhanced for the 0 ms SOA, which could suggest that attentional mechanisms of conflict resolution were engaged during simultaneous stimulus presentation in the 0 ms SOA. In addition, SOA effects in the posterior cingulate in the -200 ms SOA could reflect an anticipation of attentional control. These block effects of SOA suggest that mixed SOA presentation might lead to very different effects, both in the behavioural data and in the neural recruitment of the attentional control network (Appelbaum et al., 2012). As this was the first study to use the Stroop SOA paradigm with fMRI, the comparison of blocked vs. mixed SOAs, and how this paradigm choice affects the recruitment of conflict processing mechanisms, requires further exploration.

4.4. Distractor suppression effects in negative SOAs

One additional finding in the current data was that the LIFG was generally more active across all congruencies for negative SOAs. Specifically, more LIFG activation was observed for the -400 ms SOA congruent and control conditions and the -200 ms SOA congruent condition as compared to the corresponding congruencies in the 0 ms SOA. Previous research has suggested that within the cognitive control network the LIFG performs suppression of irrelevant information (e.g. Ye & Zhou, 2009); this finding of enhanced LIFG activation throughout the negative SOAs may therefore suggest a strategy of distractor suppression. For instance, at the time of word presentation in negative SOAs the word's eventual congruency is unknown, as the colour has not yet appeared to cause conflict. Therefore the LIFG may be suppressing all pre-exposed information, as it is irrelevant to the task, in order to avoid potential conflict when the colour appears. Importantly, the control condition also elicited enhanced LIFG activation in negative SOAs, suggesting that this mechanism is neither conflict- nor linguistically-specific, but is a global strategy of task-irrelevant distractor suppression.

This proposal of a distractor suppression mechanism in negative SOAs suggests a strategy of proactive cognitive control, which draws a parallel to the *dual mechanisms of control* theory put forth by Braver and colleagues (Braver, Gray, & Burgess, 2007; Braver, Paxton, Locke, & Barch, 2009; De Pisapia & Braver, 2006). This theory proposes that cognitive control consists of two mechanisms: one reactive, which is a 'late correction' response that uses context information transiently to resolve conflict once it has occurred; and one proactive, which uses an 'early selection' strategy to actively sustain goal-relevant information and pre-emptively reduce control demands when conflict occurs. The fact that LIFG activation occurred across all congruencies in negative SOAs suggests a sustained activation of this structure, potentially through a mechanism of proactive cognitive control. In contrast, reactive control may be more characteristic of the 0 ms SOA, in which suppression must be activated in response to the detection of conflict on every trial. Although a tentative explanation, this proposal of distractor suppression by the LIFG suggests a proactive strategy employed to lessen the influence of the non-target stimulus and highlights the dynamic nature of the executive control system in response to various cognitive demands.

5. Conclusions

In summary, the current data demonstrated both trial-specific and block-wide effects of SOA on the recruitment and behaviour of the executive control network. The network was activated to different extents in each SOA, with the largest neural interference effects in the 0 ms SOA compared to the -200 ms SOA. As the 0 ms SOA demonstrated relatively reduced behavioural interference effects, this more extensive neural activation suggests more efficient conflict processing, whereas in the -200 ms SOA this efficient processing was disrupted by the pre-exposure of the word. Response priming effects were localized to the RIFG; in the -200 ms SOA in particular, these effects can be explained by response inhibition in incongruent conditions in order to overcome the conflict created by the incorrectly primed response. In the -400 ms SOA, with longer word pre-exposure, the RIFG activation suggested more general response preparation and action updating, leading to increased behavioural facilitation but no interference. Strategic attention effects were localized to the right superior parietal lobe but were enhanced in the 0 ms SOA, suggesting that negative SOAs do not create a temporal cue; instead, attentional control mechanisms are enhanced in the 0 ms SOA to more efficiently deal with the conflict generated by simultaneous stimulus pre-exposure. Finally, word pre-exposure in the negative SOAs also appeared to recruit a proactive control strategy of distractor suppression, which is mainly carried out by the LIFG. As this was the first study to explore SOA modulation in the Stroop task with fMRI, there are ample possibilities for future research. However, overall these data have demonstrated that SOA manipulation is a valuable tool for investigating the functioning of the cognitive control network.

This chapter has shed new light on the Stroop task with SOA manipulation and suggests interesting differences in how the executive control network is recruited in different contexts of cognitive control. This experiment was intended as a starting point to determine the impact of SOA manipulation on monolingual executive control. The next chapter returns to the issue of bilingualism, concluding these explorations of bilingual cognitive control by investigating the neural origins of the bilingual advantage.

Chapter 8: The Neural Locus of the Bilingual Cognitive Advantage

The previous chapter demonstrated significant effects of SOA on the recruitment and function of the executive control network, providing important insight into the malleability of cognitive functioning in monolinguals. Returning to the main theme of this thesis, how might bilingual executive processing differ from monolinguals? This chapter investigates the functional generators of the bilingual cognitive advantage and identifies a 'neural locus' of the advantage by evaluating how and where language and executive control processing overlap in bilinguals.

1. Introduction

As reviewed in Chapter 1 (section 4.2), a wealth of literature has documented a bilingual advantage on executive control tasks. However, relatively few studies have explored the neural manifestations of this capacity. As yet there have been no attempts to localize the functional overlap of the bilingual language and executive control networks, yet doing so would provide valuable insight into the nature of the bilingual advantage. The current study attempted to identify the brain region(s) or network(s) involved in language and both domain-general and linguistically-based executive control, in order to address this important question.

1.1. The overlap of executive control and language processing

As reviewed in Chapter 1 (section 4.1), neuroimaging studies have demonstrated that bilinguals recruit areas of the cognitive control network to resolve cross-linguistic interference during language processing (e.g. Price et al., 1999; Rodriguez-Fornells et al., 2005; van Heuven et al., 2008) and during explicit language switching (Abutalebi et al., 2007, 2008; Crinion et al., 2006; Guo et al., 2011; Hernandez, 2009; Hernandez et al., 2000, 2001; Price et al., 1999; Wang et al., 2009; see Bialystok et al., 2009 and Rodriguez-Fornells et al., 2006 for reviews). Importantly, the areas recruited for bilingual language control (e.g. ACC, DLPFC, and LIFG) are also recruited by monolinguals for non-linguistic executive control. However, the engagement of executive control might be expected if bilingual language processing experiences conflict during non-selective lexical access. The more interesting question is whether this relationship is reciprocal: whether non-linguistic conflict elicits activation in language processing areas that are not necessarily related to control.

Hernandez (2009) has suggested that early bilinguals may develop different language networks than those of late bilinguals or monolinguals, specifically by assimilating areas of the executive control network. In other words, language and executive processing become co-dependent and co-activated, leading to a fundamental restructuring of these neural networks. This proposal of functional variations in neural recruitment is supported by evidence of differences between monolinguals and bilinguals in the extent and location of brain activation during non-linguistic cognitive control tasks (Abutalebi et al., 2012; Bialystok, Craik, et al., 2005; Garbin et al., 2010; Luk et al., 2010). For example, Garbin et al. (2010) reported differences in LIFG connectivity for monolinguals and bilinguals during non-verbal task switching. They proposed that the involvement of this language-related brain area in non-linguistic control demonstrates an integration of linguistic and non-linguistic control that is unique to bilingualism.

If the bilingual cognitive advantage stems from the experience of bilingual language processing, and if the advantage is domain-general and extends to non-linguistic executive function, then a brain area or network that is commonly activated for language processing, linguistic cognitive control, and non-linguistic control should be enhanced in bilinguals compared to monolinguals. However, prior study designs have been unable to fully dissociate these distinctive aspects of cognitive processing. For example, previous investigations have focused on non-linguistic conflict only (e.g. Luk et al., 2010), or linguistic conflict only (e.g. Crinion et al., 2006; Hernandez, 2009; Wang et al., 2009; van Heuven et al., 2008), or have omitted a language processing measure (e.g. Abutalebi et al., 2012; Garbin et al., 2010). To date, Ye & Zhou (2009) have performed the most comprehensive investigation of how these systems overlap by comparing language processing (comprehension of syntactically complex sentences), linguistic conflict (a Stroop task) and non-linguistic conflict (a flanker task); however, this study was conducted with Chinese monolinguals only. A direct comparison of these three aspects of cognitive processing in bilinguals is essential in order to pinpoint the neural locus of the cognitive advantage.

The current study addressed this issue by testing monolinguals and bilinguals on separable conditions of linguistic cognitive control, non-linguistic cognitive control, and language processing (via an adapted flanker task and a semantic categorization task, described in section 1.3). A conjunction analysis in each group identified brain regions that were similarly activated by all three functions. If bilinguals use domain-general cognitive control during language processing, and if these networks evolve together during bilingual development such that bilinguals also use language areas for non-linguistic cognitive control, then areas of significant activation should be observed in the bilingual conjunction analysis. In contrast, if monolinguals use distinct areas for language and non-linguistic cognitive control, this would lead to less (or no) overlap and thus a smaller extent of activation, compared to bilinguals, in the conjunction of all three tasks.

1.2. Candidates for the neural locus of the bilingual advantage

The language and executive control networks are extensive and their functions diverse, so bilingualism may consequently affect a widespread network of brain areas. Nevertheless, based on the previous literature of language and executive control, three specific a priori regions were identified that may show stronger activation in the bilingual conjunction analysis: the ACC, caudate, and LIFG.

1.2.1. The anterior cingulate cortex

The ACC is a primary hub of the executive control network (Botvinick et al., 2001, 2004; van Veen & Carter, 2002); its involvement in conflict processing is unequivocal (see Chapter 1, section 3.2.1). Although not typically involved in monolingual language processing (e.g. Gitelman et al., 2005), ACC activation has been reported for bilingual language control during switching and translation (Abutalebi et al., 2007; Guo et al., 2011; Price et al., 1999) and for cross-linguistic conflict resolution in bilingual production and comprehension (Rodriguez-Fornells et al., 2005; van Heuven et al., 2008). To illustrate, Abutalebi et al. (2012), reported a bilingual advantage on a flanker and task-switching paradigm compared to monolinguals; furthermore, bilingual performance correlated with increased grey matter density in the dorsal ACC, indicating a more efficient use of this structure by bilinguals. The ACC is thus involved in both bilingual language control and domain-general executive processing, although its participation in more basic language processing is questionable.

1.2.2. The caudate nucleus

The caudate nucleus is a central structure for language control, involved not only in bilingual translation and language switching (Abutalebi et al., 2007; Crinion et al., 2006; Luk et al., 2011; Price et al., 1999; Wang et al., 2007; van Heuven et al., 2008) but also in monolingual language processing and linguistic conflict (e.g. Ali, Green, Kherif, Devlin, & Price, 2010; Crosson et al., 2003; Mestres-Missé, Turner, & Friederici, 2012; Niendam et al., 2012; Vargha-Khadem et al., 1998; Watkins et al., 2002). For example, Crosson et al. (2003), in a language production paradigm in monolinguals, found that the right basal ganglia, including the caudate and putamen, was involved in suppressing other structures that might interfere with language processing. Mestres-Missé et al. (2012) demonstrated that grammatical language conflict elicited caudate activation that varied with the difficulty of processing. The caudate is also implicated in non-linguistic interference control (Bialystok et al., 2009; Niendam et al., 2012), specifically in inhibiting a prepotent response (Li, Yan, Sinha, & Lee, 2008; Shadmehr & Holcomb, 1999). This structure's involvement in language control and domain-general executive processing thus makes it a likely candidate for the locus of the bilingual advantage.

1.2.3. The left inferior frontal gyrus

The LIFG is typically interpreted as a language processing area given its reliable activation in language tasks (Fiebach, Friederici, Müller, & von Cramon, 2002; Gitelman et al., 2005; see Chapter 1, section 1.2.2). This area is also commonly involved in bilingual language control (Hernandez et al., 2000; Lehtonen et al., 2005; Luk et al., 2011; van Heuven et al., 2008): it is more active in bilinguals when reading complex sentences (Kovelman, Baker et al., 2008) and experiences stronger activation during the processing of a weaker L2 (De Bleser et al., 2003; Indefrey, 2006; Kim et al., 1997; Kovelman, Baker, et al., 2008; Kovelman, Shalinsky et al., 2008; Marian et al., 2003; Parker Jones et al., 2011; Perani et al., 2003). Importantly, the LIFG is also involved in domain-general cognitive control. It is activated in monolinguals not just by linguistic conflict, such as during complex sentence parsing or a Stroop task (Kovelman, Baker, et al., 2008; Novick et al., 2005; Ye & Zhou, 2009), but also by non-linguistic cognitive control (Bunge, Dudukovic et al., 2002; Garbin et al., 2010; Ye & Zhou, 2009). For example, Bunge, Dudukovic et al. (2002) found that LIFG activation was correlated with behavioural performance during interference suppression and response inhibition in a flanker task. Ye & Zhou (2009) reported LIFG activation in a conjunction analysis of syntactically complex sentence processing, linguistic conflict processing in a Stroop task, and non-linguistic conflict processing in a flanker task. Overall, the LIFG is thought to be part of the cognitive control network (Ye & Zhou, 2009), specifically involved in overriding automatic processes, resolving semantic conflict, and controlling interference from irrelevant information (Thompson-Schill, Bedny, & Goldberg, 2005; Ye & Zhou, 2009). Therefore the LIFG's involvement in language processing and domain-general executive control, in both monolinguals and bilinguals, makes it a likely candidate for the locus of the bilingual advantage.

1.3. The current study

The current study investigated linguistic and non-linguistic executive control and language processing in monolinguals and bilinguals. These domains were analyzed individually and also directly compared using a conjunction analysis to identify neural areas involved in all three. As mentioned in the previous chapter, this study originally intended to use a Stroop task with SOA manipulation. However, because direct cross-paradigm comparisons were planned, the tasks were designed such that the visual extent of stimuli and the nature of the responses were as similar as possible.

To assess linguistic and non-linguistic cognitive control, an adapted flanker task was created with a target stimulus row of arrows pointing either left or right, to which the participant always responded. Above and below the central arrows were either rows of congruently- or incongruently-pointing arrows (*non-linguistic distractors*), or directional words (*linguistic distractors*, e.g. 'left' or 'right'). The control condition consisted of flanking rows of x's ('xxxx'), containing no linguistic or semantic information.[19] Therefore all conditions maintained the same cognitive task (responding to arrows) and the same visual extent of the stimuli, such that only the nature of the distractor (linguistic or non-linguistic) changed between trials. This reduced the amount of neural activity attributable to extraneous variables when comparing linguistic and non-linguistic executive control. Similar areas of the executive control network were expected to be active for both the linguistic and non-linguistic distractor types (e.g. ACC, DLPFC, LIFG, middle frontal gyri (MFG)), although

---

[19] An additional 'semantic control' condition was also included in the design, consisting of arrows pointing up or down (for non-linguistic distractors) or the words 'up' or 'down' (for linguistic distractors). As the distractors were semantically related to the target but not a possible response option, this condition provided a mediation of conflict effects. However, due to space restrictions these results are not presented here and this condition was not included in the analyses.

with more extensive activation in language control areas (e.g. LIFG, caudate nucleus) for linguistic distractors.

Language processing was assessed via a semantic categorization task requiring the categorization of nouns as either ‘living’ or ‘nonliving’. A non-word stimulus (‘xxxx’) was also included, to which participants also performed a motor response. This task was designed such that the word > non-word contrast would eliminate extraneous brain activation associated with lower-level perceptual and motor processes, allowing for a localization of language in the brain. Semantic categorization was expected to elicit a network of areas involved in language processing and word reading (e.g. fusiform gyrus, LIFG, angular gyrus: Ferstl et al., 2008; Gitelman et al., 2005; McCandliss, Cohen, & Dehaene, 2003). Bilinguals performed this task in both of their languages, although languages were combined for the conjunction analyses.

Conjunction analyses for each group were conducted on the linguistic executive control, non-linguistic executive control, and language contrasts to identify brain areas commonly involved in all domains. If bilingualism creates a functional overlap between domain-general cognitive control and language processing, the bilingual conjunction was expected to show activation in the caudate, ACC, and/or LIFG. Importantly, the extent of activation in the conjunction analysis was expected to be greater in bilinguals than in monolinguals.

2. Methods

2.1. Participants

Participants were recruited from the National Institutes of Health (NIH)[20] community in Bethesda, MD and the University of Maryland community in College Park, MD, USA. All participants were right-handed, with no history of neurological disorder or colour-blindness and normal or corrected-to-normal vision. The monolingual participants were 15 native English speakers (6 males, 9 females) with a mean age of 24 years (full demographics presented in Table 8.1). Some (n = 12) had learned other languages, but none considered themselves fluent in anything but English. The bilingual participants were 14 native Spanish speakers (6 males, 8 females) with a mean age of 24 years. All had learned Spanish before English or both simultaneously (mean English AoA = 6 years), and were highly proficient in both languages (average subjective Spanish proficiency = 9.1 on a 10-point scale; average English proficiency = 9.7). This was a trend of a significantly higher proficiency in English than Spanish (p = 0.07), which may be expected as these participants were all living in the USA.

---

[20] This data was collected during a research placement in the lab of Barry Horwitz at the National Institute of Deafness and Communication Disorders at the NIH.

Table 8.1: Demographic and proficiency information for the bilingual and monolingual participants. Digit span score is out of a maximum span length of 9.

Group		**Spanish-English bilinguals**	**English monolinguals**
n		15	14
Age		24 (6)	25 (3)
Gender		6 male, 8 female	6 male, 9 female
Digit Span		6.8 (0.4)	7.6 (0.3)
X-Lex	*raw*	4979 (26)	4977 (34)
	adjusted	4550 (378)	4318 (578)
Y-Lex	*raw*	3954 (562)	4527 (190)
	adjusted	3418(614)	3664 (656)
Self-rated proficiency: Spanish	*speaking*	9.5 (0.9)	--
	listening	9.8 (0.4)	--
	reading	8.9 (1.6)	--
	writing	8.2 (2.1)	--
	overall	9.1 (1.1)	--
English AoA		6 (4)	--
English Years Experience		17 (8)	--
Self-rated proficiency: English	*speaking*	9.7 (0.5)	--
	listening	9.9 (0.4)	--
	reading	9.7 (0.6)	--
	writing	9.5 (0.7)	--
	overall	9.7 (0.5)	--

2.2. Materials and Design

2.2.1. Flanker task

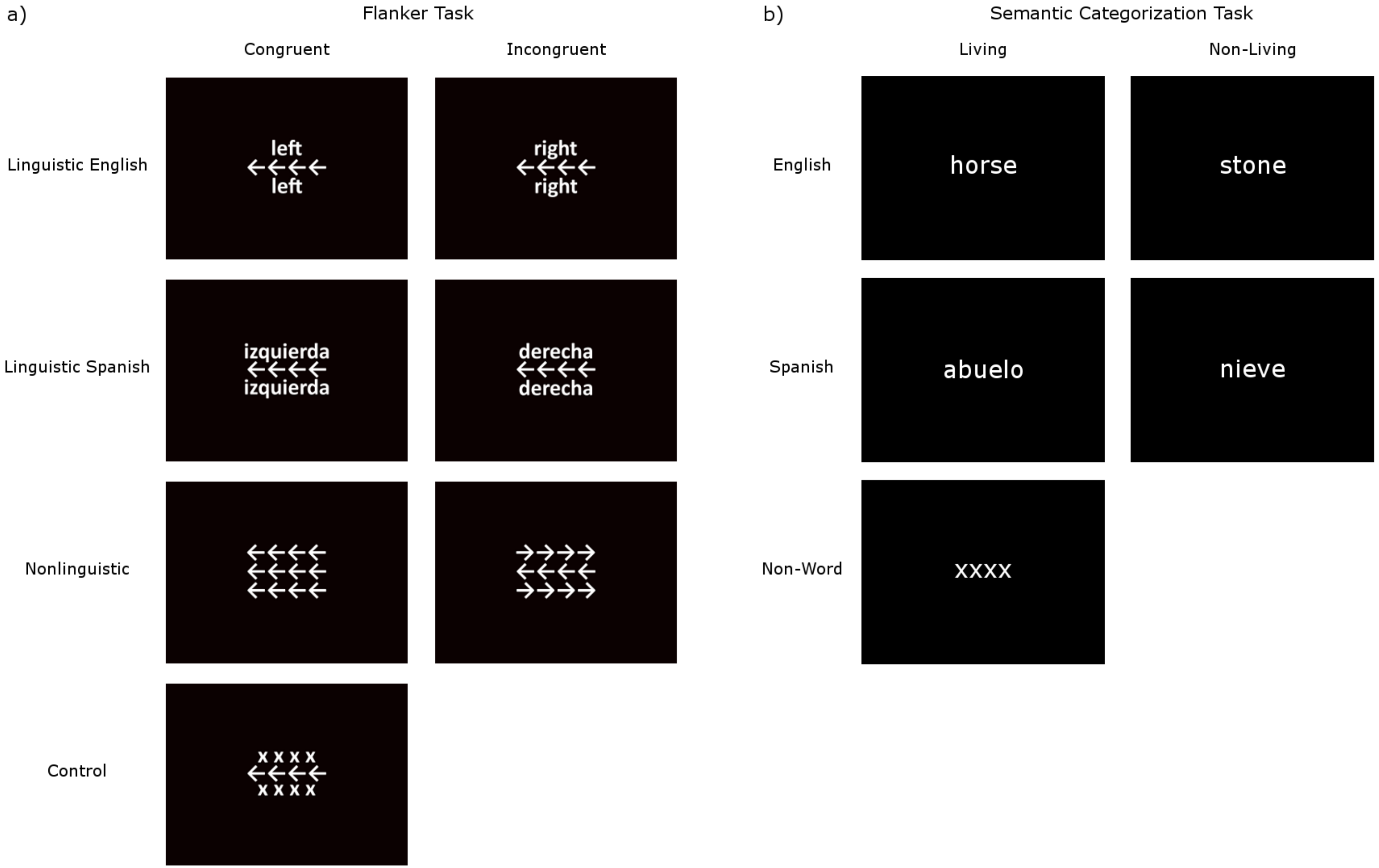
Flanker target stimuli consisted of a horizontal row of four arrows pointing either left or right (Figure 8.1a). The distractor stimuli were either other arrows (non-linguistic conditions), directional words (linguistic conditions), or a row of x's ('xxxx'; control condition). The target line of arrows was always presented in the centre of the screen, with the distractor stimuli presented on two lines above and below. In English linguistic conditions, the distractor words consisted of directional words 'left' or 'right'. In Spanish linguistic conditions (bilinguals only), the directional distractor words were 'izquierda' (left) and 'derrecha' (right).

2.2.2. Semantic categorization task

Semantic categorization stimuli consisted of nouns that were classifiable as 'living' or 'non-living' (e.g. father, book; see Figure 8.1b). An equal number of living and non-living words were included in each run. All words were between 3-7 letters long (average of 5) and were matched across languages and categories on their length and frequency (frequency measures were obtained from Subtlex-Esp and Subtlex USA; Brysbaert & New, 2009; Cuetos, Glez-

Nosti, Barbón, & Brysbaert, 2011; average frequency over both categories: 3.35 in English, 3.36 in Spanish). Cognates between languages were avoided. Non-word conditions consisted of a row of x’s (‘xxxx’), to match the visual stimulation of the words.

Figure 8.1: Example stimuli for the a) flanker and b) semantic categorization task.



2.3. Procedure

This study was run under a protocol approved by the Institutional Review Board of the NIH; all subjects gave informed written consent according to the ethics guidelines of the NIH. Before scanning, all subjects had a history and physical with the principal investigator and female participants had a urine pregnancy test. All subjects completed a safety screening questionnaire ensuring their eligibility for MRI. Before scanning, participants completed the X-Lex and Y-Lex vocabulary tests (see Chapter 6, section 2.3 for details) and practised the experimental paradigms. An adapted version of the forward digit span task[21] (e.g. Conklin, Curtis, Katsanis, & Iacono, 2000) was also administered to assess working memory capacity (results not discussed here). The scanning session was approximately 1 hour for monolinguals and 1.5 hours for bilinguals, including set-up, structural image acquisition, and experimental testing. All tasks were administered using Presentation. The experimental session for monolinguals consisted of three runs of the flanker task and two runs of the semantic categorization task; each run was approximately 5 minutes long. The experimental session for bilinguals consisted of four runs of the flanker task and four of the semantic categorization task (two in each language for each task); each run was approximately 5-6 minutes long. Task order (flanker/semantic categorization) was counterbalanced between participants and language order (Spanish/English) was counterbalanced between bilinguals. Within each task block, conditions were presented in an event-related fashion. A resting-state fMRI scan (approximately 5 minutes) was also performed at the end of the scanning session for all subjects. Subjects were offered an inconvenience allowance for their participation.

2.3.1. Flanker task

Each run of the flanker task in monolinguals consisted of 90 trials (12 each of the five congruencies presented in Figure 8.1a, as well as a ‘semantic control’ condition for linguistic and non-linguistic distractors; see Footnote 19), giving a total of 36 trials of each type across the three experimental runs. In bilinguals, the flanker task consisted of 96 trials total (18 each of linguistic congruent, incongruent and semantic control, and 9 each of non-linguistic congruent, incongruent, semantic control, and control), giving a total of 36 of each type across the four experimental runs (36 of each language for linguistic conditions). There were also 6 null-event trials in each block for all participants. On half of the null-event trials a blue square appeared in the periphery of the fixation cross (‘attentional null-event trials’), to which subjects were instructed to respond with a button-press. This was included to ensure that participants attended to the entire visual field, rather than fixating on the location of the target arrows. All participants successfully responded to these stimuli.

---

[21] The traditional forward digit span task presents numbers orally and asks participants to repeat them verbatim. The current task was similar, except numerals were presented on the computer screen at a rate of one per second and participants typed the span into the keyboard. This eliminated the confounding factor of testing language for the bilinguals. The length of the span increased by one until participants incorrectly recalled two consecutive trials of the same length (maximum span length of nine).

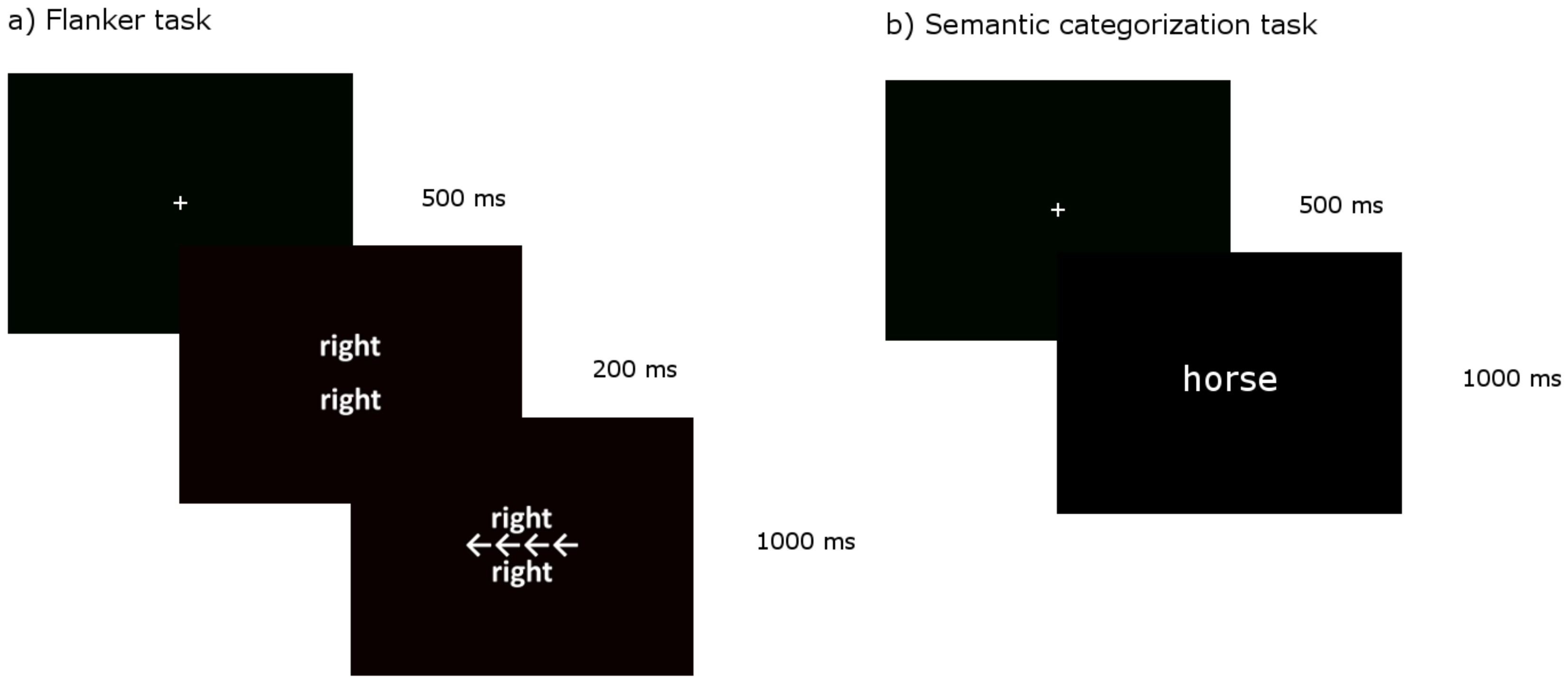
In each trial, a bold fixation cross was presented for 500 ms (Figure 8.2a). The distractor stimulus (word or arrow) then appeared for 200 ms before the target stimulus (left or right arrows) appeared in the centre of the screen. This distractor pre-exposure was included to increase interference: pilot testing established that simultaneous presentation of the word and arrow did not allow for sufficient semantic processing of the word. Based on the findings throughout this thesis of maximal interference at a -200 ms SOA, word pre-exposure was included to increase interference from the linguistic distractors. The same timing was used in the non-linguistic conditions, as pilot testing established that pre-exposure also increased interference on these trials. After target presentation, both target and distractor stimuli remained on the screen for 1000 ms. Participants indicated the directionality of the centre row of arrows with their left and right index fingers using an MRI-compatible button-box. In null-event trials, a non-bold fixation cross remained on the screen for 1200 ms. In attentional null-event trials, a blue square appeared in one of the four corners of the target periphery for 200 ms, followed by the non-bold fixation cross for 100 ms. An ISI fixation screen with a non-bold fixation cross followed each trial, varying from 1500-3000 ms in 200-ms intervals (average 2224 ms). Trial order was pseudo-randomly presented to optimize list efficiency, such that trial types were followed equally often by null-event trials and the same trial type did not occur more than 3 times in a row throughout a block.

2.3.2. Semantic categorization task

For both groups, each run of the semantic categorization task consisted of 82 trials (36 words (consisting of 18 ‘living’ and 18 ‘nonliving’ words), 36 non-words, and 10 null-event trials). Monolinguals completed two runs, performing 144 trials total (72 words, 72 non-words); bilinguals completed four runs (two in each language), performing 288 trials total (144 per language, 72 words and 72 non-words per language).

In each trial, a bold fixation cross was presented for 500 ms (Figure 8.2b), followed by the word/non-word stimulus (no SOA was included, as only one stimulus was presented). On word trials, participants categorized the words as ‘living’ or ‘non-living’ by pressing the button-box with the left (living) or right (non-living) index finger. On non-word conditions, participants were instructed to press either the left or right index finger. In null-event trials, a non-bold fixation cross was presented for 750 ms. An ISI fixation screen with a non-bold fixation cross followed each trial, varying from 1500-3000 ms in 200-ms intervals (average 2200 ms). Trial orders were again pseudo-randomly presented to optimize list efficiency.

Figure 8.2: Example trial timing for the a) flanker and b) semantic categorization task. Duration of each stimulus is indicated on the right.



2.4. fMRI scan procedure and pre-processing

Structural and functional MRI scans were acquired using a Siemens Skyra 3.0 Tesla scanner at the Nuclear Magnetic Resonance Facility of the NIH. A sagittal T1-weighted volumetric sequence (TR 7600 ms, TE 2.3 ms, flip angle 8 degrees, NSA 1.0, FOV 256 mm, 256 x 256 matrix, 1.0 mm slice thickness, no gap, 184 slices) was acquired as a structural reference scan. Approximation of field inhomogeneities was obtained using a GRE field mapping sequence (short TE = 4.92, long TE = 7.38). fMRI was performed using EpiBOLD (echoplanar blood oxygenation level dependent) imaging. For the fMRI sequences, a gradient-echo echoplanar pulse sequence was used (TR 1600 ms, TE 28 ms, flip angle 90 degrees, GRAPPA acceleration factor of 2, resolution 3.3 x 3.3 x 3.5 mm, 30 slices of 3.5 mm thickness with no gap, FOV 210 mm, matrix size 64 x 64).

The 3T used for testing was a new Siemens model and was new to the laboratory: this was the first data to be collected on it. After data collection, problems with the GRAPPA acceleration sequence were discovered which may have created and affected motion artifacts non-uniformly across the brain. Various steps were taken during pre-processing and modelling to clean up the data as much as possible (e.g. larger smoothing kernel, modelling additional motion parameters; see specifics below), but it should be noted that this fMRI data is inherently noisy.

Pre-processing and data analyses were performed using SPM8 (Wellcome Department of Cognitive Neurology; the FIL methods group, “Statistical Parametrical Mapping”, http://www.fil.ion.ucl.ac.uk/spm/). The first four scans from each functional run were removed from the data files. Field mapping was performed using the FieldMap SPM toolbox (e.g. Hutton et al., 2002), which provided a template for subsequent registration. Slice timing correction was performed to account for timing differences due to interleaved slice acquisition. For each subject, functional images were spatially realigned to the first volume of the first run to account for motion during the scan, using the template output from the FieldMap procedure. The anatomical scan was then co-registered to a mean EPI image of the realigned functional scans. The original anatomical scan was segmented using DARTEL into grey matter, white matter, and cerebro-spinal fluid to create a template of transformation parameters for normalizing the anatomical image to an MNI template brain. Functional and structural images were then normalized using these parameters. The normalized functional images were spatially smoothed using a 10 mm FWHM isotropic Gaussian kernel.

2.5. fMRI analyses

Vectors of stimuli onsets were created for each trial type; onsets were defined by the time of first stimulus presentation (i.e. the distractor, in the flanker task). Each task (flanker and semantic categorization) was modelled separately, including all of the runs (i.e. both English and Spanish runs in bilinguals). Behavioural errors and outliers were included as additional vectors in the model specification, as were the two null-event conditions. In the flanker task, the additional semantic control condition was modelled with the other trial types in the design matrix, although it was not included in any of the analyses. Six realignment parameters from the realignment step of pre-processing were included in each design matrix as covariates, as well as two autoregressive parameters for each motion direction, a displacement parameter, and the hyperbolic tangent of the displacement parameter (Power, Barnes, Snyder, Schlaggar, & Petersen, 2012). The stimuli onset vectors were convolved using a canonical HRF plus the temporal derivative. Statistical analyses based on general linear modelling (GLM) were performed by multiple linear regression of the signal time course in each voxel.

3. Results

3.1. Flanker task: behavioural data

Incorrect responses (monolinguals 2.3%, bilinguals 1.7%) and outliers (RTs of less than 200 or greater than 1000 ms[22]; monolinguals 0.4%, bilinguals 0.8%) were removed before analyses. Mean RTs for both groups are presented in Figure 8.3, and effect magnitudes are presented in Figure 8.4.

3.1.1. Monolinguals

Monolingual behavioural analyses first considered the effects of congruency and distractor type on the Flanker effects by performing a 2 (congruency: incongruent/congruent) x 2 (distractor type: linguistic/non-linguistic) ANOVA, with follow-up paired-sample *t*-tests and calculations of effect size (*r*) to compare the magnitude of significant effects. The ANOVA showed main effects of congruency ($F(1,14) = 88.68$, $p < 0.0001$) and type ($F(1,14) = 6.28$, $p < 0.05$), and an interaction of congruency and type ($F(1,14) = 20.15$, $p < 0.001$). Significant Flanker effects (i.e. differences between incongruent and congruent conditions) occurred for both linguistic ($t(14) = 3.69$, $p < 0.01$) and non-linguistic distractors ($t(14) = 9.77$, $p < 0.0001$), but the effect was larger for non-linguistic distractors (47 ms, $SE = 5$ ms; $r = 0.93$) than linguistic (17 ms, $SE = 7$ ms, $r = 0.70$; $t(28.0) = 4.42$, $p < 0.001$; Figure 8.4).

The incongruent and congruent conditions of each distractor type were next compared to the control condition using paired-sample *t*-tests (an overall ANOVA was not performed as the control condition lacked a linguistic/non-linguistic level) to identify significant interference and facilitation effects in each group. Significant interference effects occurred for both linguistic (20 ms, $SE = 5$ ms, $r = 0.74$; $t(14) = 4.17$, $p < 0.001$) and non-linguistic distractors (42 ms, $SE = 6$ ms, $r = 0.89$; $t(14) = 7.45$, $p < 0.0001$), with a significantly larger effect in the non-linguistic distractors ($t(14) = 4.87$, $p < 0.001$; Figure 8.4). No facilitation occurred in either linguistic or non-linguistic conditions (all *p*'s > 0.21).

---

[22] A lower outlier threshold was used due to the faster RTs in the flanker task.

3.1.2. Bilinguals

Bilingual analyses first considered the effects of congruency, distractor type, and language on the Flanker effects: a 2 (congruency: incongruent/congruent) x 2 (distractor type: linguistic/non-linguistic) x 2 (language: English/Spanish) ANOVA showed main effects of congruency ($F(1,13) = 23.37$, $p < 0.001$) and type ($F(1,13) = 5.00$, $p < 0.05$) but not of language ($p = 0.33$). There was a trend of an interaction between congruency and language ($F(1,13) = 3.34$, $p = 0.09$): although both English and Spanish elicited significant Flanker effects, the effect was slightly larger (collapsed across distractor type) in English (36 ms, *SE* = 11 ms, $r = 0.65$; $t(27) = 4.47$, $p < 0.001$) than in Spanish (24 ms, *SE* = 13 ms, $r = 0.47$; $t(27) = 2.73$, $p < 0.01$). However, as the interaction was a trend and the main effect of language was non-significant, all subsequent bilingual analyses were collapsed over language. There was also an interaction of congruency and type ($F(1,13) = 16.35$, $p < 0.01$): although the linguistic Flanker effect was not significant (4 ms, *SE* = 5 ms; $p = 0.41$), non-linguistic distractors showed a significant Flanker effect (55 ms, *SE* = 11 ms; $t(13) = 4.81$, $p < 0.001$) which was significantly larger than the linguistic Flanker effect ($t(13) = 4.02$, $p < 0.01$; Figure 8.4).

To identify interference and facilitation effects, the incongruent and congruent conditions of each distractor type (collapsed across language) were compared to the control condition. Significant interference occurred for both linguistic (12 ms; *SE* = 5 ms, $r = 0.40$; $t(27) = 2.28$, $p < 0.05$) and non-linguistic distractors (51 ms; *SE* = 9 ms, $r = 0.82$; $t(27) = 7.47$, $p < 0.0001$), with a larger effect in the non-linguistic conditions ($t(13) = 5.23$, $p < 0.001$; Figure 8.4). Neither distractor type showed a significant facilitation effect (all p's > 0.15).

Figure 8.3: Mean RTs for each condition and group in the flanker task.

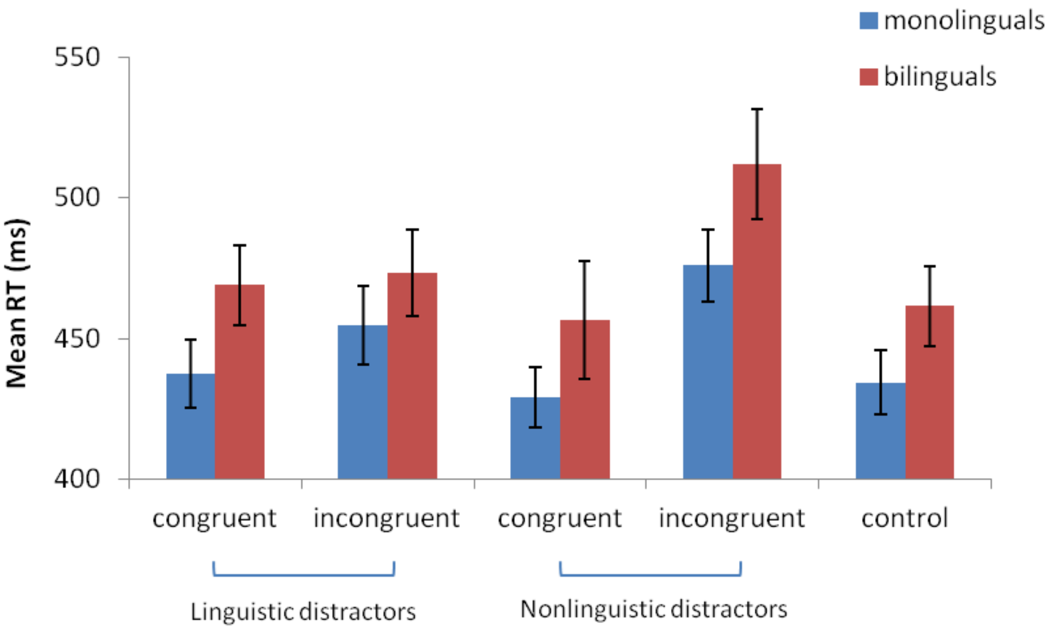
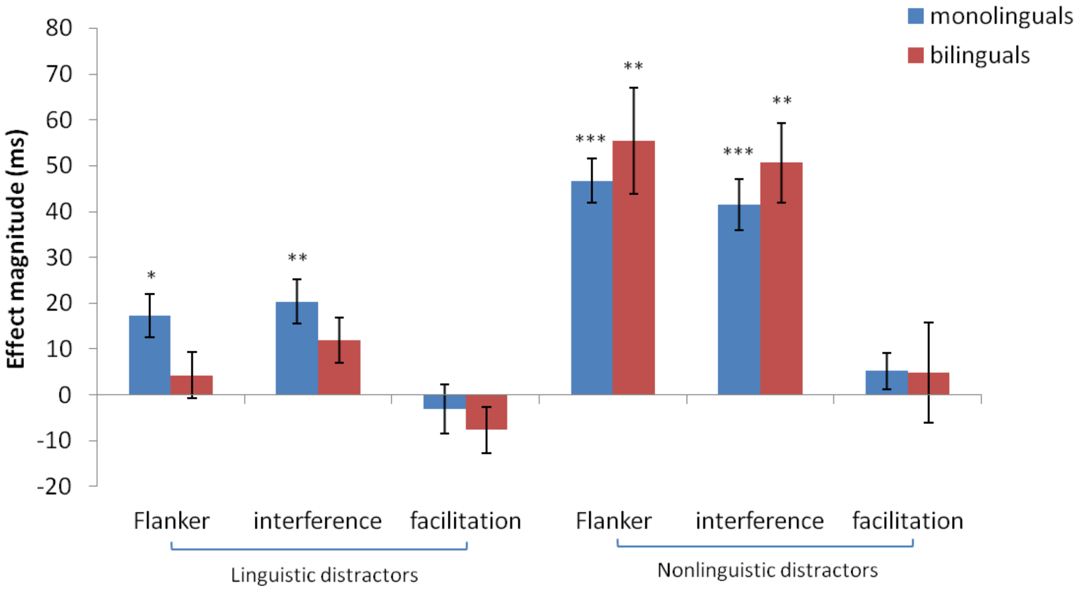


Figure 8.4: Behavioural effect magnitudes in each group. Significant effect sizes within groups are indicated by asterisks above error bars (* = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$).



3.1.3. Between-group comparisons

To assess differences in the magnitude of Flanker, interference, and facilitation effects between monolinguals and bilinguals, a 2-way (distractor type: linguistic/non-linguistic) ANOVA with group (monolingual/bilingual) as a between-subjects factor was run for each effect. Flanker effects showed a main effect of type ($F(1,54) = 32.77$, $p < 0.0001$), with larger effects for non-linguistic (51 ms, *SE* = 6 ms) than linguistic conditions (11 ms, *SE* = 4 ms; $t(45.6) = 5.70$, $p < 0.0001$). There was no effect of group ($p = 0.76$) and no interaction ($p = 0.13$), indicating no overall differences in the magnitude of Flanker effects between groups. There were also no differences in the magnitude of the non-linguistic Flanker effect between groups ($p = 0.49$). Comparing interference effects, there was a main effect of type ($F(1,54) = 23.30$, $p < 0.0001$) such that interference effects were again larger for the non-linguistic conditions (46 ms, *SE* = 5 ms) than for the linguistic conditions (16 ms, *SE* = 3 ms; $t(49.6) = 4.83$, $p < 0.0001$). However, there was no effect of group ($p = 0.96$) and no interaction ($p = 0.16$; Figure 8.4). The facilitation effects showed no main effects of group or type, and no interaction (all *p*'s > 0.13).

As in previous chapters, analyses of global RT effect compared the control condition RTs between groups. However, there was no significant difference between monolinguals (434 ms, *SE* = 11 ms) and bilinguals (461 ms, *SE* = 14 ms; $t(25.3) = 1.48$, $p = 0.15$): bilinguals actually had overall longer RTs in all trial types (Figure 8.3), although there were no statistically significant differences when comparing congruencies directly between groups (all *p*'s > 0.10).

3.2. Semantic categorization task: behavioural data

Previous research has reported that bilinguals are slower on semantic categorization tasks than monolinguals (e.g. Phillips et al., 2004), suggesting delays in language processing as predicted by the bilingual lexical disadvantage hypotheses (Chapter 1, sections 2.1 and 2.2). This effect was investigated in the current data by comparing the mean RTs between groups. For both word and non-word conditions, outliers (RTs of less than 200 ms or greater than 2000 ms: monolinguals 0.4%, bilingual English 1.0%, bilingual Spanish 0.2%) were removed from behavioural analyses. Error analyses were not performed for the semantic categorization data, as the effect of interest was semantic retrieval rather than categorization accuracy. Bilinguals were significantly slower to categorize Spanish words than monolinguals were to categorize English words (monolinguals = 722 ms, *SE* = 21 ms; bilingual Spanish = 794 ms, *SE* = 23 ms; $t(26.4) = 2.30$, $p < 0.05$). There was also a weak trend of slower categorization times for bilinguals in English compared to monolinguals (bilingual English = 775 ms, *SE* = 23 ms; $t(26.4) = 1.72$, $p = 0.10$). Categorization times for English and Spanish words did not differ within bilinguals ($p = 0.33$). The groups did not differ on non-word RTs (all *p*'s > 0.51; monolinguals = 602 ms, *SE* = 28 ms; bilingual English = 580 ms, *SE* = 13 ms; bilingual Spanish = 594 ms, *SE* = 19 ms).

3.3. Flanker task: fMRI data

In the flanker fMRI data, analyses first identified neural activation for the Flanker (incongruent > congruent), interference (incongruent > control) and facilitation (congruent > control) effects for linguistic and non-linguistic distractor types, both within and between groups. To assess the larger effects of distractor type, the data were collapsed over congruency (incongruent/congruent): this identified areas involved in ignoring distracting linguistic or non-linguistic information, regardless of the presence of conflict. Four contrasts were performed: linguistic > control, non-linguistic > control, linguistic > non-linguistic, and non-linguistic > linguistic. All analyses for the flanker task used a threshold of $p < 0.001$ and cluster extent of 20 voxels (which is a slightly smaller cluster extent than in Chapter 7, given the noisier data resulting from scanner problems; see section 2.4).

3.3.1. Monolingual main effects

In monolingual linguistic comparisons, there was no significant activation in the Flanker contrast, but both interference and facilitation activated the right angular gyrus (BA 40; Table 8.2). Facilitation additionally activated executive control areas such as the medial/superior frontal gyrus, bilateral MFG (BAs 6/8/9), and RIFG (BA 47). In non-linguistic conditions, the Flanker and interference contrasts showed no significant effects; however, non-linguistic facilitation activated the right angular gyrus (BA 40).

3.3.2. Bilingual main effects

The bilingual flanker data were collapsed over language runs such that both English and Spanish linguistic distractor words were analyzed together. For linguistic distractors, the Flanker contrast showed a large cluster of activation in the cingulate/MFG (BA 10/32/9/24), as well as activation in the LIFG (BA 44/45/46), LMFG (BA 9/6/8/32), left superior frontal gyrus (BA 9), and RMFG (BA 9/8/32; Table 8.2). As in the monolingual data, the non-linguistic conditions showed notably less activation overall: non-linguistic Flanker and interference effects elicited no significant activation, but facilitation activated the LIFG (BA 47).

3.3.3. Comparison between groups

The groups were next directly compared on each contrast using two-sample *t*-tests (Table 8.3). In the linguistic Flanker effect, bilinguals showed more activation than monolinguals in executive control areas such as the RMFG/cingulate (BAs 10/9/32/11) and bilateral MFG (BA 9/32). In linguistic interference, monolinguals showed more right angular gyrus/superior parietal lobe (BA 40) activation, whereas bilinguals showed more LIFG activation (BA 45/46).In linguistic facilitation, monolinguals activated the RMFG (BA 8/9/10), posterior cingulate (BA 31/7), and RIFG (BA 46) more than bilinguals. The groups did not differ extensively in non-linguistic Flanker or interference effects; however, for non-linguistic facilitation bilinguals showed more activation in the right supramarginal gyrus (BA 41/13) and right postcentral gyrus (BA 4/43).

Table 8.2: Main contrasts for each group using a threshold of $p < 0.001$ and 20 voxels. Brodmann areas (BA) for the entire cluster are listed; for large clusters that extend into multiple areas, regions/BAs are listed in order of their activation extent. Cluster size is reported in number of voxels. Z-score and MNI coordinates are taken from the peak of the cluster.

Group	**Distractor type**	**Contrast**	**Region**	**BA(s)**	**MNI coordinates**			**Cluster size**	**Peak Z-score**
					x	**y**	**z**		
Monolinguals	Linguistic	Flanker effect	No voxels surviving thresholding	--	--	--	--	--	--
		Interference	R angular gyrus	40	38	-46	44	127	3.69
		Facilitation	Medial/superior frontal gyrus	9,8,6	10	50	30	529	3.99
			R angular gyrus	40	52	-60	46	178	4.49
			R middle frontal gyrus	6,8	34	12	52	163	3.97
			R middle frontal gyrus	9,8	44	26	44	143	3.80
			L middle frontal gyrus	8	-42	22	50	82	4.42
			R lateral front-orbital gyrus/inferior frontal gyrus	47	42	24	-6	21	3.67
	Non-linguistic	Flanker effect	No voxels surviving thresholding	--	--	--	--	--	--
		Interference	No voxels surviving thresholding	--	--	--	--	--	--
		Facilitation	R angular gyrus	40	52	-54	40	228	4.37
Bilinguals	Linguistic	Flanker effect	Cingulate/medial/middle frontal gyrus	10,32,9,24	14	56	16	1264	5.18
			Cuneus/precuneus	31,30,23	-18	-56	28	756	4.01
			R middle temporal gyrus/middle occipital gyrus	39,40	60	-56	18	528	4.19
			L middle frontal gyrus	9,6	-38	0	34	291	4.30
			L inferior frontal gyrus	46	-50	32	16	178	4.24
			R cingulate	10,32	12	38	-2	156	4.09
			L medial frontal gyrus/RCZ	8,6,32	-8	12	50	74	3.61
			L superior frontal gyrus	9	-14	34	42	63	3.72
			L inferior frontal gyrus	44,45	-46	12	12	51	3.67
			L lateral occipitotemporal gyrus	37	-38	-58	-10	40	4.04
			L middle occipital/temporal gyrus	39	-48	-64	20	39	3.45

			R medial frontal gyrus	9	18	26	28	26	3.66
			R middle frontal gyrus	8	36	18	48	24	3.54
			R medial frontal gyrus	32	18	20	36	23	3.82
			R middle temporal gyrus	21	66	-48	-6	22	3.73
			L occipital pole/lingual gyrus	17	-12	-100	-2	21	3.60
			R cuneus/lingual gyrus	18,17	10	-84	10	21	3.43
		Interference	L inferior frontal gyrus	47,45	-48	24	-10	306	4.19
			L superior/middle temporal gyrus	40,39,22	-52	-52	24	203	3.92
			L medial occipitotemporal gyrus	18,30	-6	-66	2	35	3.42
		Facilitation	No voxels surviving thresholding	--	--	--	--	--	--
	Non-linguistic	Flanker effect	No voxels surviving thresholding	--	--	--	--	--	--
		Interference	No voxels surviving thresholding	--	--	--	--	--	--
		Facilitation	L inferior frontal gyrus	47	-36	32	-10	29	3.70

Table 8.3: Direct comparisons of monolinguals and bilinguals on the main contrasts of interest, at a threshold of $p < 0.001$ and 20 voxels.

Distractor type	**Contrast**	**Comparison**	**Region**	**BA(s)**	**MNI coordinates**			**Cluster size**	**Peak Z-score**
					x	**y**	**z**		
Linguistic	Flanker effect	monolingual > bilingual	No voxels surviving thresholding	--	--	--	--	--	--
		bilingual > monolingual	R medial frontal gyrus/cingulate	10,9,32,11	14	58	20	2955	4.87
			Precuneus/cuneus	31,23	0	-68	20	472	4.15
			Thalamus	--	0	-4	16	91	3.94
			R middle occipital gyrus/angular gyrus	39	54	-66	32	54	3.74
			L medial frontal gyrus	9,32	-12	42	28	51	3.66
			R medial frontal gyrus	9	18	26	28	40	4.13
			R lateral occipitotemporal gyrus	19	32	-50	-6	34	3.66
			L parahippocampal gyrus	19	-34	-52	0	25	3.90
	Interference	monolingual > bilingual	R angular gyrus/superior parietal lobe	40	38	-48	44	41	3.55
		bilingual > monolingual	L inferior frontal gyrus	46,45	-50	36	2	27	3.66
			R medial front-orbital gyrus/cingulate	11	2	44	-16	23	3.36
	Facilitation	monolingual > bilingual	R middle/superior frontal gyrus	8,9	32	34	50	485	4.35
			R inferior occipital gyrus	18	28	-98	-2	251	4.94
			R superior parietal lobe/posterior cingulate	31,7	8	-44	42	233	4.21
			R cingulate/medial/superior frontal gyrus	10	10	66	0	86	3.66
			R medial frontal gyrus	9	10	44	24	53	3.58
			R middle/inferior frontal gyrus	46,10	48	46	20	32	3.54
		bilingual > monolingual	No voxels surviving thresholding	--	--	--	--	--	--

Non-linguistic	Flanker effect	monolingual > bilingual	R medial occipitotemporal gyrus	30	12	-38	-8	26	3.85
		bilingual > monolingual	No voxels surviving thresholding	--	--	--	--	--	--
	Interference	monolingual > bilingual	R occipital pole/inferior occipital gyrus	18	24	-102	-2	67	3.72
		bilingual > monolingual	No voxels surviving thresholding	--	--	--	--	--	--
	Facilitation	monolingual > bilingual	No voxels surviving thresholding	--	--	--	--	--	--
		bilingual > monolingual	R superior temporal gyrus/supramarginal gyrus	41,13	40	-36	18	84	3.82
			R postcentral gyrus	43	68	-12	18	34	3.74
			R precentral/postcentral gyrus	4	8	-40	68	24	3.59

3.3.4. Linguistic vs. non-linguistic distractors

The data was next collapsed over incongruent and congruent trials to investigate global effects of linguistic and non-linguistic distractor types (Table 8.4). In monolinguals, when compared to the control condition both linguistic and non-linguistic conditions activated the right angular gyrus (BA 40) and RMFG (BA 6), with additional LMFG activation (BA 8) for linguistic distractors. In direct comparisons, linguistic conditions were significantly more active than non-linguistic in the left caudate, LIFG (BA 44/45), and right posterior cingulate (BA 30). In bilinguals, compared to the control condition the linguistic distractors activated only the LIFG (BA 47). No activity occurred for non-linguistic distractors vs. control (although there was significant LIFG activation with a lower cluster threshold of 10 voxels). In direct comparisons, the linguistic condition showed more left superior parietal lobe activation (BA 7), while the non-linguistic condition elicited more activation in visual areas.

In group comparisons of the linguistic/non-linguistic contrasts (Table 8.5) monolinguals experienced more activation than bilinguals, specifically in the RMFG (BAs 8/9/46/10), right angular gyrus (BA 40), and right superior parietal lobe (BA 7) for linguistic conditions and in the RMFG (BA 9) for non-linguistic conditions. In the linguistic > non-linguistic contrast, monolinguals showed more left caudate and left posterior cingulate (BA 30) activation.

As these linguistic vs. non-linguistic comparisons collapsed over congruency, they can be considered as an examination of conflict-independent executive processing. A global RT effect was also examined in the fMRI data by comparing the control > attentional null-event contrasts in each group; however, no significant effects remained with a cluster threshold of 20 voxels. When using a less conservative threshold of 10 voxels, clusters in the RMFG and right superior parietal lobe (BA 7) were significantly more active for bilinguals than monolinguals.

Table 8.4: Linguistic vs. non-linguistic comparisons (collapsed over congruency) for each group, using a threshold of $p < 0.001$ and 20 voxels.

Group	Contrast	Region	BA (s)	MNI coordinates			Cluster size	Peak Z-score
				x	y	z		
Monolinguals	linguistic > control	R angular gyrus	40	54	-60	46	345	4.12
		R middle frontal gyrus	6,8	30	16	50	126	3.66
		L middle frontal gyrus	8	-36	22	46	56	3.61
	non-linguistic > control	R angular gyrus	40	46	-56	54	146	3.74
		R superior/middle frontal gyrus	6	24	16	62	35	3.39
	linguistic > non-linguistic	L caudate nucleus/precentral gyrus	4	-26	-20	38	525	4.42
		R insula	13	30	-40	22	225	4.28
		L insula	13	-26	-40	26	219	4.41
		L inferior/middle frontal gyrus	45,44	-48	20	16	152	3.69
		L superior/middle temporal gyrus	22	-62	-48	12	62	3.35
		R posterior cingulate	30	28	-68	14	37	3.88
		L lateral occipitotemporal gyrus	19	-36	-50	-6	31	3.64
		R inferior occipital gyrus	18,19	44	-88	-8	22	3.85
		L lateral occipitotemporal gyrus	18	-36	-90	-16	20	3.30
	non-linguistic > linguistic	L lingual gyrus/inferior occipital gyrus	17	-10	-88	-6	20	3.83
Bilinguals	linguistic > control	L inferior frontal gyrus	47,46	-48	40	-2	40	3.49
		L inferior frontal gyrus/lateral front-orbital gyrus	47	-46	26	-10	23	3.31
	non-linguistic > control	No voxels surviving thresholding	--	--	--	--	--	--
	linguistic > non-linguistic	Cuneus/precuneus	31,7,18	2	-78	30	127	4.05
		L superior parietal lobule	7	-34	-68	56	46	3.72
		L superior parietal lobule	39,7,19	-32	-64	40	41	3.31
	non-linguistic > linguistic	R superior/middle occipital gyrus	19,18	34	-80	16	383	4.06
		L superior occipital gyrus	19,18	-26	-94	22	103	3.94
		R middle temporal gyrus	37,19	56	-64	-2	82	3.80

Table 8.5: Comparison of linguistic vs. non-linguistic comparisons between groups, using a threshold of $p < 0.001$ and 20 voxels.

Contrast	**Comparison**	**Region**	**BA (s)**	**MNI coordinates**			**Cluster size**	**Peak Z-score**
				x	**y**	**z**		
Linguistic > control	monolingual > bilingual	R inferior occipital gyrus	18	28	-98	-2	89	4.15
		R middle frontal gyrus	8,9	36	34	44	48	3.57
		R angular gyrus	40	40	-48	46	21	3.42
		R superior parietal lobule/precuneus	7	14	-64	40	20	3.51
	bilingual > monolingual	No voxels surviving thresholding	--	--	--	--	--	--
Non-linguistic > control	monolingual > bilingual	R middle frontal gyrus	9	50	26	32	28	3.41
	bilingual > monolingual	No voxels surviving thresholding	--	--	--	--	--	--
Linguistic > non-linguistic[23]	monolingual > bilingual	R superior/middle occipital gyrus	18,31	30	-70	12	234	4.20
		L caudate	--	-18	-38	20	74	4.35
		R middle temporal gyrus	37,19	58	-66	-4	55	3.46
		L inferior occipital gyrus	19	-38	-76	2	40	3.44
		L posterior cingulate	30	-22	-48	12	29	3.61
		L superior occipital gyrus	19	-26	-92	26	25	3.51
	bilingual > monolingual	No voxels surviving thresholding	--	--	--	--	--	--

---

[23] The non-linguistic > linguistic group comparison generated the same clusters as the linguistic > non-linguistic, but with opposite effects (i.e. significant activation in bilinguals).

3.4. Semantic categorization task: fMRI data

In the semantic categorization task, the word > non-word contrast was analyzed using a more conservative threshold of $p < 0.0001$ and 20 voxels due to the larger extent of activation (Table 8.6). Living and non-living word conditions were combined, as the effect of interest was the neural areas activated by semantic retrieval, regardless of the result of the semantic decision. In monolinguals, the word > non-word comparison activated the LIFG/insula (BA 9/13/45/46/47), right insula (BA 13/47), right cingulate (BA 32), and lingual gyrus. For bilinguals, analyses were combined across languages as well as split between English and Spanish. The collapsed-language analyses (Table 8.6) showed activation in areas such as the left superior parietal lobe/angular gyrus (BA 7/40) and LIFG (BA 45/46/47). As in the monolingual data, the RCZ/cingulate (BAs 32/6/24) was also activated. The English-only comparison showed one cluster in the LIFG/insula (BA 13/47), but the Spanish-only contrast showed a large extent of activation that largely overlapped with the combined-language contrast, indicating that Spanish drove the overall effects. The groups were also compared on the word > non-word contrasts (Table 8.6). Bilinguals showed more activation than monolinguals in one cluster in the left superior parietal lobe/angular gyrus (BA 40).

Table 8.6: Results of the semantic categorization contrasts for each group, and direct comparisons of monolinguals and bilinguals on the word > non-word contrasts, at $p < 0.0001$ and 20 voxels.

Group	**Contrast**	**Region**	**BA(s)**	**MNI coordinates**			**Cluster size**	**Peak Z-score**
				x	**y**	**z**		
Monolinguals	Word > non-word	R lingual gyrus	17,18	12	-84	0	231	5.97
		L lateral occipitotemporal gyrus	37	-34	-48	-18	146	5.70
		L lingual gyrus/medial occipitotemporal gyrus	17,18	-10	-86	2	146	4.59
		L inferior frontal gyrus	46,13,45	-52	32	14	105	4.52
		R insula/lateral front-orbital gyrus	47,13	26	30	-10	86	5.03
		L insula/inferior frontal gyrus	47	-40	20	-8	36	4.30
		L lateral occipitotemporal gyrus	19,18	-36	-80	-10	26	4.29
		R cingulate	32	10	30	20	24	4.10
Bilinguals	Word > non-word	Medial frontal gyrus/cingulate/RCZ	32,6,24	8	8	48	420	4.65
		L superior parietal lobe/angular gyrus	7	-26	-66	36	263	4.56
		L middle/inferior frontal gyrus/precentral gyrus	9,45,46	-56	14	32	246	4.65
		L inferior/middle frontal gyrus	46	-50	32	16	145	4.97
		L insula/inferior frontal gyrus	47,13	-30	18	-2	133	4.24
		R inferior occipital gyrus	18,19	38	-84	-2	98	4.34
		L uncus/ hippocampus/ parahippocampal gyrus	--	-26	-12	-14	59	4.42
		L lateral occipitotemporal gyrus	37	-40	-62	-8	47	4.25
		L medial occipitotemporal gyrus	19	-8	-48	-8	45	4.25
	English word > non-word	L insula/inferior frontal gyrus	13,47	-34	20	2	33	4.40
	Spanish word > non-word	R inferior/superior occipital gyrus	19,18	38	-84	-6	353	4.47
		Medial frontal gyrus/cingulate/RCZ	32,6,24	8	6	54	233	4.35
		L angular gyrus/superior parietal lobe	7	-26	-66	32	216	4.73
		L middle/inferior frontal gyrus/precentral gyrus	9,45,46	-56	12	32	198	4.34
		L lateral occipitotemporal gyrus	37	-40	-64	-6	115	4.30

		L cuneus/medial occipitotemporal gyrus	30,23,31	-4	-70	10	111	4.06
		L inferior frontal gyrus	46	-44	30	14	64	4.26
		R medial occipitotemporal gyrus	30	32	-50	6	58	4.73
		Medial/superior frontal gyrus	6	0	10	66	55	4.16
		L putamen/uncus	--	-26	-4	-12	44	4.32
		R insula/inferior frontal gyrus	47,13	38	12	-2	40	4.08
		L inferior frontal gyrus/precentral gyrus	44,22,47	-60	10	6	37	4.35
		L inferior frontal gyrus	47	-44	28	0	20	3.89
Bilinguals > monolinguals	Word > non-word	L superior parietal lobe/angular gyrus	40	-24	-62	34	210	4.55
Monolinguals > bilinguals	Word > non-word	No voxels surviving thresholding	--	--	--	--	--	--

3.5. Conjunction analyses

The current study primarily aimed to identify how bilinguals differentially activate the executive control and language networks compared to monolinguals; this was investigated with conjunction analyses. As the bilingual advantage generally extends beyond conflict control to more general executive processing, the results of the linguistic/non-linguistic contrasts (linguistic > control and non-linguistic > control) were used in the conjunctions. By collapsing over congruency, analyses focused on general distractor management regardless of the presence of conflict. The language contrasts (word > non-word) were also included in the conjunctions. These analyses therefore identified areas that were commonly activated in domain-general linguistic control, domain-general non-linguistic control, and language processing.

The first-level contrasts of linguistic > control, non-linguistic > control, and word > non-word were entered into a second-level three-way ANOVA and a conjunction was performed with all three main effects, using a statistical threshold of $p < 0.01$ uncorrected and a cluster threshold of 10 voxels. A conjunction analysis is a more stringent statistical test since it requires that activation be significant in each individual contrast as well in the conjunction; therefore using a lower statistical threshold is common practice (Fan, Flombaum et al., 2003; Wager et al., 2005; Nichols, Brett, Andersson, Wager, & Poline, 2005).

In monolinguals, there were no significant areas of activation surviving thresholding, indicating largely dissimilar neural regions for linguistic and non-linguistic control and language processing (Figure 8.5). In the bilinguals, however, the conjunction analysis showed a significant cluster of activation (37 voxels) in the LIFG (BA 47, MNI coordinates -32, 26, -12, peak Z-score = 2.66; see Figure 8.5 and Figure 8.6). Importantly, the LIFG was the site of functional overlap of language and executive control for bilinguals but not monolinguals.

Figure 8.5: Overlaid conjunction of the linguistic > control, non-linguistic > control, and word > non-word contrasts at $p < 0.01$ and a cluster extent of 20 voxels for a) monolinguals and b) bilinguals. Axial slices are shown from z = -25 to z = 70.

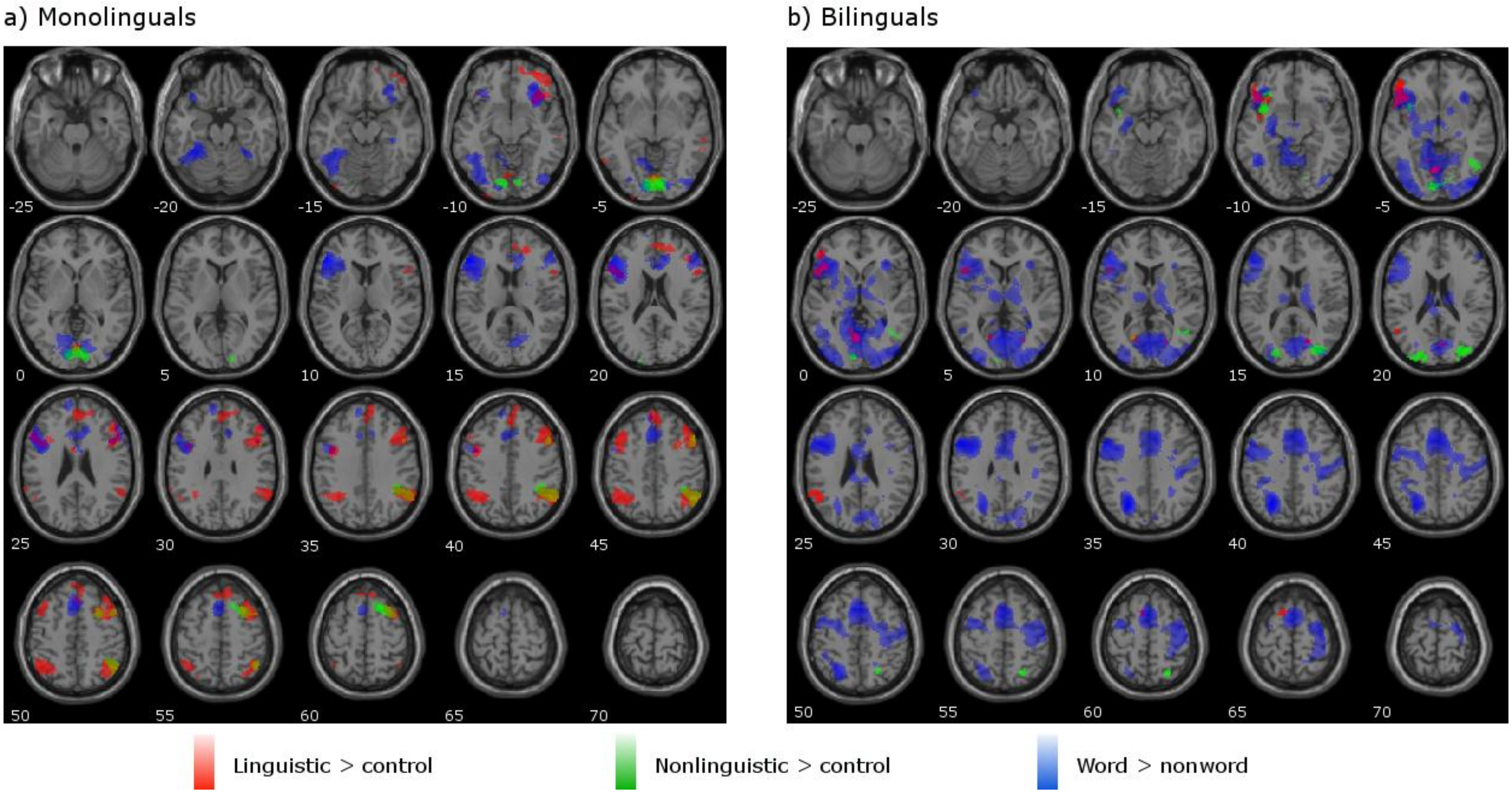
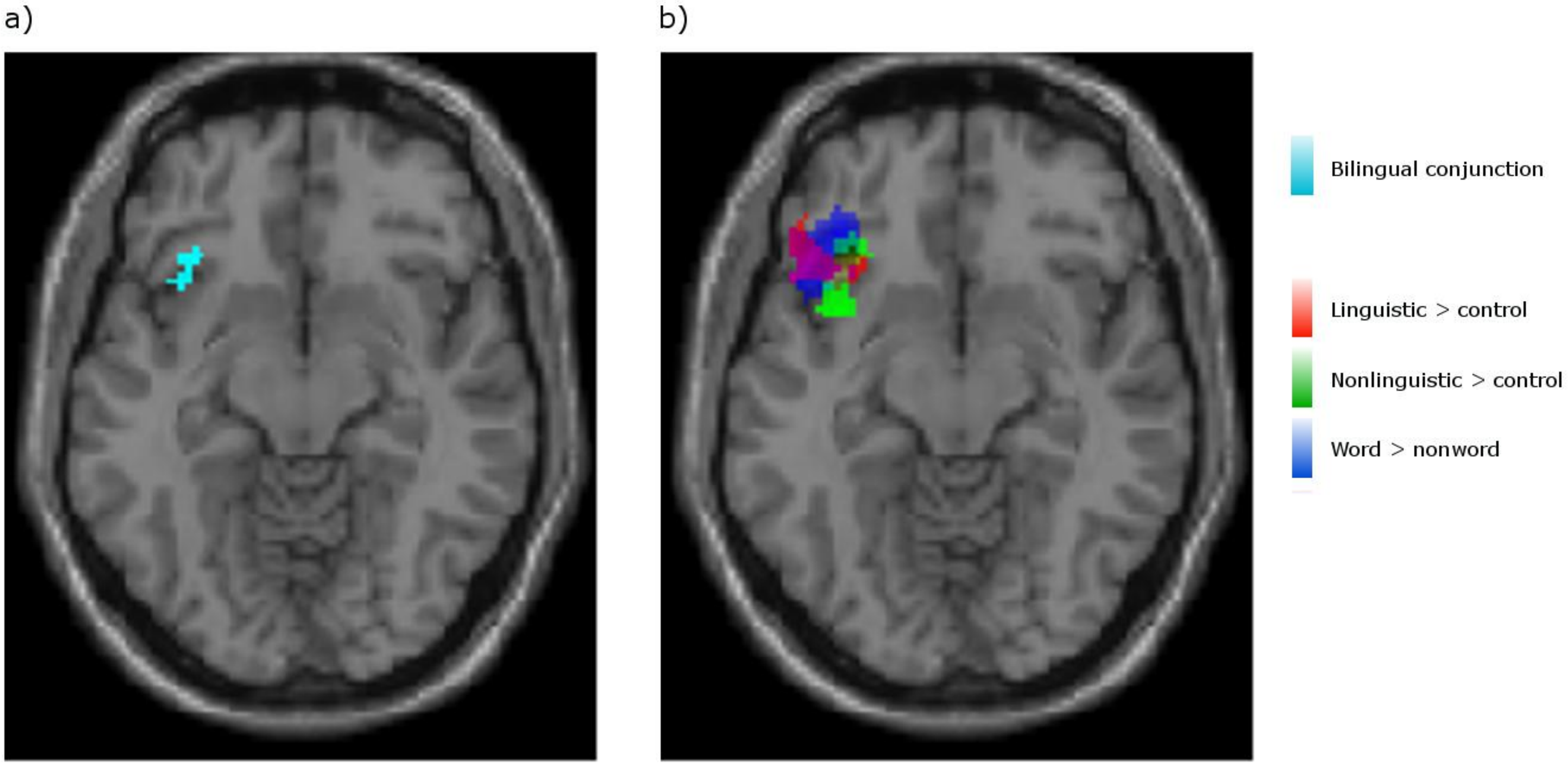


Figure 8.6: a) Conjunction of all three contrasts for bilinguals, at z = -10. b) Focus on the LIFG activation in the bilingual conjunction (using an ROI mask of 20 mm around the statistical peak at -32, 26, -12), at z = -10.



4. Discussion

The current chapter sought to identify a neural locus of the bilingual cognitive advantage by examining group differences in the functional overlap of cognitive control and language processing. If the recruitment of executive control during bilingual language processing leads to an integration of these two systems, a specific region or network that is involved in both should be enhanced in bilinguals. To investigate this, linguistic and non-linguistic cognitive control and language processing were compared between and within groups and were contrasted using a conjunction analysis. Each domain is addressed in turn.

4.1. Cognitive control in monolinguals and bilinguals

Behaviourally, both groups showed larger effects for non-linguistic than linguistic flanker conditions. This could be due to the temporal limitations of semantic access: word reading is a slower process than responding to arrows, so the linguistic distractors may have been too slow to cause strong interference (e.g. see Chapter 2, section 2.1). Alternatively, ignoring printed words may be a more familiar procedure than ignoring arrows. For example, although the eye fixates on one word when reading, peripherally-visible words must be ignored to avoid distraction and comprehension errors. The distractor words appeared above and below the target stimuli in this paradigm, which may have created a situation similar to reading. If ignoring printed words is a more practised ability, this could have reduced the influence of linguistic distractors and created smaller effects.

One again a negative correlation was observed between the behavioural and neural data: larger behavioural effects occurred for non-linguistic conditions, whereas more extensive neural activation occurred for the linguistic effects. This replicates previous findings (Booth et al., 2003; Egner & Hirsch, 2005a, 2005b; Fan, Fossella et al., 2003), as well those of the previous fMRI experiment (Chapter 7). Although semantic access in the linguistic distractors may have occurred too slowly to cause behavioural interference, the slow time scale of fMRI may be more sensitive to this process, which could explain this inverse effect. Alternatively, the inverse relationship in linguistic conditions could indicate that both groups experienced more efficient cognitive processing when dealing with linguistic distractors, perhaps due to the familiarity with ignoring words during reading, as mentioned.

4.1.1. <u>Bilingual interference control</u>

According to the BICA hypothesis, conflict control should be enhanced in bilinguals: this was evaluated by comparing Flanker and interference effects between groups to assess linguistic and non-linguistic conflict processing. Behaviourally, there were no significant differences in the magnitude of Flanker or interference effects. However, Figure 8.4 demonstrates that the bilinguals showed numerically smaller conflict effects in the linguistic conditions compared to bilinguals, which could suggest a trend of a bilingual advantage only for linguistic stimuli. No significant differences occurred in non-linguistic conflict; bilinguals instead showed overall larger conflict effects than monolinguals, which does not support previous research reporting a bilingual advantage on non-linguistic conflict (e.g. Garbin et al., 2010; Luk et al., 2010; see section 4.1.3 below).

Canonical areas of the cognitive control network were activated by Flanker and interference effects in both groups, including the left and right MFG, right parietal lobe/angular gyrus, LIFG, and the cingulate/RCZ. The between-group comparisons revealed no differences in the amount or extent of neural activation for non-linguistic conflict effects. However, in the linguistic conflict effects there were notable differences in network activation: for linguistic interference specifically, bilinguals activated the LIFG, whereas monolinguals activated the right angular gyrus/superior parietal lobe. This could suggest functional differences in the management of linguistic conflict. For example, one issue in the executive control literature is whether conflict resolution is achieved by enhancement of the target stimulus or by suppression of the non-target stimulus (Cohen et al., 1990; Egner & Hirsch, 2005a; Miller & Cohen, 2001). Recall from Chapter 7 that the right superior parietal lobe has been implicated in visuospatial processes such as top-down biasing of attention towards the relevant stimulus attribute (Corbetta et al., 1993; Culham & Kanwisher, 2001; Milham et al., 2003; Rushworth et al., 2001), while the LIFG is involved in suppressing irrelevant stimuli (Novick et al., 2005, 2009; Thompson-Schill et al., 1998; Ye & Zhou, 2009). The disparate activations in linguistic interference may indicate that monolinguals manage linguistic conflict by adopting a target amplification strategy (i.e. by recruiting the right parietal lobe to direct attention towards the relevant stimulus) while bilinguals adopt a distractor suppression strategy (by recruiting the LIFG to inhibit the irrelevant words). Furthermore, LIFG recruitment may reflect a more efficient control mechanism for linguistic conflict, as bilinguals showed generally smaller (although not statistically significant) behavioural linguistic interference effects. Therefore the data suggest functionally distinct mechanisms for conflict control in bilingualism, as predicted by the BICA hypothesis.

4.1.2. Bilingual global executive processing

As in previous chapters, a behavioural global RT effect was assessed by comparing the control condition between groups. In contradiction to the BEPA hypothesis, bilinguals were slower in all conditions (although this was not statistically significant). There were no differences between the groups in the neural comparisons of the control condition, although a less conservative threshold identified greater activation for bilinguals than monolinguals in the RMFG and right superior parietal lobe (BA 7). This could indicate a global enhancement of executive control activation throughout the entire block, which carried over to the control condition (see Chapter 7). However, since bilinguals showed slower overall RTs this may instead be more reflective of processing difficulties rather than efficiency.

Conflict non-specific executive control processing was also assessed by comparing the neural response to distracting linguistic and non-linguistic information, regardless of the presence of conflict (i.e. collapsed over congruency). Monolinguals showed more activity than bilinguals, specifically in the RMFG for the non-linguistic distractors and in the RMFG, right angular gyrus, caudate, and left posterior cingulate for linguistic distractors. As these areas are involved in domain-general and linguistic cognitive control (e.g. Luk et al., 2011; Nee et al., 2007; Niendam et al., 2012), their stronger activation in monolinguals could indicate that bilinguals are less sensitive to, or are better able to suppress, the effects of distracting information, especially when linguistic in nature. Since these differences occurred when collapsing across congruency, this suggests global differences in executive processing in bilinguals, supporting the BEPA hypothesis.

4.1.3. Bilingual behavioural performance

Contrary to the predictions and to the results of previous chapters, the current data showed no behavioural evidence for a bilingual advantage in either interference or global RT effects. Although not statistically significant, bilinguals in fact showed a disadvantage compared to monolinguals, with longer global RTs and larger non-linguistic conflict effects. Other studies have also reported neural and electrophysiological differences in the absence of behavioural effects (e.g. Bialystok et al., 2005; Kousaie & Phillips, 2011). However, one explanation for the performance disadvantage in bilinguals may have been the novelty of the scanning environment: the majority of bilingual participants had not previously had an MRI scan, so the unfamiliar environment may have affected their behavioural RTs. In contrast, all monolinguals participants were familiar with MRI testing, so their behavioural performance may not have been affected.

To investigate this possibility, some of the bilingual participants were retested behaviourally, performing the same task but outside of the scanner. Only five bilingual participants were available for follow-up testing, so no strong conclusions can be drawn from this retesting data. The overall pattern was similar: compared to the original group of monolinguals, the retested bilinguals showed numerically smaller linguistic Flanker (monolinguals = 17 ms, SE = 5 ms; bilinguals = 9 ms, SE = 6 ms) and linguistic interference (monolinguals = 20 ms, SE = 5 ms; bilinguals = 19 ms, SE = 5 ms) effects, but larger non-linguistic Flanker (monolinguals 47 ms, SE = 5 ms; bilinguals = 49 ms, SE = 8 ms) and non-linguistic interference (monolinguals 42 ms, SE = 6 ms; bilinguals 61 ms, SE = 13 ms), although this was still statistically non-significant in every effect (all p's > 0.21). Compared to their individual original data, the overall RTs at retest were significantly faster ($t(4) = 3.15$, $p < 0.05$). Compared to the full group of monolinguals, the retest bilingual global RTs (415 ms, SE = 25 ms) were numerically faster than those of monolinguals (447 ms, SE = 12 ms), but this was still not a statistically significant global RT advantage ($t(5.8) = 1.17$, $p = 0.29$). Therefore the unfamiliar scanning environment may have contributed to longer overall RTs in the original data; however, bilinguals still showed a disadvantage in the non-linguistic conflict effects.

The novelty of the current flanker paradigm renders these behavioural effects difficult to interpret. Although similar to other established conflict tasks, this flanker task was created specifically for this study; some pilot testing was done before data collection, but a full experiment should be performed to determine the typical behavioural and neural patterns generated by this task. The pre-exposure of distractor arrows was particularly unique: although distractor word pre-exposure in the Stroop task is well-studied, SOA manipulation in a non-linguistic flanker task has not been extensively investigated. Further research using this paradigm is needed, especially to determine whether the observed RT patterns are typical of bilingual performance on this task. Nevertheless, the identification of differences in the location and extent of neural activation supports the idea of functional differences in conflict processing between monolinguals and bilinguals.

4.2. Language processing in monolinguals and bilinguals

A semantic categorization task was included in the current study as a measure of basic language processing. Behaviourally, bilinguals were slower in both languages to categorize words as living or non-living than monolinguals. This replicates previous findings (e.g. Phillips et al., 2004) and supports the bilingual lexical disadvantage hypotheses, suggesting that bilinguals experience delayed lexical access in both their L1 and L2 compared to monolinguals (Pyers et al., 2009). Neurally, both groups activated canonical language processing areas like the LIFG and left angular gyrus (Binder et al., 1997; Gitelman et al., 2005). Between-group comparisons also demonstrated more extensive activation for bilinguals in the left angular gyrus, an area commonly involved in language processing (e.g. Binder et al., 1997; Gitelman et al., 2005). This replicates previous reports of more extensive language activation, reflecting more effortful processing, for bilinguals than monolinguals (e.g. Kovelman, Baker, et al., 2008; Kovelman, Shalinsky, et al., 2008; Parker Jones et al., 2011).

When investigating language activation in each individual language in bilinguals, there was substantially more activation in the Spanish-only contrasts than the English-only, suggesting that Spanish drove the overall effects of language activation. Spanish may have generated stronger neural activation than English because it was the native language and therefore occupied a greater neural representation in the brain. On the other hand, the participants were overall more proficient in English, so the stronger Spanish activation could reflect processing difficulties in accessing the less-dominant representations.

Interestingly, both groups also showed cingulate activity in the language contrast. Although not generally active during language processing (Gitelman et al., 2005), the cingulate cortex is involved in decision making and response selection (e.g. Duncan & Owen, 2000; Ridderinkhof, Ullsperger et al., 2004). In the current paradigm, the requirement of a semantic decision may have created additional demands on the cognitive control system, as reflected by cingulate activation. In the between-group comparisons the cingulate was not present, suggesting that this area was activated not by aspects of linguistic processing (e.g. more cross-linguistic conflict in bilinguals) but by the nature of the cognitive task.

4.3. The neural locus of the bilingual advantage

As discussed, the current data identified significant differences in the management of linguistic and non-linguistic cognitive control and language processing between monolinguals and bilinguals. However, the primary objective of this experiment was to identify a neural locus of the bilingual advantage by comparing how these processes overlapped in monolinguals and bilinguals. To do so, the contrasts of general linguistic and non-linguistic processing (collapsed over congruency for each distractor type) and language processing were subjected to a conjunction analysis, which identified areas that were commonly active in all three domains.

The monolingual conjunction showed no significant areas of activation, indicating that executive control and language processing involve functionally distinct areas of the brain. In contrast, the bilingual conjunction revealed a significant cluster in the LIFG. This supports previous literature, indicating that the LIFG is universally involved in linguistic cognitive control (Kovelman, Baker, et al., 2008; Novick et al., 2009, 2005), non-linguistic executive processing[24] (Bunge, Dudukovic, et al., 2002; Ye & Zhou, 2009), and language control (Costafreda et al., 2006; Montant et al., 2011). Importantly, the LIFG was the site of overlap of all three processing domains in bilinguals but not in monolinguals, illustrating that bilingualism fundamentally alters the functional involvement of this structure. Therefore, as predicted, the LIFG emerged as the neural locus of the bilingual advantage.

As seen in the main contrasts (Table 8.2), LIFG activation was present in the bilingual conjunction analysis because it was elicited for linguistic Flanker, linguistic interference, and non-linguistic facilitation effects: therefore it was active in the linguistic incongruent and non-linguistic congruent conditions. This double dissociation of conflict and distractor type highlights the domain-general functionality of the LIFG. For example, if this area were involved in language control, it would be expected in linguistic but not non-linguistic conditions; if it were involved in domain-general control, it would be expected in incongruent but not congruent conditions. Its presence in both suggests that this is a key area of functional overlap in many cognitive processes, including language and executive control. In bilinguals, more extensive daily use of this structure, due to the co-activation of language and cognitive control, may enhance its functioning such that it becomes a central part of processing for both language and domain-general executive control (Garbin et al., 2010; Hernandez, 2009). The importance of the LIFG in bilingual cognitive functioning will be discussed in more detail in Chapter 9.

---

[24] Note that the LIFG was not active in the bilingual non-linguistic > control condition (Table 8.4), which was entered into the conjunction analysis: a significant area of 11 voxels was active at $p < 0.001$, but this did not survive the 20-voxel threshold. However, the main contrasts (Table 8.2) confirm that LIFG activation occurred in the non-linguistic facilitation contrast.

In sum, the current data suggested that the LIFG is the primary neural locus of the bilingual advantage. As mentioned earlier, data acquisition problems may have created noisy fMRI data, yet despite these problems with the data a significant difference between groups emerged in the LIFG. This lends credence to the idea of functional differences in bilingualism and suggests that the LIFG was the area most strongly activated by all three processing domains. Future research investigating this question may identify additional loci of the cognitive advantage; nonetheless, the current data have provided a valuable base of evidence regarding the neural correlates of the bilingual advantage on which future studies can build.

5. Conclusions

The current chapter has therefore suggested different functional organizations of the executive control and language networks in bilingualism. In particular, the left inferior frontal gyrus emerged as the locus of the bilingual advantage due to its ubiquitous involvement in domain-general processing in bilinguals. The broad involvement of the LIFG in cognitive control and language processing may selectively enhance this structure in bilinguals, reciprocally enhancing domain-general executive processing. The General Discussion, presented in the next chapter, will not only explore this possibility but will also synthesize the data collected throughout this thesis into a coherent story of bilingual cognitive processing.

Chapter 9: General Discussion

Although the majority of the world's current population is bilingual, the precise developmental and cognitive effects of using multiple languages remain poorly understood. The field of neurobilingualism, a relatively new addition to cognitive psychology and linguistics, aims to understand how multiple languages are represented and managed in the brain. It is now known that the daily use of multiple languages profoundly affects cognitive functioning, in both detrimental and beneficial ways (Bialystok, 2009; Bialystok et al., 2009). This thesis has contributed to this knowledge by exploring the multifarious effects of bilingualism, specifically lexical processing speed and cognitive control abilities, using a combination of behavioural and neuroimaging methods.

These issues were primarily investigated using a Stroop task which, as a linguistically-based conflict paradigm, assesses both language proficiency and executive control abilities. Importantly, SOA manipulation was employed to separate these two factors. Despite being in the literature for over forty years, the Stroop SOA paradigm has remained fairly unexplored; throughout this thesis, it has provided insight into lexical processing and cognitive control abilities in bilinguals, as well as the functional recruitment of executive processing in monolinguals. Part 1 of this chapter reviews the new knowledge on the Stroop SOA paradigm that has been acquired throughout the studies reported here.

The consequences of bilingualism arise in language processing speed: reduced experience with language results in weaker connections between words and concepts, which may create delays in lexical access in the less-dominant L2 (the *bilingual L2 lexical disadvantage hypothesis*) as well as in the native language (the *bilingual L1 lexical disadvantage hypothesis*). The current data addressed lexical processing speed by investigating behavioural delays in conflict processing, as indicated by a negative shift in peak interference effects in Stroop SOA patterns. ERP was also employed to evaluate delays in early windows of orthographic processing. Part 2 of this chapter reviews the evidence for and against lexical processing delays in the L1 and L2, as well as addressing other issues and factors affecting language processing.

In contrast to the disadvantages in lexical processing speed, bilingualism confers benefits in executive control abilities. The parallel activation of both languages creates cross-linguistic influences which necessitate the engagement of language control mechanisms for successful communication. This more frequent engagement of cognitive control enhances executive processing in bilinguals, creating performance advantages on cognitive control tasks compared to monolinguals (the *bilingual cognitive advantage hypothesis*). Specifically, bilinguals may experience superior abilities in resolving conflict (the *bilingual inhibitory control advantage (BICA) hypothesis*) and/or in domain-general executive processing, independent of conflict (the *bilingual executive processing advantage (BEPA) hypothesis*;

Hilchey & Klein, 2011). This thesis examined executive control abilities via the magnitude of behavioural interference effects and control condition RTs, the amplitude of conflict-related ERP components and control condition waveforms, and the extent and amount of neural activity in the executive control network. Part 3 of this chapter addresses the bilingual cognitive advantage hypothesis, interpreting the evidence for and against the BICA and BEPA hypotheses and presenting a new proposal of how bilinguals excel in cognitive control.

To briefly review the structure and main findings of this thesis, Chapter 3 performed a preliminary behavioural investigation of the effects of bilingualism on Stroop SOA effects in English monolinguals and two groups of bilinguals (English-Chinese and Chinese-English). A bilingual cognitive advantage occurred only for the bilinguals who were immersed in an L2 environment. There was evidence of lexical processing delays in the bilingual L2 but not the L1, although these effects may have been driven by script differences. Chapter 4 used long-latency SOAs in Chinese-English bilinguals with EEG to examine the bilingual lexical processing delay more closely, particularly whether delays exist in early orthographic processing. The bilingual L1 was not delayed, but orthographic recognition in the bilingual L2 occurred 100 ms later than in the L1 or monolinguals, indicating a significant and fundamental delay in non-native language processing.

Chapter 5 used the same dataset as Chapter 4 but focused on the bilingual cognitive advantage via conflict-related ERP components, specifically the N_{inc}. The groups did not differ in component amplitude, suggesting no differences in conflict detection, although a more sustained N_{inc} in the L2 may have reflected language processing difficulties. When comparing the control condition, however, there was evidence that bilinguals experienced enhanced executive processing in the absence of conflict or semantic salience. Chapter 6 further investigated how script similarity modulates the bilingual cognitive advantage by testing three groups of bilinguals with language pairs ranging from high- to low-overlap (L1s of German, Polish, and Arabic). Similar-script bilinguals demonstrated superior domain-general executive processing, since high orthographic overlap creates more cross-linguistic activation and increases the daily demands on cognitive control.

Chapter 7 investigated the neural effects of SOA on the executive control network by translating the SOA Stroop task to fMRI. In monolinguals, SOA elicited both trial-specific effects on interference and global, block-wide effects on response priming and attentional control, as well as a strategy of proactive distractor stimulus suppression in negative SOAs. Finally, Chapter 8 also employed fMRI to investigate how language and executive control overlap in the brain. A conjunction analysis revealed no significant overlap in monolinguals, whereas bilinguals recruited the left inferior frontal gyrus for linguistic and non-linguistic executive control and language processing, suggesting that this structure is the source of the bilingual cognitive advantage.

Part 1 of this chapter first summarizes the new findings reported throughout this thesis regarding SOA manipulation in the Stroop task. Parts 2 and 3 summarize and interpret the data on bilingual lexical processing speed and executive control abilities, respectively, providing suggestions for future research and discussing implications for the fields of bilingualism and cognitive psychology.

1. Part 1: Insights into SOA Manipulation in the Stroop Task

SOA manipulation in the Stroop task was first introduced in the 1970's and 1980's (Dyer, 1971; Glaser & Glaser, 1982), but interest then waned until the recent work of Roelofs (2010a) and Appelbaum et al. (2009, 2012). Only recently has this paradigm been employed with EEG to better understand the timecourse of conflict processing (Appelbaum et al., 2012; Appelbaum, Meyerhoff et al., 2009). The experiments reported in this thesis, using a combination of behavioural, EEG, and fMRI methods, have provided valuable advances in understanding how this paradigm engages cognitive processing.

Firstly, data collected during my Master's year demonstrated that manual SOA tasks elicited peak interference effects at the -200 ms SOA, rather than the 0 ms SOA as found in vocal tasks (Chapter 2). This may occur because word pre-exposure allows time for semantic conflict to interfere with the faster manual response at the -200 ms SOA, whereas the slower vocal response is most affected by simultaneous presentation at the 0 ms SOA. This holds important implications for the Stroop literature, as most manual Stroop paradigms use only simultaneous presentation (i.e. 0 ms SOA) and may therefore underestimate the amount of conflict generated. A -200 ms SOA could be employed in lieu of a 0 ms SOA to maximize the amount of conflict in manual Stroop tasks. Additionally, researchers using other conflict tasks could utilize SOA manipulation in pilot studies to identify the window of maximal interference and thereby elicit larger cognitive differences between populations.

The use of the SOA Stroop task with EEG has also extended the understanding of how the conflict-related ERP components, the N_{inc} and LPC (see Chapters 1 and 5), are modulated by SOA manipulation. Chapter 5 illustrated that the forward shift in negative SOAs is not linear: in the -400 ms SOA, the N_{inc} and LPC were shifted forward by approximately 200 ms, a similar latency as reported in Appelbaum et al.'s -200 ms SOA. As word recognition occurs within approximately 200 ms (e.g. Dell'Acqua et al., 2007), this suggests that conflict processing is limited by the latency of lexical access: any further pre-exposure of the word beyond 200 ms is superfluous because full semantic access has already occurred. A comprehensive range of SOAs is needed to identify the window of word pre-exposure that generates the largest forward shifts. The use of long-latency SOA manipulation in Chapter 5 also elucidated the function of the N_{inc} component:an N_{inc} occurred in the +400 ms SOA after a response had been executed, suggesting that this component is primarily involved in conflict detection rather than resolution.

The fMRI data in Chapter 7 illuminated the effects of SOA on the executive control network in monolinguals. Four areas of the executive control network were sensitive to the trial-specific effects of SOA on Stroop interference. These areas were more active in the 0 ms SOA, which also elicited relatively small behavioural interference effects, indicating that more extensive neural activation in these areas led to successful behavioural performance. The RIFG was sensitive to the global SOA effects of response priming in negative SOAs, specifically performing action updating and response inhibition. Blocked SOA presentation affected attentional control processes in the right superior parietal lobe, being most active for the 0 ms SOA; this suggests that with simultaneous stimulus presentation, attention is directed towards the relevant stimulus for efficient conflict resolution. Finally, negative SOAs elicited activation in the LIFG across all congruencies, suggesting a strategy of proactive distractor suppression regardless of the presence of conflict or semantic salience. Thus SOA manipulation exerted both trial-specific and block-wide effects on the recruitment and functionality of the executive control network.

Because word pre-exposure at different latencies modulates the recruitment of the executive control network, the Stroop SOA task has proven a useful technique for specifying the various functions of ERP conflict components and regions of the executive control network. Although further exploration with neuroimaging methods is required, this is a valuable paradigm for manipulating conflict processing and cognitive control.

2. Part 2: Bilingual Lexical Processing Speed

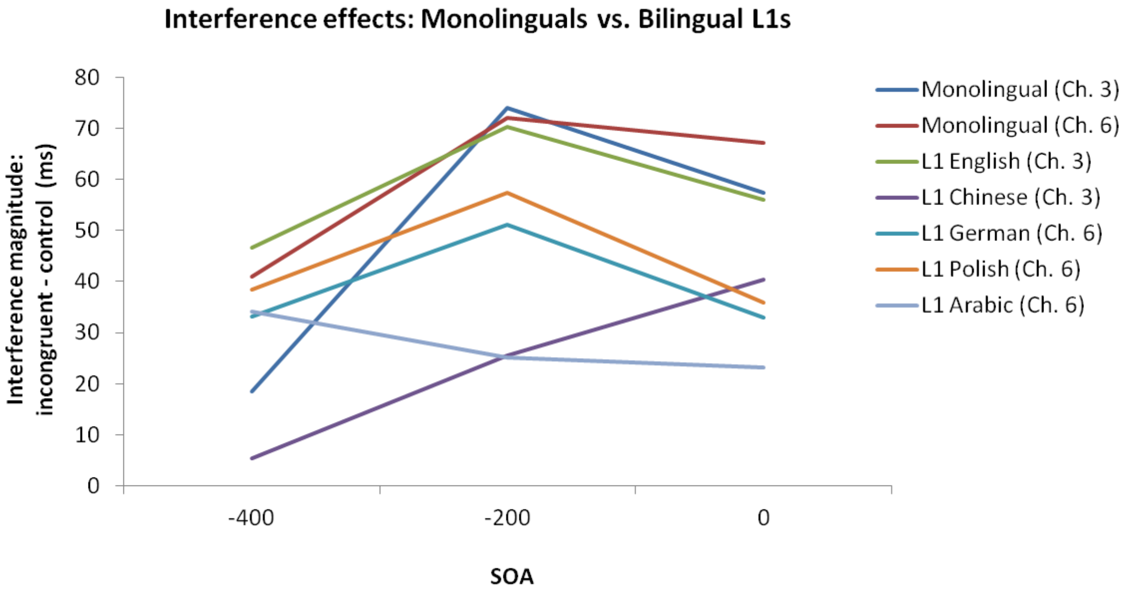
One theme of this thesis investigated the timecourse of lexical processing, particularly the finding that bilinguals show delays in production and comprehension speed (e.g. Bialystok, 2009; Bialystok et al., 2009). This delay is thought to arise from reduced frequency of language use and lower language proficiency, not only in a weaker L2 (the bilingual L2 lexical disadvantage hypothesis, based on the temporal delay assumption of the BIA+ model: Dijkstra & van Heuven, 2002) but also in the L1 compared to monolinguals (the bilingual L1 lexical disadvantage hypothesis, based on the reduced frequency/weaker links hypothesis: (Gollan, Montoya, Fennema-Notestine, et al., 2005; Pyers et al., 2009). In this thesis, lexical processing delays were identified in the behavioural data via the pattern of RTs generated with SOA manipulation: delayed language processing would create a negative shift in interference effects such that the peak interference occurs at an earlier SOA. In the ERP data, lexical processing was investigated via the N170 effect, i.e. the difference in amplitude between words and symbol strings at the peak of the N170 component, which indexes orthographic recognition and early lexical processing. The evidence for and against these two hypotheses will be presented next, followed by a consideration of the factors affecting lexical processing speed in bilinguals.

2.1. Bilingual L1 lexical disadvantage hypothesis

Delays in the native language of bilinguals were assessed by comparing the bilingual L1 data to that of monolinguals. Figure 9.1 presents the behavioural interference effects for all monolinguals and bilingual L1 groups tested in this thesis (except the monolinguals and Chinese-English bilinguals of Chapters 4 and 5, who did not perform a -200 ms SOA; their data are discussed below). Because the peak interference in monolinguals for a manual

Stroop task occurred at the -200 ms SOA (as determined in Chapter 2), a peak interference effect at the -400 ms SOA would indicate delayed lexical access. Most groups, both monolinguals and bilinguals, showed peak interference at the -200 ms SOA (Figure 9.1); the two exceptions were the Chinese-English bilinguals of Chapter 3 and the Arabic-English bilinguals of Chapter 6. The Chinese-English bilinguals demonstrated a positive shift compared to other groups, as the peak interference occurred at 0 ms rather than -200 ms SOA. This contradicts the predicted pattern and may be a result of script differences (see section 2.3.1 below). The Arabic-English bilinguals, in contrast, demonstrated peak interference effects at the -400 ms SOA, which could suggest delayed lexical access in the L1 for this group. Overall, however, the behavioural data yielded no strong evidence for a bilingual L1 delay. Many other cognitive processes occur between lexical access and conflict resolution, so additional factors such as script may modulate the latency of peak interference effects in the SOA Stroop task (see section 2.3). Ultimately, the latency of peak Stroop interference may not be the best reflection of lexical access speed; the precise temporal resolution of EEG may be a more accurate measure.

Figure 9.1: Interference effects for monolinguals and bilinguals' L1 across negative SOAs for all groups (with the exception of the English monolinguals and Chinese-English bilinguals from Chapter 4, who did not perform a -200 ms SOA). Chapters containing the original data are indicated in the legend.

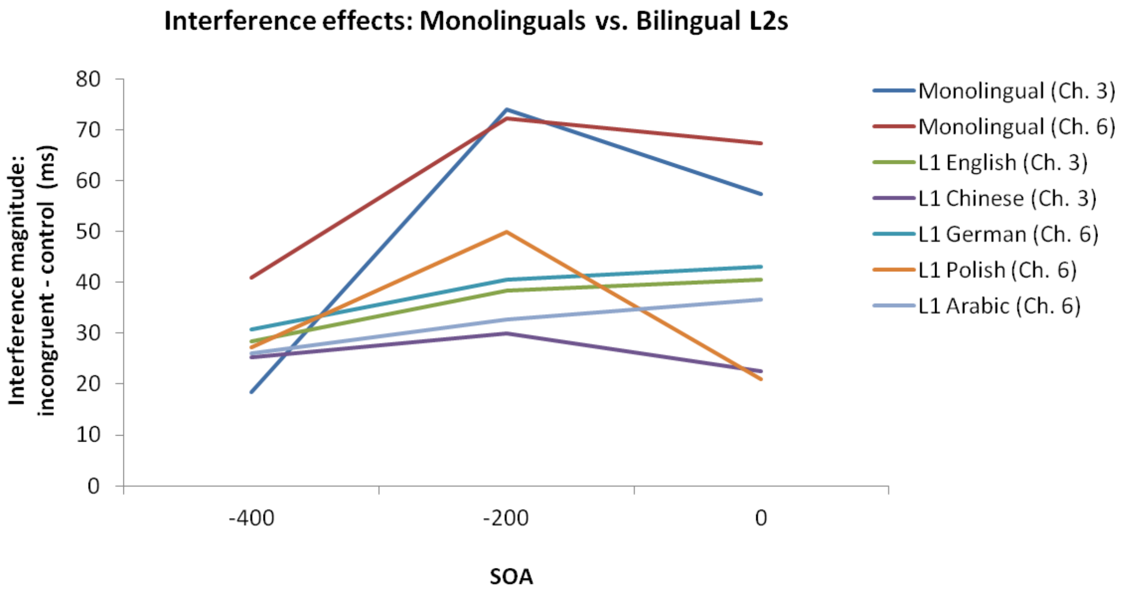


In the ERP data of Chapter 4, no differences occurred in the latency of the N170 effect between monolinguals and the bilingual L1, indicating no delay in L1 lexical processing, in contrast to other studies (Ardal et al., 1990; Gollan, Montoya, Fennema-Notestine, et al., 2005; Ivanova & Costa, 2008; Proverbio et al., 2002). As mentioned in Chapter 1 (section 2.3), the production modality may be more susceptible to bilingual delays than the comprehension modality (Gollan et al., 2011), so the use of a comprehension-based Stroop task could have attenuated the L1 delays. Additionally, previously-documented L1 delays have occurred at later ERP components such as the N400 (e.g. Moreno & Kutas, 2005; Newman et al., 2012), indicating difficulties at the level of semantic integration. Chapter 8 also investigated language processing speed via semantic categorization, demonstrating that bilinguals were significantly slower at categorizing nouns, in both languages, compared to monolinguals. Therefore the current data indicate that L1 delays do not occur at early windows of orthographic recognition, but that reduced proficiency associated with bilingualism may impact higher-level, proficiency-driven language processes (see section 2.3.3 below). Further research is needed to assess precisely at what level of linguistic processing the L1 delay begins.

2.2. Bilingual L2 lexical disadvantage hypothesis

Delays in the non-native language were assessed by comparing the L2 data to both the L1 and to monolinguals. As can be seen in Figure 9.2, which presents the behavioural interference effects for all monolinguals and bilingual L2s, there was a split in the data: monolinguals, Polish-English, and Chinese-English bilinguals showed peak interference at -200 ms, whereas English-Chinese, German-English, and Arabic-English bilinguals experienced peak interference at 0 ms. However, no bilingual groups experienced peak interference at the -400 ms SOA, suggesting no lexical processing delays in the L2. Support for an L2 delay instead came in Chapter 3 when comparing the L2 Chinese with L1 Chinese: there was a difference in overall peak effects such that the majority of participants showed a more negative peak interference for the L2 (negative SOAs) than the L1 (0 ms SOA). Chapter 8 also demonstrated slower semantic categorization speeds for bilinguals in both languages compared to monolinguals, suggesting delays at higher-level semantic processes.

Figure 9.2: Interference effects for monolinguals and bilinguals' L2 across negative SOAs for all groups (with the exception of Chapters 4 and 5). Chapters containing the original data are indicated in the legend.



The EEG data in Chapter 4 provided strong evidence for an L2 lexical processing delay in early linguistic processing: the distinction between words and symbol strings occurred not at the N170 peak, as in monolinguals and the L1, but 100 ms later at an N2 component peaking at approximately 250 ms. As discussed in Chapter 4, the N2 may reflect automatic translation from the L2 back into the L1: an N250 is often reported in the translation priming literature (Liu & Perfetti, 2003; Schoonbaert et al., 2011) and a prime duration as short as 60 ms can trigger translation back into the L1 (Zhang et al., 2011). This extra processing step of L2-L1 translation could explain why lexical access is delayed in a second language.

The L2 delay documented in the ERP data adds to a growing body of literature suggesting that reduced proficiency leads to inherent delays in language processing across a range of time windows and linguistic levels (Newman et al., 2012; Phillips et al., 2006; Proverbio et al., 2009). Importantly, the fact that L2 delays occurred at early levels of orthographic recognition suggests that processing difficulties occur at higher-level integration stages, but also lower at the individual word level. A delay so early in processing, which is potentially compounded throughout the entire linguistic process, may contribute to considerable difficulties in second-language communication.

2.2.1. Magnitude of interference between L1 and L2

As discussed in Chapter 2 (section 2.1), smaller interference effects are often reported for the L2 compared to the L1, which has been attributed to weaker connection strengths (and thus slower processing) in the non-native language (e.g. Braet et al., 2011; Heidlmayr et al., 2012; Mohamed Zied et al., 2004; Naylor et al., 2012; Sumiya & Healy, 2004). This effect was investigated in the current data by comparing L1 and L2 interference in all bilingual groups at the 0 ms SOA; this SOA allows for the closest comparison with the literature, which all used simultaneous presentation. As seen in Figure 9.3, the effect was generally replicated. Significantly larger interference occurred in the L1 than the L2 for the English-Chinese bilinguals of Chapter 3 and the Chinese-English bilinguals of Chapter 5 (all *p*'s < 0.05), with a trend in the Polish-English bilinguals of Chapter 6 ($p = 0.09$). (Although note that there were some disparities with the previous literature, as the German-English and Arabic-English bilinguals actually showed larger interference in the L2.)

However, regardless of the magnitude of the delay in conceptual access, eventually the concept will become activated and interfere with colour naming. Therefore if weaker connection strengths and delayed lexical access drive these smaller Stroop effects in the L2, allowing more time for word processing (i.e. pre-exposing the word) may equalize the interference between the languages. To test this hypothesis, the largest interference effect across the entire range of SOAs was identified for each subject and language; this allowed for the varying speeds of lexical access within individuals, providing a better measure of the relative strength of interference from each language. As seen in Figure 9.4, this technique eliminated the differences between the L1 and L2 (all *p*'s > 0.11), supporting the idea that the reduced interference in the L2 stems from slower lexical access and weaker connection strengths.

Figure 9.3: Interference effects in L1 and L2 for each bilingual group at the 0 ms SOA, with significant differences between the L1 and L2 marked with asterisks (§ = trend; * = $p < 0.05$). CE = Chinese-English; EC = English-Chinese; GE = German-English; PE = Polish-English; AE = Arabic-English. Chapters containing the original data are indicated in the legend.

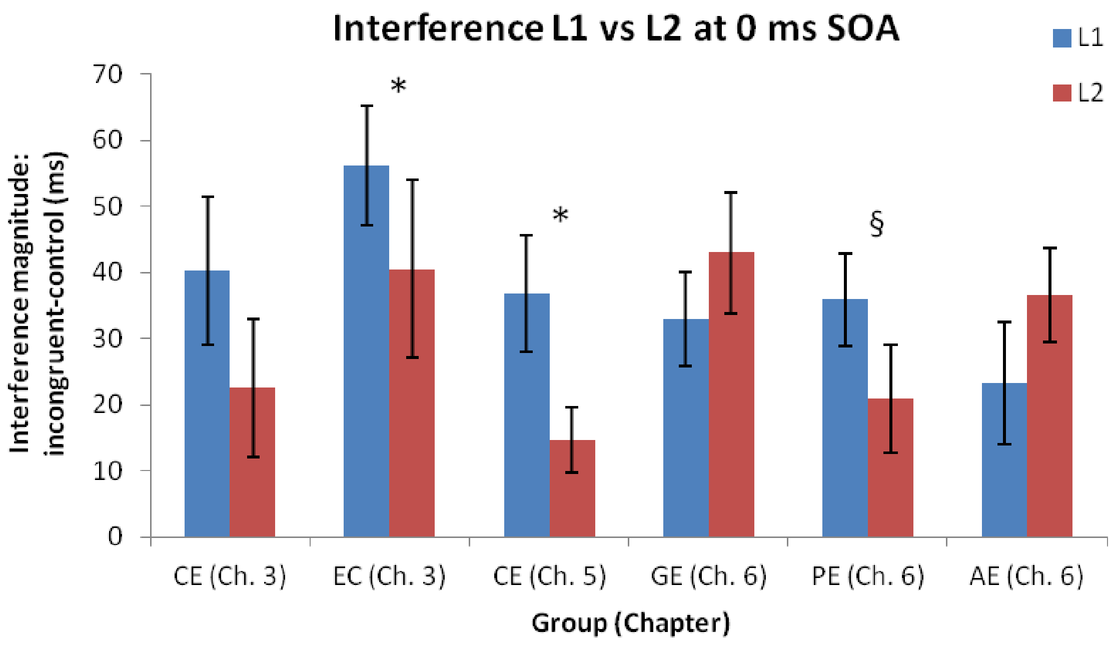
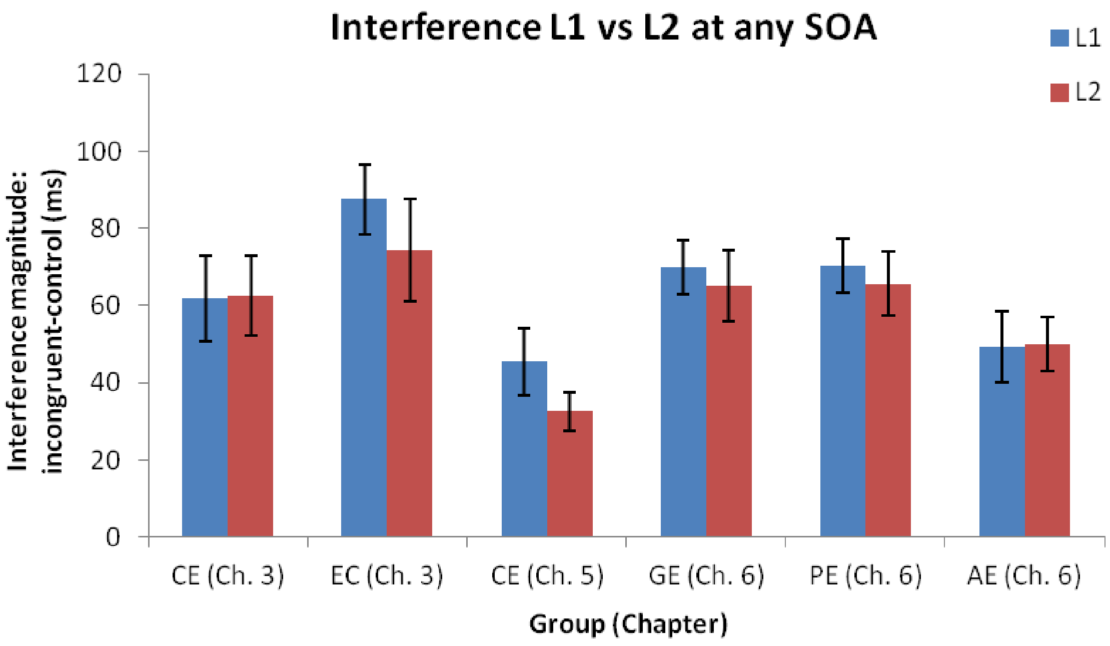


Figure 9.4: Interference effects in L1 and L2 for all bilingual groups when taking the peak interference at any SOA.



2.3. Factors modulating lexical processing speed

Lexical access speed is a dynamic feature of language processing, as evidenced by the mixed and often-conflicting evidence on processing delays documented throughout the current data and the previous literature. This thesis has identified a number of factors which may affect lexical access speed. Most notably, the latency of peak interference effects and the magnitude of the L2 delay may be affected by script, proficiency, and the level of linguistic processing under investigation.

2.3.1. Effects of script similarity

Script has played a recurring role throughout this thesis. As discussed in Chapters 3 and 6, script-specific lexical factors can affect processes of phonological access (e.g. Perfetti et al., 2005; Saalbach & Stern, 2004), orthographic recognition (e.g. Bar-Kochva, 2011; Meschyan & Hernandez, 2006), language production speed (Bates et al., 2003), and the neural representations of languages in the brain (e.g. Bick et al., 2011; Bolger et al., 2005; Tan, Laird et al., 2005). The orthographic characteristics of language may also be responsible for some of the patterns of results observed here.

For example, in Chapter 3, notable differences in RT patterns emerged between the English and Chinese languages. Specifically, Chinese generated peak interference effects at the 0 ms SOA, whereas English yielded peak interference at the -200 ms SOA. These patterns occurred both in native and non-native speakers, suggesting an effect of the language rather than of proficiency. As discussed in Chapter 3, given the extant debates regarding the role of phonology in each script, these patterns may suggest that phonological mediation is slower in English than in Chinese. However, the EEG evidence from Chapter 4 did not demonstrate differences in orthographic recognition speed between English monolinguals and the L1 Chinese. Thus despite the script differences, orthographic recognition occurred at similar speeds for English and Chinese. Admittedly, the Stroop tasks used here did not include a manipulation of phonology, so phonological differences between English and Chinese would be difficult to identify in the ERP data. As concluded in Chapter 3, more evidence is needed to understand how phonology is mediated in alphabetic and logographic languages, specifically regarding the timecourse of phonological activation in each writing system.

The Arabic bilinguals of Chapter 6 showed a negative shift in peak interference when performing in the L1 Arabic (section 2.1, Figure 9.1), suggesting delays in native-language processing. However, given the lack of behavioural evidence for L1 delays in other groups, other linguistic characteristics of Arabic (e.g. the fact that it is read right-to-left) may account for these apparent delays in lexical processing. Therefore although there was no evidence for script effects in early orthographic processing, other higher-level processes such as conflict detection and resolution may be more susceptible to such effects, generating the differences in peak interference effects seen in the Chinese-English and Arabic-English bilinguals (see section 2.3.3).

As well as affecting the latency of peak interference effects, script may also modulate the magnitude of the L2 delay. The EEG data of Chapter 4 demonstrated a significant 100 ms delay in orthographic recognition in the L2. However, as these effects were observed in Chinese-English bilinguals, the delay may have been enhanced by the dissimilar orthographies. For example, identifying words in a different writing system may be more difficult when processing a second language, which could generate a delay only for different-script bilinguals. Previous studies have reported an L2 delay for bilinguals from various language backgrounds, including Chinese (Liu & Perfetti, 2003; Weber-Fox & Neville, 1996), Spanish (Moreno & Kutas, 2005; Newman et al., 2012), French (Ardal et al., 1990), German (Proverbio et al., 2009; Spalek et al., 2011), Italian, and Slovenian (Proverbio et al., 2009). Nevertheless, the documented L2 delays in lexical processing observed in this thesis may be a result of script similarity; this factor should be carefully considered in future research.

2.3.2. Effects of proficiency on the L2 delay

Proficiency is also an important factor to consider in lexical processing speed, particularly in the L2. As reviewed in Chapter 1 (section 2.1), delays in bilingual processing may originate from weaker connections between words and concepts in the language architecture, as weaker weights require more processing time to reach an activation threshold. However, connections can be modified and strengthened with experience (e.g. Cohen et al., 1990), predicting that stronger connections as a result of increased proficiency lead to faster processing. Similarly, the temporal delay assumption places the locus of the delay on the lower resting-level activation of words, resulting from the lower subjective word frequency; however, with higher frequency of use (i.e. increased proficiency), this resting level activation may also increase. In other words, higher proficiency should lead to smaller L2 delays compared to the L1 or to monolinguals. On the contrary, previous studies performing explicit manipulations have reported no effect of proficiency on the L2 delay (e.g. Ardal et al., 1990; Newman et al., 2012); an alternative suggestion is that L2 AoA is the more influential factor modulating the bilingual delay (e.g. Proverbio et al., 2009; Weber-Fox & Neville, 1996). Therefore the possibility that L2 processing speed is affected by proficiency, while an intriguing possibility, requires a more comprehensive and systematic evaluation in order to be substantiated.

2.3.3. Delays across levels of linguistic processing

Another factor which may modulate the presence and/or magnitude of a lexical processing delay is the linguistic level under investigation. For example, no delays in early orthographic recognition were observed between monolinguals and the L1 Chinese in Chapter 4, whereas the L1 Chinese behavioural data of Chapter 3 demonstrated a shift in the peak of interference, suggesting differences in language processing speeds. Furthermore, in Chapter 8 bilinguals demonstrated significant delays in semantic categorization. Therefore it may be that L1 lexical delays are manifest *after* early orthographic recognition and are compounded during the processing stream, generating delays at later semantic processing levels (e.g. Hahne, 2001; Moreno & Kutas, 2005; Newman et al., 2012).

In light of this possibility, the fact that the L2 experienced a 100 ms delay in early lexical processing is significant, as this may lead to more significant delays in higher-level processing. Early L2 delays of a similar magnitude have been previously reported (Liu & Perfetti, 2003; Proverbio et al., 2009), although delays of varying magnitudes have also been observed across a range of linguistic processes (see Table 1.1 in Chapter 1). For example, Gollan et al. (2008) documented a delay of 500 ms on picture naming in bilinguals' L2 compared to monolinguals, while Ardal et al. (1990) observed a delay of only 21 ms between L1 and L2 in comprehension. Further work is required to better understand the L2 delay, as the magnitude of this delay may be affected by modality (production/comprehension) and a number of other individual factors already discussed.

Interestingly, despite the evidence for L2 delays in lexical processing, in the ERP data of Chapter 5, the onset of the N_{inc} was similar for all groups and languages, indicating no L2 delays in conflict detection. A number of other cognitive functions occur between orthographic recognition and conflict detection which may have contributed to this ostensible compensation in lexical access speed. From a computational point of view, nodes build up activation until they reach a particular threshold, so the lack of L2 conflict processing delays in light of the observed lexical processing delay suggests that partial semantic activation can trigger conflict detection processes. However, although the onset of conflict detection was not delayed, a more sustained N_{inc} occurred in the L2 0 ms SOA compared to the other groups and the L2 generated smaller behavioural interference. This could suggest that although conflict detection is triggered by partial semantic activation, full conflict processing must wait until complete semantic access occurs; because semantic access takes longer, the N_{inc} is sustained and smaller behavioural interference occurs. As mentioned in Chapter 5, the literature on bilingual cognitive control with EEG is scarce, so additional research is required to investigate the timecourse of bilingual conflict processing.

In sum, the current data demonstrated that lexical processing speed exerts differential effects depending on the cognitive level being evaluated. More evidence using precise temporal techniques such as EEG and a range of linguistic processing levels is needed to identify when and how lexical delays occur in bilinguals.

2.4. Conclusions on bilingual lexical processing speed

In summary, the work presented in this thesis has demonstrated that bilinguals do not experience delays in their native language at time windows of early orthographic processing, although temporal difficulties may emerge at later levels such as semantic evaluation. In contrast, the fact that an L2 delay occurred early in orthographic recognition indicates that reduced proficiency in a language can have a fundamental impact on the functioning of the language system. Overall, these data demonstrate significant delays in non-native language processing and bring to light a number of factors that may modulate this delay, which will be interesting questions for future research to explore.

A number of research questions have already been discussed, mainly regarding the influence of script and proficiency on the magnitude of the delay. Also of interest will be evaluating how the L1 is affected by L2 delays. If language delays arise from reduced frequency of use, then an increased frequency of L2 use (i.e. higher proficiency) would necessarily mean a decreased frequency L1 use; whether this would be reflected in slower L1 lexical access is unclear. Ultimately, a better understanding of the nature of bilingual processing delays is needed, including how processing speed is affected by factors such as script, proficiency, AoA, and language immersion.

One issue to note in the current dataset is that the strongest evidence for a bilingual delay came from the ERP data; the latencies of peak behavioural interference effects yielded weak and often contradictory evidence of processing delays. Despite the sanguine expectations, inferring lexical processing speed from conflict effects may be an unsuitable way of investigating this issue, as many other factors, beyond lexical processing speed, are likely responsible for determining where the peak interference effects fall in an SOA Stroop task. Alternative language paradigms such as lexical decision tasks may be more appropriate for assessing language processing speed in bilinguals.

With well over half the modern world being bilingual, processing delays hold important implications for our understanding of the bilingual language system and of the nature of the difficulties that second-language speakers face. The fact that delays can occur at early stages of L2 processing implies that these effects may be compounded at higher-level stages such as the semantic and sentence level. Furthermore, the resolution of such processing delays may contribute to the more effortful processing required to process a second language efficiently. When so much of daily life revolves around being able to rapidly produce and comprehend language, a delay in early linguistic processing has important implications for bilingual communication.

3. Part 3: Bilingual Executive Control Abilities

The second theme of this thesis considered executive control abilities: specifically, the phenomenon that bilinguals outperform monolinguals and, in this domain, show a ‘bilingual cognitive advantage’. This is believed to arise from non-selective lexical access, which creates cross-linguistic influences that require cognitive control on a daily basis. Such cognitive demands enhance the executive processing system in a domain-general way, as evidenced by the extension of the cognitive advantage to non-linguistic cognitive control. Two specific subsets of the bilingual cognitive advantage were evaluated: the bilingual inhibitory control advantage (BICA) and the bilingual executive processing advantage (BEPA; Hilchey & Klein, 2011). The evidence for each of these will be discussed in turn.

3.1. Evidence for the BICA hypothesis

To review, the BICA hypothesis invokes the IC model (Green, 1998) in suggesting that bilinguals use inhibitory control mechanisms to resolve linguistic interference (Chapter 1, section 4.4). As inhibitory control becomes inextricably linked with language, these control mechanisms become enhanced in bilinguals. The BICA hypothesis specifically proposes more efficient processing in the presence of conflict, leading to an ‘interference advantage’. This is exhibited as faster incongruent RTs and consequently smaller interference effects in the behavioural data, amplitude differences in the conflict-related ERP components (specifically, smaller N_{inc} amplitudes than monolinguals: Heidlmayr et al., 2012; Kousaie & Phillips, 2012), and differences in the extent or location of brain activation in conflict comparisons (i.e. Flanker/interference effects) in the fMRI data. However, for conditions in which conflict is absent, such as control and congruent conditions, the BICA hypothesis predicts equivalent performance for monolinguals and bilinguals; therefore any group differences in situations that do not contain conflict, such as control trials, would be evidence against this hypothesis.

Limited behavioural evidence for the BICA hypothesis was observed in the current data. In Chapter 3, smaller interference effects occurred for Chinese-English bilinguals but not English-Chinese bilinguals, suggesting an interference advantage only for bilinguals immersed in their L2. These effects were also modulated by proficiency, highlighting that the interference advantage is sensitive to individual differences in language experience. Chapter 5 revealed smaller behavioural interference effects in the L2 English but not the L1 Chinese, which does not constitute an advantage because superior executive control abilities within individuals should also occur in the L1 (see Chapter 3 section 6.2). In Chapter 6, an interference advantage occurred in the Stroop task for Arabic-English bilinguals compared to monolinguals, but not for German-English or Polish-English bilinguals. However, as there were also no differences between groups in the Simon interference effects, the Arabic-English interference advantage is more likely an effect of script (see section 3.6 below). In Chapter 8, bilinguals demonstrated a non-significant trend towards a behavioural interference advantage in linguistic but not non-linguistic Flanker effects. In the EEG data of Chapter 5, there were no overall differences in N_{inc} amplitude between the groups. However, a more sustained N_{inc} occurred in the L2, which could reflect more effortful processing of the word stimulus in the L2 due to the need to inhibit the stronger L1. This would support the IC model, which suggests that the stronger language requires more inhibitory control to overcome the influence of the stronger language (Green, 1998).

The fMRI data of Chapter 8 demonstrated group differences in the linguistic interference contrast: whereas bilinguals recruited the LIFG, monolinguals activated the right angular gyrus. Chapter 8 proposed that because the behavioural linguistic Flanker effects were generally smaller in bilinguals, this could suggest a different, more efficient processing strategy for bilinguals in the face of linguistic conflict. Specifically, as the LIFG is involved in suppression of irrelevant stimuli (Novick et al., 2005, 2009; Thompson-Schill et al., 1998; Ye & Zhou, 2009), whereas the right angular gyrus is involved in visuospatial attention

(Corbetta et al., 1993; Culham & Kanwisher, 2001; Milham et al., 2003; Rushworth et al., 2001), these differences may suggest that bilinguals use a strategy of irrelevant stimulus suppression, whereas monolinguals use a strategy of target amplification (Egner & Hirsch, 2005a). Thus monolinguals and bilinguals may engage different mechanisms for resolving linguistic conflict, supporting the BICA hypothesis.

Therefore the current data demonstrated limited evidence in support of the BICA hypothesis. Overall, as concluded by Hilchey & Klein (2011), the interference advantage was sensitive to a number of individual and task-specific factors such as immersion experience, script, and the linguistic nature of the conflict. The evidence for the BEPA hypothesis, however, was more robust.

3.2. Evidence for the BEPA hypothesis

The BEPA hypothesis claims that, rather than being specific to conflict processing, the bilingual cognitive advantage affects more general executive processing due to the need to maintain the relevant language and monitor the environment for language membership (Bialystok et al., 2009; Colzato et al., 2008), as proposed by the BIA+ model of word recognition (Dijkstra & van Heuven, 2002). This creates a general enhancement of goal maintenance and monitoring abilities which benefits all trial types, predicting a ‘global RT advantage’ (i.e. faster RTs on all conditions) but not necessarily a reduction in interference effects (see Chapter 1, Figure 1.16). The global RT advantage was evaluated in the current data by comparing the control conditions between groups, both behaviourally and in the ERP data. As the control stimuli in all tasks contained no conflicting (or linguistic) information, any variations in performance would demonstrate differences in domain-general, rather than conflict-specific, executive processing.

The current behavioural evidence for the BEPA hypothesis was limited. Chapter 3 demonstrated no global RT advantage for either bilingual group, but a significant advantage occurred in both languages for the Chinese-English bilinguals of Chapter 5. Chapter 6 demonstrated significantly faster RTs for German and Polish bilinguals compared to Arabic bilinguals in both the Stroop and Simon tasks. This indicates a larger global RT advantage for same-script bilinguals than different-script bilinguals; however, none of the bilingual groups differed significantly from monolinguals. Finally, Chapter 8 actually demonstrated a global RT disadvantage, with bilinguals performing slower overall on all flanker conditions (though this was not statistically significant).

Despite the limited behavioural evidence for a global RT advantage, strong support for the BEPA hypothesis came from the EEG data of Chapter 5. When comparing the control condition, the bilingual waveform was more negative than monolinguals early in the N_{inc} windows, as well as in the -400 ms SOA before the second stimulus (the colour) appeared. Since these differences occurred in the control condition, which contained no conflict or linguistic information, this suggests that the bilingual advantage is not limited to situations of conflict. Moreover, the fact that differences arose before the onset of conflict in the -400 ms

SOA may suggest that bilinguals experience a general enhancement in monitoring or distractor suppression (see section 3.4 below), as predicted by the BEPA hypothesis.

In sum, the current data yielded mixed evidence for both the BICA and BEPA hypotheses. Although the behavioural data was contradictory, the EEG data demonstrated differences in general monitoring and conflict-independent control, while the fMRI data suggested differences in linguistic conflict processing mechanisms. Therefore the bilingual cognitive advantage appears to consist of both conflict-processing and domain-general executive control enhancements (see section 3.5).

3.3. The neural locus of the bilingual advantage

In Chapter 8, fMRI was employed to identify the site(s) of functional overlap between linguistic executive control, non-linguistic executive control, and language processing in monolinguals and bilinguals. Specifically, differences in the amount or location of overlap between groups might explain the domain-general executive control advantages demonstrated by bilinguals. Using a conjunction of contrasts identifying brain regions sensitive to linguistic distractors, non-linguistic distractors, and language, bilinguals showed a region of overlap in the LIFG which was not present in monolinguals. This supports previous evidence demonstrating that the LIFG is involved in language processing as well as in linguistic and domain-general executive control (Bialystok, Craik et al., 2005; Bunge, Hazeltine et al., 2002; De Bleser et al., 2003; Garbin et al., 2010; Indefrey, 2006; Kovelman, Baker et al., 2008; Kovelman, Shalinsky et al., 2008; Lehtonen et al., 2005; Luk et al., 2011; Marian et al., 2003; Novick et al., 2009, 2005; Parker Jones et al., 2011; Perani et al., 2003; Ye & Zhou, 2009) and suggests that this structure is the primary neural locus of the bilingual advantage.

As suggested by Garbin et al. (2010) and Hernandez (2009), the use of cognitive control in bilingual language processing may restructure the organizations of these two networks such that they become intertwined and co-dependent. As the LIFG is involved in both networks, it is exercised every time both are co-activated in bilinguals and is therefore selectively enhanced. Reciprocally, because the LIFG is also involved in domain-general cognitive processes including inhibition, distractor suppression, and selection of task-relevant information (see section 3.5), the bilingual advantage extends to non-linguistic executive control.

3.4. The bilingual advantage in distractor suppression

Taken together, the present data suggest a novel mechanism of enhanced executive processing in bilinguals, presented here as the *distractor suppression hypothesis*. Rather than exhibiting an advantage only on conflict trials, the enhanced monitoring and inhibitory control requirements of bilingualism may additionally enhance abilities in suppressing or ignoring the influence of irrelevant stimuli. This proposal comes from a combination of evidence in the current dataset.

Firstly, the monolingual fMRI data of Chapter 7 demonstrated that in negative SOAs of the Stroop task the LIFG was active for all congruencies, including the control condition. As the LIFG is involved in cognitive control via suppression of irrelevant information (e.g. Ye & Zhou, 2009), this was interpreted as a strategy of distractor suppression, in which potential upcoming conflict was avoided by suppressing all pre-exposed information, regardless of the presence of conflict or semantic salience (see Chapter 7, section 4.4). Secondly, the control waveforms in the EEG data of Chapter 5 (section 4.2.3) showed more negative amplitudes for bilinguals; importantly, in the -400 ms SOA the onset of these group differences began before the second stimulus arrived. This suggests cognitive differences in how bilinguals managed the distractor stimulus: as suggested by the fMRI data, they may have engaged a strategy of distractor suppression. If so, the more negative ERP amplitudes and correspondingly faster behavioural control RTs observed in Chapter 5 suggest that this mechanism was more efficient in bilinguals, perhaps due to the daily experience of suppressing or ignoring the non-target language. Finally, Chapter 8 demonstrated that the LIFG was selectively enhanced by bilingualism due to its common involvement in both language and executive control. As the LIFG allegedly performed distractor suppression in the negative SOAs of the Stroop task in monolinguals (Chapter 7), its selective enhancement may lead to an enhanced ability of distractor suppression in bilinguals.

In short, this new hypothesis proposes that bilinguals experience an executive processing advantage by virtue of being better able to proactively ignore or suppress[25] distracting or irrelevant stimuli and, furthermore, that the LIFG is the locus of this enhanced ability in bilinguals. Importantly, the evidence here comes in part from evaluations of the control condition, meaning that this ability is not specific to the presence of conflict. Suppression can, however, be considered a form of inhibitory control. This hypothesis therefore reconciles the BICA and BEPA hypotheses, proposing a form of inhibitory control that is not conflict-specific but benefits the executive processing system more generally.

More evidence is required to replicate these findings and to substantiate this inchoate hypothesis. For example, this proposal assumes that the more negative EEG waveforms in the bilingual control condition reflected distractor suppression mechanisms originating from the LIFG; confirmatory evidence, such as replication with source localization or MEG, is needed to verify the neural generator of this effect. Furthermore, testing the SOA Stroop task in bilinguals with neuroimaging (i.e. replicating Chapter 7 with bilinguals) would determine whether bilinguals engage the LIFG for distractor suppression to the same extent as monolinguals. The proposal of a distractor suppression advantage in bilinguals would also predict a number of other outcomes, specifically in facilitation and alerting/orienting effects, which are explained below.

---

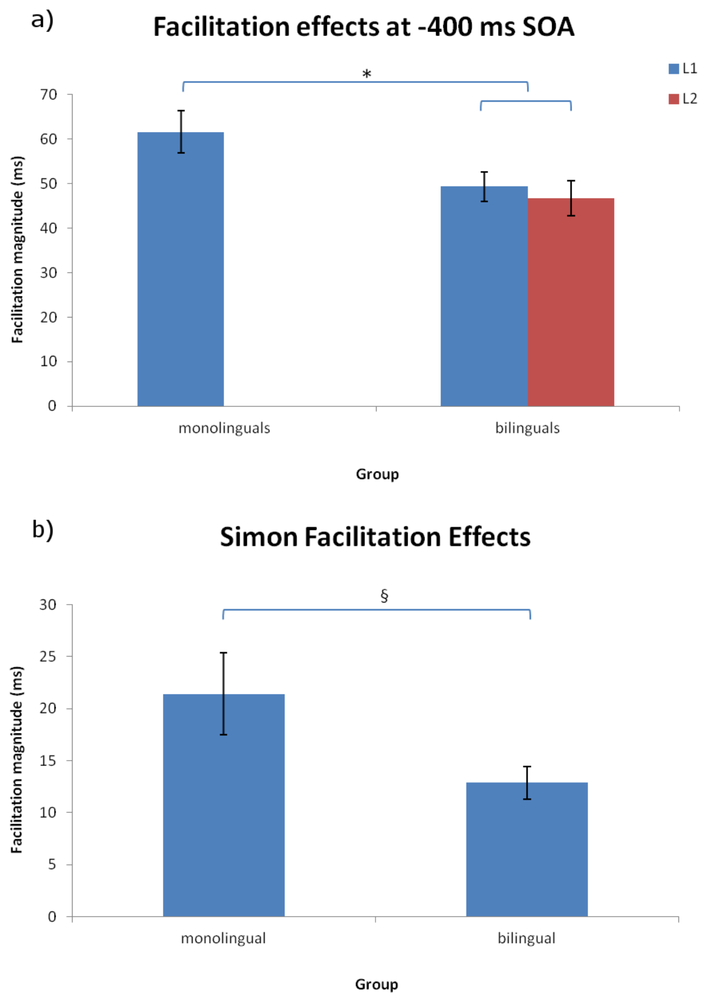
[25] Specifically, it may be that *ignoring* irrelevant stimuli is the dominant mechanism in comprehension, while *suppression* is engaged more during production; see Chapter 1, section 1.4.

3.4.1. Facilitation effects

If bilinguals are better at ignoring the influence of distracting information, independent of the presence of conflict or the semantic relevance to the task, they may also demonstrate smaller facilitation effects. As discussed in Chapter 2 (section 3.5.2), previous research has found that individuals with impaired cognitive control show not only increased interference but also increased facilitation effects (e.g. Zelazo et al., 2004). This may result from an increased susceptibility to the influence of the distractor word, either by inadvertent word reading in a congruent condition (MacLeod & MacDonald, 2000; Wright & Wanley, 2003) or via the same cognitive mechanism as interference effects (Roelofs, 2010b). In other words, an enhanced ability to ignore the distracting word information would generate not only smaller interference effects, but also smaller facilitation effects, for bilinguals.

To test this proposal, the facilitation effects from the -400 ms SOA (the SOA generating maximal facilitation effects) were collapsed across all participants from Chapters 3, 5, and 6, and compared between monolinguals and bilinguals (Figure 9.5a). Bilinguals experienced significantly smaller facilitation effects in both languages (L1: 49 ms, *SE* = 3 ms; L2: 47 ms, *SE* = 4 ms) compared to the monolinguals (62 ms, *SE* = 5 ms; all *p*’s < 0.05), but the L1 and L2 did not differ (*p* = 0.60). The facilitation effects from the non-linguistic Simon task of Chapter 6 were also evaluated, collapsing over all bilingual groups (Figure 9.5b). There was a strong statistical trend of a larger facilitation effect for monolinguals (21 ms, *SE* = 4 ms) than bilinguals (13 ms, *SE* = 2 ms; *t*(22.5) = 2.02, *p* = 0.06). These behavioural data therefore support the distractor suppression hypothesis, demonstrating smaller facilitation effects for bilinguals than monolinguals.

Figure 9.5: Facilitation effects for a) the Stroop -400 ms SOA, collapsed over all monolingual and bilingual groups from Chapters 3, 5 and 6; and b) the Simon task of Chapter 6, collapsed over bilingual groups.



As reported in Chapter 8, the behavioural facilitation effects in the Flanker task showed no differences between the groups, in either the linguistic or non-linguistic conditions. However, in the neural data, the linguistic facilitation contrast showed more extensive activation for monolinguals than bilinguals in the RMFG, RIFG, and posterior cingulate. This suggests increased recruitment of executive control for monolinguals, which may be indicative of greater susceptibility to the word stimulus.

Overall, bilinguals showed smaller facilitation effects than monolinguals, supporting the theory that they are better able to ignore or suppress the distracting influence of the word stimulus. Additionally, the mere fact that differences arose between monolinguals and bilinguals in the magnitude of facilitation effects contradicts the predictions of the BICA hypothesis, as these effects contain no conflict. Instead, bilinguals demonstrated enhancements in domain-general cognitive control abilities that may specifically be related to distractor suppression.

Facilitation effects should be interpreted cautiously in cognitive control tasks, as the nature and locus of these effects are still debated. Evidence of facilitation in bilinguals is particularly conflicting: for example, some researchers have reported larger facilitation effects for bilinguals than monolinguals (Bialystok et al., 2008; Hernández et al., 2010; Luk et al., 2010), which is contradictory to previous literature reporting smaller facilitation effects with better cognitive control. Although facilitation effects hold potential for being a useful method of comparing bilingual cognitive control abilities, more research is first needed to better understand these effects.

3.4.2. Orienting and alerting effects

If bilinguals are better able to ignore distracting stimuli, they may also be less affected by invalid or uninformative cues, predicting smaller alerting and orienting effects in attentional tasks. Investigations of orienting and alerting abilities in bilinguals are scarce and have produced mixed evidence. Some studies have reported no differences in orienting ability between monolinguals and bilinguals (Colzato et al., 2008; Hernández et al., 2010). However, Colzato et al. (2008) also reported that bilinguals showed no facilitation from spatial cues, which would suggest that they were unaffected by the irrelevant or unreliable stimuli. Using the ANT task (see Chapter 1, section 4.2), Costa et al. (2008) reported a larger alerting effect for bilinguals such that they were aided more by the presence of a cue signalling the upcoming stimulus presentation. This seemingly contradicts the distractor suppression hypothesis; however, in the ANT the spatial cue always validly signals the upcoming target and is therefore not an irrelevant stimulus, so larger alerting effects in bilinguals may indicate superior abilities in directing attention towards task-relevant attributes.

As these attentional paradigms assess spatial alerting and orienting, they are somewhat uninformative for bilingualism, since there is no reason why bilingualism should enhance spatial abilities. However, an important feature of these tasks is the temporal manipulation of stimulus presentation using cueing. Throughout this thesis, the temporal variability of SOA manipulation has proven a useful method of investigating cognitive control mechanisms; this technique should be used in the future to better assess bilingual differences in executive control processing. The majority of extant research into the bilingual advantage has merely documented advantages across different tasks and populations. While this is helpful, the future of the field requires a strategic manipulation of task paradigms in order to break apart the various aspects of cognitive control and better identify their modulation by bilingualism.

3.4.3. Conclusions on the distractor suppression hypothesis

To summarize, a critical evaluation of the data collected throughout this thesis has suggested that bilinguals are better able to suppress or ignore the influence of distracting stimuli and that this ability is localized to the LIFG. Although tentative, this suggestion offers a new way of looking at the bilingual advantage and encourages the use of psychological paradigms that can tease apart the various components of cognitive control, in the hopes of better understanding the cognitive impacts of bilingualism.

3.5. The influences of production and comprehension in the bilingual advantage

One important issue raised in bilingualism literature is the precise cognitive locus at which the bilingual advantage arises. Some have proposed that the source of the bilingual advantage lies in production, in the need to resolve linguistic conflict or apply inhibitory control at the level of output (Emmorey, Luk, Pyers, & Bialystok, 2008; Green, 1998). Evidence supporting this proposal comes from bimodal bilinguals, who are fluent in both a spoken language and a signed language such as British or American Sign Language. For such bilinguals, conflict at the production level does not exist: they can sign and speak at the same time. Therefore if the bilingual advantage arises from the management of cross-linguistic interference during production, bimodal bilinguals should not show a cognitive advantage relative to monolinguals. Emmorey et al. (2008) tested this hypothesis using a flanker task with monolinguals, bimodal bilinguals, and unimodal bilinguals (those who use two spoken languages), and reported that bimodal bilinguals and monolinguals performed equivalently, whereas unimodal bilinguals performed faster than both groups in all conditions. Unimodal bilinguals therefore showed a global RT advantage whereas bimodal bilinguals demonstrated no cognitive advantages, suggesting that the bilingual advantage stems from executive control requirements during language production. (Interestingly, the presence of a global RT advantage suggests that the advantage does not necessarily stem from the need to resolve conflict between languages, as proposed by the IC model, but from more general executive processes involved in production.)

Alternatively, some have argued that the bilingual advantage arises at the level of comprehension. Testing pre-verbal babies, Kovács & Mehler (2009a) found that bilingual infants exhibited enhanced cognitive flexibility and inhibitory control compared to monolingual infants. Bilingual infants also learned new speech patterns more quickly than monolinguals, demonstrating more flexible learning (Kovács & Mehler, 2009b). As the babies had not yet learned to speak, the source of this cognitive ability must come not from resolving interference at the production level but from monitoring for language membership at the input level, as would be predicted by the BEPA hypothesis and the BIA+ model of language comprehension.

This seemingly conflicting evidence forces the conclusion that bilingualism enhances all of these abilities: resolving conflict, suppressing task-irrelevant information, and monitoring the environment. Although inhibitory control has been more strongly attributed to language production (the IC model, Green, 1998) and monitoring and/or selection to comprehension (the BIA+ model: Dijkstra & van Heuven, 2002), communication relies on both comprehension and production on a daily basis. Thus the mechanisms underlying language control in both of these modalities are likely enhanced in bilinguals (although inhibition may be a more cognitively demanding process than selection: Emmorey, Petrich, & Gollan, 2012).

The discovery of the LIFG as the neural locus of the bilingual advantage, an area ubiquitously involved in higher-level cognitive functioning, highlights the fact that the bilingual advantage is pervasive and is not limited to just one mechanism of cognitive control. The current data has provided evidence for enhanced inhibitory control, monitoring, and distractor suppression abilities in bilinguals; the literature has additionally proposed advantages in domains such as cognitive flexibility and theory of mind (Bialystok & Senman, 2004; Bialystok & Shapero, 2005; see Chapter 1, section 4.2). Similarly, the LIFG has been implicated in a number of cognitive functions, including – but not limited to – inhibitory control, interference suppression, semantic selection, and goal maintenance. For example, an early interpretation of LIFG function proposed that this area selected semantic information from among competing alternatives (Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997). Furthermore, recent work from De Baene et al. (2012) has proposed that the LIFG is involved in representing goals during task preparation. The BIA+ model proposes that language control is performed by the task/decision system which implements goal maintenance and language selection; if the LIFG is involved in these cognitive processes, its selective enhancement in bilinguals would explain the benefit in domain-general executive processing. Therefore while the cognitive demands of production and comprehension may selectively enhance certain functions, the documented advantages across a range of cognitive abilities suggests that the bilingual advantage results from the holistic bilingual experience and affects a wide array of cognitive functioning.

3.6. Factors affecting bilingual cognitive control

The data presented here have illustrated that executive control is a complex topic, full of interacting factors and latent variables. One such factor is that of script similarity. As addressed in Chapter 6, non-selective access in two orthographically-similar languages would create more cross-linguistic interference than in different-script languages with less orthographic overlap (Dijkstra & van Heuven, 2002). This overlap creates more Stroop interference for same-script bilinguals (Brauer, 1998; van Heuven et al., 2011), as they must manage cross-linguistic conflict as well as the semantic and response Stroop conflict. This was confirmed by Chapter 6: in both L1 and L2, German and Polish bilinguals had larger Stroop and interference effects compared to Arabic-English bilinguals.

Although detrimental to the magnitude of Stroop conflict effects, linguistic overlap also enhanced the bilingual cognitive advantage in same-script bilinguals: in both Stroop and Simon tasks, German-English bilinguals showed the largest global RT advantages, followed by Polish-English, with the smallest effects (and therefore worst executive processing abilities) for Arabic-English bilinguals. The fact that this advantage occurred in the global RT effects suggests that the increased cross-linguistic interference does not just affect inhibitory control abilities in same-script bilinguals, but enhances more general executive processing abilities such as monitoring for language membership. More evidence on this issue is required, as the current data comprises one of only a few studies explicitly manipulating script similarity (Bialystok, Craik et al., 2005; Linck et al., 2008). Nevertheless, these results demonstrated that script may affect cognitive control abilities. This holds important implications for bilingualism research investigating the cognitive advantage, as mixing bilingual language backgrounds could create spurious effects in the data or, alternatively, obscure the veracity of the advantage.

Another factor to consider in bilingual executive control is language immersion, which refers to the experience of living in the foreign-language country or being in an environment where the non-native language is primarily used. Hearing and speaking the foreign language every day presumably places increased demands on the inhibitory control system: for example, Linck et al. (2009) have suggested that L2 immersion increases the amount of L1 inhibition, which may consequently improve cognitive control abilities. Furthermore, intriguing data from an unpublished study by Baus et al. (2011) has suggested that improvements in cognitive control abilities can be observed after just one month of L2 immersion. Supporting this proposal, in Chapter 3 a bilingual cognitive advantage occurred for Chinese-English bilinguals, who were immersed in the L2 environment, but not for English-Chinese bilinguals living in their native country. However, these English-Chinese bilinguals were the only participants who were not tested in an immersion environment and mixed evidence was found for a bilingual advantage from the other groups. Therefore further research on the role of immersion is needed to clarify this issue. An influence of immersion experience, as well as script, on cognitive control would highlight the malleable nature of cognitive abilities and the shifting character of the bilingual advantage.

3.7. Conclusions on bilingual executive control

In general, this comprehensive evaluation of the current data has illustrated that bilinguals exhibit an advantage on executive control tasks compared to monolinguals; the various facets of these cognitive control abilities, however, are complex. Although there was mixed support for both the BICA and BEPA hypotheses, the observed differences in control conditions, in the absence of conflict, suggest that bilinguals experience a domain-general enhancement of cognitive control that is not limited to conflict resolution abilities. More specifically, an integrated interpretation of the data has suggested that bilinguals also experience heightened abilities in distractor suppression and are better able to suppress or ignore the influence of irrelevant stimuli. The common use of the LIFG for management of the cognitive demands of bilingual language processing suggests that this structure is the neural locus of the cognitive advantage; the centrality of this structure reciprocally confers a domain-general cognitive enhancement across a variety of functions.

Bilingual cognitive control is an emergent field, with numerous unanswered questions and unidentified influences. For example, what level of proficiency is needed to confer an advantage? Does the number of languages one speaks affect the magnitude of the advantage? Does the advantage decay over time if bilingualism is not maintained? The opportunities for future work are ripe and many questions are already beginning to be investigated. The need for careful consideration of the bilingual population (with regards to factors like language similarity and immersion experience) has been described, as well as for new paradigms that can more comprehensively tease apart the various threads of this advantage in order to better understand how bilingualism changes the cognitive control system. Neuroimaging will in particular be a valuable technique in the future for understanding the nature of the bilingual advantage.

The bilingual cognitive advantage phenomenon also holds important clinical implications for related fields such as neurology. For example, popular interest in this issue has been generated by reports that the enhanced cognitive demands of bilingualism confer a ‘cognitive reserve’ which protects against the detrimental effects of aging and delays the onset of dementia (Bialystok, Craik, & Freedman, 2007; Bialystok, Craik, & Ryan, 2006; Chertkow et al., 2010; Craik, Bialystok, & Freedman, 2010; Schweizer, Ware, Fischer, Craik, & Bialystok, 2012; see Bialystok, Craik, & Luk, 2012 for a review). This suggests that bilingualism may not just confer cognitive changes but may also alter the structure and chemistry of the brain. Although the precise mechanisms have yet to be understood, the cognitive effects of bilingualism therefore have important and wide-ranging implications for the future of diagnostic treatments and interventions.

4. Conclusions

The experiments presented here have explored various aspects of cognitive functioning in bilinguals, specifically lexical access speed and executive control abilities. The evidence has provided important information on issues far beyond these initial topics, not just into bilingual cognitive functioning but into matters such as the neural strategies of conflict processing in a Stroop task and the importance of cross-linguistic script influences. The conclusion that lexical access speed and cognitive functioning interact in linguistic cognitive control is inevitable. However, the knowledge gained here regarding each of these factors may help to better understand the effects of bilingualism on cognitive control.

A state shared by the majority of the world today, bilingualism is a complex and ever-changing experience. The effects that bilingualism exerts on the mind and brain are similarly complex; the cognitive effects of this experience are only just starting to be understood. Thankfully, this fascinating field is still in its infancy, with a vast number of questions still to be addressed. With the advent of new and advancing neuroimaging techniques, our understanding of bilingualism will inevitably expand in the future. Nevertheless, it is becoming increasingly clear that bilingualism confers a range of cognitive effects, both beneficial and detrimental in nature, which affect everyday life in intricate and widespread ways.

References

Abutalebi, J. (2008). Neural aspects of second language representation and language control. *Acta Psychologica*, *128*(3), 466–478.

Abutalebi, J., Annoni, J.-M., Zimine, I., Pegna, A. J., Seghier, M. L., Lee-Jahnke, H., Lazeyras, F., et al. (2008). Language control and lexical competition in bilinguals: An event-related fMRI study. *Cerebral Cortex*, *18*(7), 1496–1505.

Abutalebi, J., Brambati, S. M., Annoni, J.-M., Moro, A., Cappa, S. F., & Perani, D. (2007). The neural cost of the auditory perception of language switches: an event-related functional magnetic resonance imaging study in bilinguals. *The Journal of Neuroscience*, *27*(50), 13762–13769.

Abutalebi, J., Della Rosa, P. A., Green, D. W., Hernandez, M., Scifo, P., Keim, R., Cappa, S. F., et al. (2012). Bilingualism Tunes the Anterior Cingulate Cortex for Conflict Monitoring. *Cerebral Cortex*, *22*(9), 2076-2086.

Abutalebi, J., & Green, D. W. (2007). Bilingual language production: The neurocognition of language representation and control. *Journal of Neurolinguistics*, *20*, 242–275.

Abutalebi, J., & Green, D. W. (2008). Control mechanisms in bilingual language production: Neural evidence from language switching studies. *Language and Cognitive Processes*, *23*(4), 557–582.

Aisenberg, D., & Henik, A. (2012). Stop being neutral: Simon takes control! *The Quarterly Journal Of Experimental Psychology*, *65*(2), 295–304.

Ali, N., Green, D. W., Kherif, F., Devlin, J. T., & Price, C. J. (2010). The role of the left head of caudate in suppressing irrelevant words. *Journal of Cognitive Neuroscience*, *22*(10), 2369–2386.

Appelbaum, L. G., Boehler, C., Won, R., Davis, L., & Woldorff, M. G. (2012). Strategic Allocation of Attention Reduces Temporally Predictable Stimulus Conflict. *Journal of Cognitive Neuroscience*, *24*(9), 1834–1848.

Appelbaum, L. G., Liotti, M., Perez, R., Fox, S. P., & Woldorff, M. G. (2009). The temporal dynamics of implicit processing of non-letter, letter, and word-forms in the human visual cortex. *Frontiers in Human Neuroscience*, *3*(56), 1–11.

Appelbaum, L. G., Meyerhoff, K. L., & Woldorff, M. G. (2009). Priming and backward influences in the human brain: Processing interactions during the Stroop interference effect. *Cerebral Cortex*, *19*(11), 2508–2521.

Ardal, S., Donald, M. W., Meuter, R., Muldrew, S., & Luce, M. (1990). Brain responses to semantic incongruity in bilinguals. *Brain and Language*, *39*(2), 187–205.

Aron, A. R., Robbins, T. W., & Poldrack, R. A. (2004). Inhibition and the right inferior frontal cortex. *Trends in Cognitive Sciences*, *8*(4), 170–177.

Ashburner, J. (2007). A fast diffeomorphic image registration algorithm. *NeuroImage*, *38*(1), 95–113.

Atkinson, C. M., Drysdale, K. A., & Fulham, W. R. (2003). Event-related potentials to Stroop and reverse Stroop stimuli. *International Journal of Psychophysiology*, *47*(1), 1–21.

Badre, D., & Wagner, A. D. (2004). Selection, integration, and conflict monitoring: Assessing the nature and generality of prefrontal cognitive control mechanisms. *Neuron*, *41*(3), 473–487.

Badzakova-Trajkov, G., Barnett, K. J., Waldie, K. E., & Kirk, I. J. (2009). An ERP investigation of the Stroop task: the role of the cingulate in attentional allocation and conflict resolution. *Brain Research*, *1253*, 139–148.

Bar-Kochva, I. (2011). Does processing a shallow and a deep orthography produce different brain activity patterns? An ERP study conducted in Hebrew. *Developmental Neuropsychology*, *36*(7), 933–938.

Barch, D. M., Braver, T. S., Akbudak, E., Conturo, T., Ollinger, J., & Snyder, A. Z. (2001). Anterior cingulate cortex and response conflict: effects of response modality and processing domain. *Cerebral Cortex*, *11*, 837–848.

Barch, D. M., Braver, T. S., Nystrom, L. E., Forman, S. D., Noll, D. C., & Cohen, J. D. (1997). Dissociating working memory from task difficulty in human prefrontal cortex. *Neuropsychologia*, *35*(10), 1373–1380.

Barch, D. M., Braver, T. S., Sabb, F. W., & Noll, D. C. (2000). Anterior cingulate and the monitoring of response conflict: Evidence from an fMRI study of overt verb generation. *Journal of Cognitive Neuroscience*, *12*(2), 298–309.

Bartolotti, J., Marian, V., Schroeder, S. R., & Shook, A. (2011). Bilingualism and inhibitory control influence statistical learning of novel word forms. *Frontiers in Psychology*, *2*(324), 1–10.

Bates, E., D’Amico, S., Jacobsen, T., Székely, A., Andonova, E., Devescovi, A., Herron, D., et al. (2003). Timed picture naming in seven languages. *Psychonomic Bulletin & Review*, *10*(2), 344–380.

Baus, C., Costa, A., & Carreiras, M. (2011). On the effects of a brief L2 immersion on executive control. Aix Workshop on Neurobilingualism, Aix-en-Provence, September 12 – 14, 2011. [Poster].

Bentin, S., Allison, T., Puce, A., Perez, E., & McCarthy, G. (1996). Electrophysiological studies of face perception in humans. *Journal of Cognitive Neuroscience*, *8*(6), 551–565.

Bentin, S., Mouchetant-Rostaing, Y., Giard, M. H., Echallier, J. F., & Pernier, J. (1999). ERP manifestations of processing printed words at different psycholinguistic levels: Time course and scalp distribution. *Journal of Cognitive Neuroscience*, *11*(3), 235–260.

Besner, D. (2001). The myth of ballistic processing: Evidence from Stroop's paradigm. *Psychonomic Bulletin & Review, 8*(2), 324–330.

Bialystok, E. (1999). Cognitive complexity and attentional control in the bilingual mind. *Child Development, 70*(3), 636–644.

Bialystok, E. (2006). Effect of bilingualism and computer video game experience on the Simon task. *Canadian Journal of Experimental Psychology, 60*(1), 68–79.

Bialystok, E. (2009). Bilingualism: The good, the bad, and the indifferent. *Bilingualism: Language and Cognition, 12*(01), 3–11.

Bialystok, E. (2010). Global-local and trail-making tasks by monolingual and bilingual children: Beyond inhibition. *Developmental Psychology, 46*(1), 93–105.

Bialystok, E. (2011). Reshaping the mind: The benefits of bilingualism. *Canadian Journal of Experimental Psychology, 65*(4), 229–235.

Bialystok, E., Craik, F. I. M., & Freedman, M. (2007). Bilingualism as a protection against the onset of symptoms of dementia. *Neuropsychologia, 45*(2), 459–464.

Bialystok, E., Craik, F. I. M., Grady, C., Chau, W., Ishii, R., Gunji, A., & Pantev, C. (2005). Effect of bilingualism on cognitive control in the Simon task: evidence from MEG. *NeuroImage, 24*(1), 40–49.

Bialystok, E., Craik, F. I. M., Green, D. W., & Gollan, T. H. (2009). Bilingual Minds. *Psychological Science in the Public Interest, 10*(3), 89–129.

Bialystok, E., Craik, F. I. M., Klein, R., & Viswanathan, M. (2004). Bilingualism, aging, and cognitive control: evidence from the Simon task. *Psychology and Aging, 19*(2), 290–303.

Bialystok, E., Craik, F. I. M., & Luk, G. (2012). Bilingualism: Consequences for mind and brain. *Trends in Cognitive Sciences, 16*(4), 240–250.

Bialystok, E., Craik, F.I.M., & Luk, G. (2008). Cognitive control and lexical access in younger and older bilinguals. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 34*(4), 859–873.

Bialystok, E., Craik, F. I. M., & Ruocco, A. C. (2006). Dual-modality monitoring in a classification task: the effects of bilingualism and ageing. *Quarterly Journal of Experimental Psychology, 59*(11), 1968–1983.

Bialystok, E., Craik, F. I. M., & Ryan, J. (2006). Executive control in a modified antisaccade task: Effects of aging and bilingualism. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 32*(6), 1341–1354.

Bialystok, E., & Depape, A.-M. (2009). Musical expertise, bilingualism, and executive functioning. *Journal of Experimental Psychology: Human Perception and Performance, 35*(2), 565–574.

Bialystok, E., & Feng, X. (2009). Language proficiency and executive control in proactive interference: Evidence from monolingual and bilingual children and adults. *Brain and Language*, *109*(2-3), 93–100.

Bialystok, E., & Martin, M. M. (2004). Attention and inhibition in bilingual children: evidence from the dimensional change card sort task. *Developmental Science*, *7*(3), 325–339.

Bialystok, E., Martin, M. M., & Viswanathan, M. (2005). Bilingualism across the lifespan: The rise and fall of inhibitory control. *International Journal of Bilingualism*, *9*(1), 103–119.

Bialystok, E., & Senman, L. (2004). Executive processes in appearance-reality tasks: The role of inhibition of attention and symbolic representation. *Child Development*, *75*(2), 562–579.

Bialystok, E., & Shapero, D. (2005). Ambiguous benefits: The effect of bilingualism on reversing ambiguous figures. *Developmental Science*, *8*(6), 595–604.

Bialystok, E., & Viswanathan, M. (2009). Components of executive control with advantages for bilingual children in two cultures. *Cognition*, *112*(3), 494–500.

Bick, A. S., Goelman, G., & Frost, R. (2011). Hebrew brain vs. English brain: Language modulates the way it is processed. *Journal of Cognitive Neuroscience*, *23*(9), 2280–22290.

Biederman, I., & Tsao, Y. C. (1979). On processing Chinese ideographs and English words: Some implications from Stroop-Test results. *Cognitive Psychology, 11*(2), 125–132.

Binder, J. R., Frost, J. A., Hammeke, T. A., Cox, R. W., Rao, S. M., & Prieto, T. (1997). Human brain language areas identified by functional magnetic resonance imaging. *The Journal of Neuroscience*, *17*(1), 353–362.

Blais, C., & Besner, D. (2007). A reverse Stroop effect without translation or reading difficulty. *Psychonomic Bulletin & Review*, *14*(3), 466–469.

Bloem, I., & La Heij, W. (2003). Semantic facilitation and semantic interference in word translation: Implications for models of lexical access in language production. *Journal of Memory and Language*, *48*(3), 468–488.

Bloem, I., van den Boogaard, S., & La Heij, W. (2004). Semantic facilitation and semantic interference in language production: Further evidence for the conceptual selection model of lexical access. *Journal of Memory and Language*, *51*(2), 307–323.

Blumenfeld, H. K., & Marian, V. (2011). Bilingualism influences inhibitory control in auditory comprehension. *Cognition*, *118*(2), 245–57.

Boehm, S. G., Dering, B., & Thierry, G. (2011). Category-sensitivity in the N170 range: a question of topography and inversion, not one of amplitude. *Neuropsychologia*, *49*(7), 2082–2089.

Bolger, D. J., Perfetti, C. A., & Schneider, W. (2005). Cross-cultural effect on the brain revisited: Universal structures plus writing system variation. *Human Brain Mapping, 25*(1), 92–104.

Booth, J. R., Burman, D. D., Meyer, J. R., Gitelman, D. R., Parrish, T. B., & Mesulam, M. M. (2003). Relation between brain activation and lexical performance. *Human Brain Mapping, 19*(3), 155–169.

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review, 108*(3), 624–652.

Botvinick, M. M., Cohen, J. D., & Carter, C. S. (2004). Conflict monitoring and anterior cingulate cortex: an update. *Trends in Cognitive Sciences*, *8*(12), 539–546.

Braet, W., Noppe, N., Wagemans, J., & Op de Beeck, H. (2011). Increased Stroop interference with better second-language reading skill. *Quarterly Journal of Experimental Psychology, 64*(3), 596–607.

Brauer, M. (1998). Stroop interference in bilinguals: The role of similarity between the two languages. In A. F. Healy & L. Bourne (Eds.), *Foreign Language Learning: Psycholinguistic Studies on Training and Retention* (pp. 317–337). Mahwah, NJ: Erlbaum.

Braver, T. S., Gray, J. R., & Burgess, G. C. (2007). Explaining the many varieties of working memory variation: Dual mechanisms of cognitive control. In A. R. A. Conway, C. Jarrold, M. J. Kane, A. Miyake, & J. N. Towse (Eds.), *Variations in Working Memory* (pp. 76–106). New York, NY: Oxford University Press.

Braver, T. S., Paxton, J. L., Locke, H. S., & Barch, D. M. (2009). Flexible neural mechanisms of cognitive control within human prefrontal cortex. *Proceedings of the National Academy of Sciences, 106*(18), 7351–7356.

Brett, M., Anton, J. L., Valabregue, R., & Poline, J. B. Region of interest analysis using an SPM toolbox. (abstract). Presented at the 8th International Conference on Functional Mapping of the Human Brain, June 2-6, 2002, Sendai, Japan. Available on CD-ROM in NeuroImage, Vol 16, No 2.

Briellmann, R. S., Saling, M. M., Connell, A. B., Waites, A. B., Abbott, D. F., & Jackson, G. D. (2004). A high-field functional MRI study of quadri-lingual subjects. *Brain and Language*, *89*, 531–542.

Brown, T. L. (2011). The relationship between Stroop interference and facilitation effects: Statistical artifacts, baselines, and a reassessment. *Journal of Experimental Psychology: Human Perception and Performance, 37*(1), 85–99.

Brysbaert, M., & Duyck, W. (2010). Is it time to leave behind the Revised Hierarchical Model of bilingual language processing after fifteen years of service? *Bilingualism: Language and Cognition*, *13*(03), 359–371.

Brysbaert, M., & New, B. (2009). Moving beyond Kucera and Francis: A critical evaluation of current word frequency norms and the introduction of a new and improved word frequency measure for American English. *Behavior Research Methods*, *41*(4), 977–990.

Brysbaert, M., Verreyt, N., & Duyck, W. (2010). Models as hypothesis generators and models as roadmaps. *Bilingualism: Language and Cognition*, *13*(03), 383–384.

Bunge, S. A., Dudukovic, N. M., Thomason, M. E., Vaidya, C. J., & Gabrieli, J. D. E. (2002). Immature frontal lobe contributions to cognitive control in children: Evidence from fMRI. *Neuron*, *33*(2), 301–311.

Bunge, S. A., Hazeltine, E., Scanlon, M. D., Rosen, A. C., & Gabrieli, J. D. E. (2002). Dissociable Contributions of Prefrontal and Parietal Cortices to Response Selection. *NeuroImage*, *17*(3), 1562–1571.

Calabria, M., Hernández, M., Branzi, F. M., & Costa, A. (2012). Qualitative Differences between Bilingual Language Control and Executive Control: Evidence from Task-Switching. *Frontiers in Psychology*, *2*(399), 1–10.

Caldas, A. L., Machado-Pinheiro, W., Souza, L. B., Motta-Ribeiro, G. C., & David, I. A. (2012). The Stroop matching task presents conflict at both the response and nonresponse levels: An event-related potential and electromyography study. *Psychophysiology*, *49*(9), 1215–1224.

Carlson, S. M., & Meltzoff, A. N. (2008). Bilingual experience and executive functioning in young children. *Developmental Science*, *11*(2), 282–298.

Carter, C. S., Macdonald, A. M., Botvinick, M. M., Ross, L. L., Stenger, V. A., Noll, D., & Cohen, J. D. (2000). Parsing executive processes: strategic vs. evaluative functions of the anterior cingulate cortex. *Proceedings of the National Academy of Sciences*, *97*(4), 1944–1948.

Chee, M. W., Hon, N., Lee, H. L., & Soon, C. S. (2001). Relative language proficiency modulates BOLD signal change when bilinguals perform semantic judgments. *NeuroImage*, *13*, 1155–1163.

Chen, H., & Ho, C. (1986). Development of Stroop interference in Chinese-English bilinguals. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *12*(3), 397–401.

Chen, S., & Melara, R. D. (2009). Sequential effects in the Simon task: Conflict adaptation or feature integration? *Brain Research*, *1297*, 89–100.

Chertkow, H., Whitehead, V., Phillips, N., Wolfson, C., Atherton, J., & Bergman, H. (2010). Multilingualism (But Not Always Bilingualism) Delays the Onset of Alzheimer Disease: Evidence From a Bilingual Community. *Alzheimer Disease and Associated Disorders*, *24*(2), 118–125.

Christoffels, I. K., Firk, C., & Schiller, N. O. (2007). Bilingual language control: An event-related brain potential study. *Brain Research*, *1147*, 192–208.

Chua, F. K. (1999). Phonological recoding in Chinese logograph recognition. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *25*(4), 876–891.

Coderre, E. L., Filippi, C. G., Newhouse, P. A., & Dumas, J. A. (2008). The Stroop effect in kana and kanji scripts in native Japanese speakers: An fMRI study. *Brain and Language*, *107*(2), 124–132.

Cohen, J. D., Dunbar, K., & McClelland, J. L. (1990). On the control of automatic processes: a parallel distributed processing account of the Stroop effect. *Psychological Review*, *97*(3), 332–361.

Colomé, À. (2001). Lexical Activation in Bilinguals' Speech Production: Language-Specific or Language-Independent? *Journal of Memory and Language*, *45*(4), 721–736.

Colzato, L. S., Bajo, M. T., van den Wildenberg, W., Paolieri, D., Nieuwenhuis, S., La Heij, W., & Hommel, B. (2008). How does bilingualism improve executive control? A comparison of active and reactive inhibition mechanisms. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *34*(2), 302–312.

Conklin, H. M., Curtis, C. E., Katsanis, J., & Iacono, W. G. (2000). Verbal Working Memory Impairment in Schizophrenia Patients and Their First-Degree Relatives: Evidence From the Digit Span Task. *American Journal of Psychiatry*, *157*, 275–277.

Consonni, M., Cafiero, R., Marin, D., Tettamanti, M., Iadanza, A., Fabbro, F., & Perani, D. (2012). Neural convergence for language comprehension and grammatical class production in highly proficient bilinguals is independent of age of acquisition. *Cortex*, 1–7. doi:10.1016/j.cortex.2012.04.009

Corbetta, M., Miezin, F. M., Shulman, G. L., & Petersen, S. E. (1993). A PET study of visuospatial attention. *The Journal of Neuroscience*, *13*(3), 1202–1226.

Costa, A., Hernández, M., Costa-Faidella, J., & Sebastián-Gallés, N. (2009). On the bilingual advantage in conflict processing: Now you see it, now you don't. *Cognition*, *113*(2), 135–149.

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

Costa, A., Miozzo, M., & Caramazza, A. (1999). Lexical selection in bilinguals: Do words in the bilingual's two lexicons compete for selection? *Journal of Memory and Language*, *397*, 365–397.

Costa, A., Santesteban, M., & Ivanova, I. (2006). How do highly proficient bilinguals control their lexicalization process? Inhibitory and language-specific selection mechanisms are both functional. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *32*(5), 1057–1074.

Costafreda, S. G., Fu, C. H. Y., Lee, L., Everitt, B., Brammer, M. J., & David, A. S. (2006). A systematic review and quantitative appraisal of fMRI studies of verbal fluency: role of the left inferior frontal gyrus. *Human Brain Mapping*, *27*, 799–810.

Craik, F. I. M., Bialystok, E., & Freedman, M. (2010). Delaying the onset of Alzheimer disease: Bilingualism as a form of cognitive reserve. *Neurology*, *75*, 1726–1729.

Craik, F.I. M., & Bialystok, E. (2006). Cognition through the lifespan: mechanisms of change. *Trends in Cognitive Sciences*, *10*(3), 131–138.

Crinion, J., Turner, R., Grogan, A., Hanakawa, T., Noppeney, U., Devlin, J. T., Aso, T., et al. (2006). Language control in the bilingual brain. *Science*, *312*(5779), 1537–1540.

Crosson, B., Benefield, H., Cato, M. A., Sadek, J. R., Moore, A. B., Wierenga, C. E., Gopinath, K., et al. (2003). Left and right basal ganglia and frontal activity during language generation: Contributions to lexical, semantic, and phonological processes. *Journal of the International Neuropsychological Society*, *9*(7), 1061–1077.

Cuetos, F., Glez-Nosti, M., Barbón, A., & Brysbaert, M. (2011). SUBTLEX-ESP: Spanish word frequencies based on film subtitles. *Psicológica*, *32*, 133–143.

Culham, J. C., & Kanwisher, N. G. (2001). Neuroimaging of cognitive functions in human parietal cortex. *Current Opinion in Neurobiology*, *11*(2), 157–163.

Cunnington, R., Windischberger, C., Deecke, L., & Moser, E. (2003). The preparation and readiness for voluntary movement: A high-field event-related fMRI study of the Bereitschafts-BOLD response. *NeuroImage*, *20*(1), 404–412.

Dalrymple-Alford, E. C. (1972). Associative facilitation and interference in the Stroop color-word task. *Perception & Psychophysics*, *11*(4), 274–276.

Davidson, M. C., Amso, D., Anderson, L. C., & Diamond, A. (2006). Development of cognitive control and executive functions from 4 to 13 years: Evidence from manipulations of memory, inhibition, and task switching. *Neuropsychologia*, *44*(11), 2037–2078.

De Baene, W., Albers, A. M., & Brass, M. (2012). The what and how components of cognitive control. *NeuroImage, 63*(1),203-211.

De Bleser, R., Dupont, P., Postler, J., Bormans, G., Speelman, D., Mortelmans, L., & Debrock, M. (2003). The organisation of the bilingual lexicon: A PET study. *Journal of Neurolinguistics*, *16*(4-5), 439–456.

De Pisapia, N., & Braver, T. S. (2006). A model of dual control mechanisms through anterior cingulate and prefrontal cortex interactions. *Neurocomputing*, *69*, 1322–1326.

Degani, T., & Tokowicz, N. (2010). Semantic ambiguity within and across languages: an integrative review. *Quarterly Journal of Experimental Psychology*, *63*(7), 1266–1303.

Dehaene, S., Dupoux, E., Mehler, J., Cohen, L., Paulesu, E., Perani, D., van de Moortele, P. F., et al. (1997). Anatomical variability in the cortical representation of first and second language. *Neuroreport*, *8*(17), 3809–3815.

Dell'Acqua, R., Pesciarelli, F., Jolicoeur, P., Eimer, M., & Peressotti, F. (2007). The interdependence of spatial attention and lexical access as revealed by early asymmetries in occipito-parietal ERP activity. *Psychophysiology*, *44*(3), 436–443.

Dijkstra, T., & van Heuven, W. (2002). The architecture of the bilingual word recognition system: From identification to decision. *Bilingualism: Language and Cognition*, *5*(03), 175–197.

Ding, G., Perry, C., Peng, D., Ma, L., Li, D., Xu, S., Luo, Q., et al. (2003). Neural mechanisms underlying semantic and orthographic processing in Chinese-English bilinguals. *Neuroreport*, *14*(12), 1557–1562.

Dosenbach, N. U. F., Fair, D. A., Miezin, F. M., Cohen, A. L., Wenger, K. K., Dosenbach, R., Fox, M. D., et al. (2007). Distinct brain networks for adaptive and stable task control in humans. *Proceedings of the National Academy of Sciences*, *104*(26), 11073–11078.

Duncan, J., & Owen, A. M. (2000). Common regions of the human frontal lobe recruited by diverse cognitive demands. *Trends in Neurosciences*, *23*(10), 475–483.

Dyer, F. N. (1971). The duration of word meaning responses: Stroop interference for different preexposures of the word. *Psychonomic Science*, *25*(4), 229–231.

Dyer, F. N., & Severance, L. J. (1973). Stroop interference with successive presentations of separate incongruent words and colors. *Journal of Experimental Psychology*, *98*(2), 438–439.

Egner, T., & Hirsch, J. (2005a). Cognitive control mechanisms resolve conflict through cortical amplification of task-relevant information. *Nature Neuroscience*, *8*(12), 1784–1790.

Egner, T., & Hirsch, J. (2005b). The neural correlates and functional integration of cognitive control in a Stroop task. *NeuroImage*, *24*(2), 539–547.

Elston-Güttler, K. E., & Friederici, A. D. (2005). Memory and Language Native and L2 processing of homonyms in sentential context. *Journal of Memory and Language*, *52*, 256–283.

Emmorey, K., Luk, G., Pyers, J. E., & Bialystok, E. (2008). The source of enhanced cognitive control in bilinguals: evidence from bimodal bilinguals. *Psychological Science*, *19*(12), 1201–1206.

Emmorey, K., Petrich, J., & Gollan, T. H. (2012). Bilingual processing of ASL-English code-blends: The consequences of accessing two lexical representations simultaneously. *Journal of Memory and Language*, *67*(1), 199–210.

Eriksen, B., & Eriksen, C. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Attention, Perception, & Psychophysics*, *16*(1), 143–149.

Falkenstein, M., Hielscher, H., Dziobek, I., Schwarzenau, P., Hoormann, J., Sunderman, B., & Hohnsbein, J. (2001). Action monitoring, error detection, and the basal ganglia: An ERP study. *Neuroreport*, *12*(1), 157–161.

Fan, J., Flombaum, J. I., McCandliss, B. D., Thomas, K. M., & Posner, M. I. (2003). Cognitive and Brain Consequences of Conflict. *NeuroImage*, *18*, 42–57.

Fan, J., Fossella, J., Sommer, T., Wu, Y., & Posner, M. I. (2003). Mapping the genetic variation of executive attention onto brain activity. *Proceedings of the National Academy of Sciences*, *100*(12), 7406–7411.

Fan, J., McCandliss, B. D., Sommer, T., Raz, A., & Posner, M. I. (2002). Testing the efficiency and independence of attentional networks. *Journal of Cognitive Neuroscience*, *14*(3), 340–347.

Ferstl, E., Neumann, J., Bogler, C., & Von Cramon, D. Y. (2008). The extended language network: A meta-analysis of neuroimaging studies on text comprehension. *Human Brain Mapping*, *29*(5), 581–593.

Festman, J., Rodriguez-Fornells, A., & Münte, T. F. (2010). Individual differences in control of language interference in late bilinguals are mainly related to general executive abilities. *Behavioral and Brain Functions*, *6*(5), 1–12.

Fiebach, C. J., Friederici, A. D., Müller, K., & von Cramon, D. Y. (2002). fMRI evidence for dual routes to the mental lexicon in visual word recognition. *Journal of Cognitive Neuroscience*, *14*(1), 11–23.

Fiez, J., & Petersen, S. E. (1998). Neuroimaging studies of word reading. *Proceedings of the National Academy of Sciences*, *95*(3), 914–921.

Friederici, A. D., & Meyer, M. (2004). The brain knows the difference: Two types of grammatical violations. *Brain Research*, *1000*(1-2), 72–77.

Frost, R. (1998). Toward a strong phonological theory of visual word recognition: True issues and false trails. *Psychological Bulletin*, *123*(1), 71–99.

Frühholz, S., Godde, B., Finke, M., & Herrmann, M. (2011). Spatio-temporal brain dynamics in a combined stimulus-stimulus and stimulus-response conflict task. *NeuroImage*, *54*, 622–634.

Garavan, H., Ross, T. J., & Stein, E. A. (1999). Right hemispheric dominance of inhibitory control: An event-related functional MRI study. *Proceedings of the National Academy of Sciences*, *96*(14), 8301–8306.

Garbin, G., Sanjuan, A., Forn, C., Bustamante, J. C., Rodriguez-Pujadas, A., Belloch, V., Hernandez, M., et al. (2010). Bridging language and attention: Brain basis of the impact of bilingualism on cognitive control. *NeuroImage*, *53*(4), 1272–1278.

Gerard, L., & Scarborough, D. L. (1989). Language-specific lexical access of homographs by bilinguals. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *15*(2), 305–315.

Gitelman, D. R., Nobre, A. C., Sonty, S., Parrish, T. B., & Mesulam, M.-M. (2005). Language network specializations: An analysis with parallel task designs and functional magnetic resonance imaging. *NeuroImage*, *26*(4), 975–985.

Glaser, M. O., & Glaser, W. R. (1982). Time course analysis of the Stroop phenomenon. *Journal of Experimental Psychology: Human Perception and Performance*, *8*(6), 875–894.

Glaser, W. R., & Glaser, M. O. (1989). Context effects in stroop-like word and picture processing. *Journal of Experimental Psychology: General*, *118*(1), 13–42.

Goetz, P. J. (2003). The effects of bilingualism on theory of mind development. *Bilingualism: Language and Cognition*, *6*(1), 1–15.

Goldfarb, L., & Tzelgov, J. (2007). The cause of the within-language Stroop superiority effect and its implications. *Quarterly Journal of Experimental Psychology*, *60*(2), 179–185.

Gollan, T. H., & Acenas, L. A. R. (2004). What is a TOT? Cognate and translation effects on tip-of-the-tongue states in Spanish-English and Tagalog-English bilinguals. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *30*(1), 246–269.

Gollan, T. H., Montoya, R. I., & Bonanni, M. P. (2005). Proper names get stuck on bilingual and monolingual speakers' tip of the tongue equally often. *Neuropsychology*, *19*(3), 278–287.

Gollan, T. H., Montoya, R. I., Cera, C., & Sandoval, T. C. (2008). More use almost always means a smaller frequency effect: Aging, bilingualism, and the weaker links hypothesis. *Journal of Memory and Language*, *58*(3), 787–814.

Gollan, T. H., Montoya, R. I., Fennema-Notestine, C., & Morris, S. K. (2005). Bilingualism affects picture naming but not picture classification. *Memory & Cognition*, *33*(7), 1220–1234.

Gollan, T. H., Montoya, R. I., & Werner, G. A. (2002). Semantic and letter fluency in Spanish-English bilinguals. *Neuropsychology*, *16*(4), 562–576.

Gollan, T. H., & Silverberg, N. B. (2001). Tip-of-the-tongue states in Hebrew-English bilinguals. *Bilingualism: Language and Cognition*, *4*(1), 63–83.

Gollan, T. H., Slattery, T. J., Goldenberg, D., Van Assche, E., Duyck, W., & Rayner, K. (2011). Frequency drives lexical access in reading but not in speaking: The frequency-lag hypothesis. *Journal of Experimental Psychology: General*, *140*(2), 186–209.

Gray, J. R., Chabris, C. F., & Braver, T. S. (2003). Neural mechanisms of general fluid intelligence. *Nature Neuroscience*, *6*(3), 316–322.

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

Grossi, G., Savill, N., Thomas, E., & Thierry, G. (2010). Posterior N1 asymmetry to English and Welsh words in Early and Late English-Welsh bilinguals. *Biological Psychology, 85*(1), 124–133.

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.

Guo, T., Peng, D., & Liu, Y. (2005). The role of phonological activation in the visual semantic retrieval of Chinese characters. *Cognition, 98*(2), B21–B34.

Hahne, A. (2001). What’s different in second-language processing? Evidence from event-related brain potentials. *Journal of Psycholinguistic Research*, *30*(3), 251–266.

Hahne, A., & Friederici, A. D. (2001). Processing a second language: late learners’ comprehension mechanisms as revealed by event-related brain potentials. *Bilingualism: Language and Cognition*, *4*(2), 123–141.

Hampshire, A., Chamberlain, S., & Monti, M. (2010). The role of the right inferior frontal gyrus: inhibition and attentional control. *Neuroimage, 50*, 1313–1319.

Hansen, L. (2001). Language attrition: The fate of the start. *Annual Review of Applied Linguistics*, *21*, 60–73.

Hanslmayr, S., Pastötter, B., Bäuml, K.-H., Gruber, S., Wimber, M., & Klimesch, W. (2008). The electrophysiological dynamics of interference during the Stroop task. *Journal of Cognitive Neuroscience*, *20*(2), 215–225.

Hasegawa, M., Carpenter, P. A., & Just, M. A. (2002). An fMRI study of bilingual sentence comprehension and workload. *NeuroImage*, *15*(3), 647–660.

Hauk, O., Patterson, K., Woollams, A., Watling, L., Pulvermüller, F., & Rogers, T. T. (2006). [Q:] When would you prefer a SOSSAGE to a SAUSAGE? [A:] At about 100 msec. ERP correlates of orthographic typicality and lexicality in written word recognition. *Journal of Cognitive Neuroscience, 18*(5), 818–832.

Hauk, O., & Pulvermüller, F. (2004). Effects of word length and frequency on the human event-related potential. *Clinical Neurophysiology*, *115*(5), 1090–1103.

Hauk, O., Pulvermüller, F., Ford, M., Marslen-Wilson, W. D., & Davis, M. H. (2009). Can I have a quick word? Early electrophysiological manifestations of psycholinguistic processes revealed by event-related regression analysis of the EEG. *Biological Psychology, 80*(1), 64–74.

Heidlmayr, K., Moutier, S., Hemforth, B., & Isel, F. (2012). Bilingualism and executive functions: ERP evidence from a Stroop test. CNS 2012, Chicago, Illinois, March 31 – April 3, 2012. [Poster].

Hernandez, A. E. (2009). Language switching in the bilingual brain: What's next? *Brain and Language*, *109*, 133–140.

Hernandez, A. E., Dapretto, M., Mazziotta, J., & Bookheimer, S. (2001). Language switching and language representation in Spanish-English bilinguals: an fMRI study. *NeuroImage*, *14*(2), 510–520.

Hernandez, A. E., Martinez, A., & Kohnert, K. (2000). In search of the language switch: An fMRI study of picture naming in Spanish-English bilinguals. *Brain and Language*, *73*(3), 421–431.

Hernandez, A. E., & Meschyan, G. (2006). Executive function is necessary to enhance lexical processing in a less proficient L2: Evidence from fMRI during picture naming. *Bilingualism: Language and Cognition*, *9*(2), 177–188.

Hernández, M., Costa, A., Fuentes, L. J., Vivas, A. B., & Sebastián-Gallés, N. (2010). The impact of bilingualism on the executive control and orienting networks of attention. *Bilingualism: Language and Cognition*, *13*(03), 315–325.

Hervais-Adelman, A. G., Moser-Mercer, B., & Golestani, N. (2011). Executive control of language in the bilingual brain: integrating the evidence from neuroimaging to neuropsychology. *Frontiers in Psychology*, *2*(234), 1–8.

Hilchey, M. D., & Klein, R. M. (2011). Are there bilingual advantages on nonlinguistic interference tasks? Implications for the plasticity of executive control processes. *Psychonomic Bulletin & Review*, *18*(4), 625–658.

Holmes, A., & Pizzagalli, D. A. (2008). Response conflict and frontocingulate dysfunction in unmedicated participants with major depression. *Neuropsychologia*, *46*(12), 2904–2913.

Horwitz, B., Rumsey, J. M., & Donohue, B. C. (1998). Functional connectivity of the angular gyrus in normal reading and dyslexia. *Proceedings of the National Academy of Sciences*, *95*(15), 8939–8944.

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. (2011). Language selection in bilingual word production: electrophysiological evidence for cross-language competition. *Brain Research*, *1371*, 100–109.

Hutton, C., Bork, A., Josephs, O., Deichmann, R., Ashburner, J., & Turner, R. (2002). Image distortion correction in fMRI: A quantitative evaluation. *NeuroImage*, *16*(1), 217–240.

Illes, J., Francis, W. S., Desmond, J. E., Gabrieli, J. D., Glover, G. H., Poldrack, R., Lee, C. J., et al. (1999). Convergent cortical representation of semantic processing in bilinguals. *Brain and Language*, *70*(3), 347–363.

Indefrey, P. (2006). A Meta-analysis of Hemodynamic Studies on First and Second Language Processing: Which Suggested Differences Can We Trust and What Do They Mean? *Language Learning*, *56*, 279–304.

Itier, R. J., Latinus, M., & Taylor, M. J. (2006). Face, eye and object early processing: What is the face specificity? *NeuroImage*, *29*(2), 667–676.

Ivanova, I., & Costa, A. (2008). Does bilingualism hamper lexical access in speech production? *Acta Psychologica*, *127*(2), 277–288.

Kerkhofs, R., Dijkstra, T., Chwilla, D. J., & de Bruijn, E. R. A. (2006). Testing a model for bilingual semantic priming with interlingual homographs: RT and N400 effects. *Brain Research*, *1068*(1), 170–183.

Kim, C., Chung, C., & Kim, J. (2010). Multiple cognitive control mechanisms associated with the nature of conflict. *Neuroscience Letters*, *476*(3), 156–160.

Kim, C., Kroger, J. K., & Kim, J. (2011). A functional dissociation of conflict processing within anterior cingulate cortex. *Human Brain Mapping*, *32*(2), 304–312.

Kim, K. H., Relkin, N. R., Lee, K. M., & Hirsch, J. (1997). Distinct cortical areas associated with native and second languages. *Nature*, *388*, 171–174.

King, J. A., Korb, F. M., & Egner, T. (2012). Priming of Control: Implicit Contextual Cuing of Top-down Attentional Set. *The Journal of Neuroscience*, *32*(24), 8192–8200.

Kohnert, K. J., Hernandez, A. E., & Bates, E. (1998). Bilingual performance on the boston naming test: Preliminary norms in Spanish and English. *Brain and Language*, *65*(3), 422–440.

Kornblum, S., Stevens, G. T., Whipple, A., & Requin, J. (1999). The effects of irrelevant stimuli: 1. The time course of stimulus-stimulus and stimulus-response consistency effects with Stroop-like stimuli, Simon-like tasks, and their factorial combinations. *Journal of Experimental Psychology: Human Perception and Performance*, *25*(3), 688–714.

Kousaie, S., & Phillips, N. A. (2012). Conflict monitoring and resolution: Are two languages better than one? Evidence from reaction time and event-related brain potentials. *Brain Research*, *1446*, 71–90.

Kousaie, S., & Phillips, N. A. (2011). Ageing and bilingualism: Absence of a “bilingual advantage” in Stroop interference in a nonimmigrant sample. *Quarterly Journal of Experimental Psychology*.

Kovelman, I., Baker, S. A., & Petitto, L.-A. (2008). Bilingual and monolingual brains compared: a functional magnetic resonance imaging investigation of syntactic processing and a possible “neural signature” of bilingualism. *Journal of Cognitive Neuroscience*, *20*(1), 153–169.

Kovelman, I., Shalinsky, M. H., Berens, M. S., & Petitto, L. A. (2008). Shining new light on the brain's "Bilingual Signature": A functional Near Infrared Spectroscopy investigation of semantic processing. *NeuroImage*, *39*(3), 1457–1471.

Kovács, Á. M., & Mehler, J. (2009a). Cognitive gains in 7-month-old bilingual infants. *Proceedings of the National Academy of Sciences*, *106*(16), 6556–6560.

Kovács, Á. M., & Mehler, J. (2009b). Flexible learning of multiple speech structures in bilingual infants. *Science*, *325*(5940), 611–612.

Kroll, J. F., Bobb, S. C., & Wodniecka, Z. (2006). Language selectivity is the exception, not the rule: Arguments against a fixed locus of language selection in bilingual speech. *Bilingualism: Language and Cognition*, *9*(02), 119–135.

Kroll, J. F., Dussias, P. E., Bogulski, C. A., & Valdes Kroff, J. R. (2012). Juggling Two Languages in One Mind: What Bilinguals Tell Us About Language Processing and its Consequences for Cognition. In B. H. Ross (Ed.), *The Psychology of Learning and Motivation* (pp. 229–262). Elsevier: USA.

Kroll, J. F., & Stewart, E. (1994). Category interference in translation and picture naming: Evidence for asymmetric connections between bilingual memory representations. *Journal of Memory and Language*, *33*, 149–174.

Kroll, J. F., van Hell, J. G., Tokowicz, N., & Green, D. W. (2010). The Revised Hierarchical Model: A critical review and assessment. *Bilingualism: Language and Cognition*, *13*(3), 373–381.

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.

Kuo, L.-J., & Anderson, R. C. (2012). Effects of early bilingualism on learning phonological regularities in a new language. *Journal of Experimental Child Psychology*, *111*(3), 455–467.

Kutas, M., & Hillyard, S. (1980). Reading Senseless Sentences: Brain Potentials Reflect Semantic Incongruity. *Science*, *207*(4427), 203–205.

Larson, M. J., Kaufman, D. A. S., & Perlstein, W. M. (2009). Neural time course of conflict adaptation effects on the Stroop task. *Neuropsychologia*, *47*(3), 663–670.

Lau, E. F., Phillips, C., & Poeppel, D. (2008). A cortical network for semantics: (de)constructing the N400. *Nature Reviews Neuroscience*, *9*(12), 920–933.

Lehtonen, M., Hultén, A., Rodriguez-Fornells, A., Cunillera, T., Tuomainen, J., & Laine, M. (2012). Differences in word recognition between early bilinguals and monolinguals: Behavioral and ERP evidence. *Neuropsychologia*, *50*(7), 1362–1371.

Lehtonen, M., & Laine, M. (2003). How word frequency affects morphological processing in monolinguals and bilinguals. *Bilingualism: Language and Cognition*, *6*(3), 213–225.

Lehtonen, M., Laine, M., Niemi, J., Thomsen, T., Vorobyev, V. A., & Hugdahl, K. (2005). Brain correlates of sentence translation in Finnish-Norwegian bilinguals. *Neuroreport*, *16*(6), 607–610.

Levy, B. J., & Wagner, A. D. (2011). Cognitive control and right ventrolateral prefrontal cortex: reflexive reorienting, motor inhibition, and action updating. *Annals of the New York Academy of Sciences*, *1224*, 40–62.

Li, C. S. R., Yan, P., Sinha, R., & Lee, T. W. (2008). Sub-cortical processes of motor response inhibition during a stop signal task. *NeuroImage*, *41*(4), 1352–1363.

Libben, M. R., & Titone, D. A. (2009). Bilingual lexical access in context: evidence from eye movements during reading. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *35*(2), 381–390.

Lin, S. E., Chen, H. C., Zhao, J., Li, S., He, S., & Weng, X. C. (2011). Left-lateralized N170 response to unpronounceable pseudo but not false Chinese characters-the key role of orthography. *Neuroscience*, *190*, 200–206.

Linck, J. A., Hoshino, N., & Kroll, J. F. (2008). Cross-language lexical processes and inhibitory control. *The Mental Lexicon*, *3*(3), 349–374.

Linck, J. A., Kroll, J. F., & Sunderman, G. (2009). Losing access to the native language while immersed in a second language: evidence for the role of inhibition in second-language learning. *Psychological Science*, *20*(12), 1507–1515.

Liotti, M., Woldorff, M. G., Perez, R., & Mayberg, H. S. (2000). An ERP study of the temporal course of the Stroop color-word interference effect. *Neuropsychologia*, *38*(5), 701–711.

Liu, X., Banich, M. T., Jacobson, B. L., & Tanabe, J. L. (2004). Common and distinct neural substrates of attentional control in an integrated Simon and spatial Stroop task as assessed by event-related fMRI. *NeuroImage*, *22*(3), 1097–1106.

Liu, Y., & Perfetti, C. A. (2003). The time course of brain activity in reading English and Chinese: An ERP study of Chinese bilinguals. *Human Brain Mapping*, *18*(3), 167–175.

Liu, Y., Perfetti, C. A., & Hart, L. (2003). ERP evidence for the time course of graphic, phonological, and semantic information in Chinese meaning and pronunciation decisions. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *29*(6), 1231–1247.

Liu, Y,, Hao, M., Li, P., & Shu, H. (2011). Timed picture naming norms for Mandarin Chinese. *PLoS ONE*, *6*(1), e16505.

Logan, G. D. (1980). Attention and automaticity in Stroop and priming tasks: Theory and data. *Cognitive Psychology*, *12*(4), 523–553.

Lorenzen, B., & Murray, L. L. (2008). Bilingual aphasia: a theoretical and clinical review. *American Journal of Speech-Language Pathology*, *17*(3), 299–317.

Lovett, M. C. (2002). Modeling selective attention: Not just another model of Stroop (NJAMOS). *Cognitive Systems Research*, *3*(1), 67–76.

Lu, C., & Proctor, R. W. (1994). Processing of an irrelevant location dimension as a function of the relevant stimulus dimension. *Journal of Experimental Psychology: Human Perception and Performance*, *20*(2), 286–298.

Luck, S., Heinze, H., Mangun, G., & Hillyard, S. (1990). Visual event-related potentials index focused attention within bilateral stimulus arrays. II. Functional dissociation of P1 and N1 components. *Electroencephalography and Clinical Neurophysiology*, *75*, 528–542.

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

Luk, G., Green, D. W., Abutalebi, J., & Grady, C. (2011). Cognitive control for language switching in bilinguals: A quantitative meta-analysis of functional neuroimaging studies. *Language and Cognitive Processes*, 1–10. doi: 10.1080/01690965.2011.613209.

MacLeod, C. M. (1991). Half a century of research on the Stroop effect: an integrative review. *Psychological Bulletin*, *109*(2), 163–203.

MacLeod, C.M., & Dunbar, K. (1988). Training and Stroop-like interference: evidence for a continuum of automaticity. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *14*(1), 126–135.

MacLeod, C. M., & MacDonald, P. A. (2000). Interdimensional interference in the Stroop effect: Uncovering the cognitive and neural anatomy of attention. *Trends in Cognitive Sciences*, *4*(10), 383–391.

Macnamara, J., & Kushnir, S. L. (1971). Linguistic independence of bilinguals: The input switch. *Journal of Verbal Learning and Verbal*, *87*, 480–487.

Magezi, D. A., Khateb, A., Mouthon, M., Spierer, L., & Annoni, J.-M. (2012). Cognitive control of language production in bilinguals involves a partly independent process within the domain-general cognitive control network: Evidence from task-switching and electrical brain activity. *Brain and Language*, *122*(1), 55–63.

Mahendra, N., Plante, E., Magloire, J., Milman, L., & Trouard, T. P. (2003). fMRI variability and the localization of languages in the bilingual brain. *NeuroReport*, *14*(9), 1225–1228.

Maldjian, J., Laurienti, P. J., Kraft, R. A., & Burdette, J. H. (2003). An automated method for neuroanatomic and cytoarchitectonic atlas-based interrogation of fMRI datasets. *NeuroImage*, *19*(3), 1233–1239.

Mangun, G. R., Buonocore, M. H., Girelli, M., & Jha, A. P. (1998). ERP and fMRI measures of visual spatial selective attention. *Human Brain Mapping*, *6*(5-6), 383–389.

Marian, V., Spivey, M., & Hirsch, J. (2003). Shared and separate systems in bilingual language processing: Converging evidence from eyetracking and brain imaging. *Brain and Language*, *86*(1), 70–82.

Markela-Lerenc, J., Ille, N., Kaiser, S., Fiedler, P., Mundt, C., & Weisbrod, M. (2004). Prefrontal-cingulate activation during executive control: Which comes first? *Cognitive Brain Research*, *18*(3), 278–287.

Martin-Rhee, M. M., & Bialystok, E. (2008). The development of two types of inhibitory control in monolingual and bilingual children. *Bilingualism: Language and Cognition*, *11*(1), 81–93.

Maurer, U., Brem, S., Bucher, K., & Brandeis, D. (2005). Emerging neurophysiological specialization for letter strings. *Journal of Cognitive Neuroscience*, *17*(10), 1532–1552.

Maurer, U., Rossion, B., & McCandliss, B. D. (2008). Category specificity in early perception: Face and word n170 responses differ in both lateralization and habituation properties. *Frontiers in Human Neuroscience*, *2*(18), 1–7.

McCandliss, B. D., Cohen, L., & Dehaene, S. (2003). The visual word form area: expertise for reading in the fusiform gyrus. *Trends in Cognitive Sciences*, *7*(7), 293–299.

McKenna, F. P., & Sharma, D. (1995). Intrusive cognitions: An investigation of the emotional Stroop task. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *21*(6), 1595–1607.

Meara, P. M. (2005). *X_Lex: the Swansea Vocabulary Levels Test. v2.05.* Swansea: Lognostics.

Meara, P. M., & Miralpeix, I. (2006). *Y_Lex: the Swansea Advanced Vocabulary Levels Test. v2.05.* Swansea: Lognostics.

Melcher, T., & Gruber, O. (2009). Decomposing interference during Stroop performance into different conflict factors: an event-related fMRI study. *Cortex*, *45*(2), 189–200.

Meschyan, G., & Hernandez, A. E. (2006). Impact of language proficiency and orthographic transparency on bilingual word reading: An fMRI investigation. *NeuroImage*, *29*(4), 1135–1140.

Mestres-Missé, A., Turner, R., & Friederici, A. D. (2012). An anterior-posterior gradient of cognitive control within the dorsomedial striatum. *NeuroImage*, *62*(1), 41–47.

Meuter, R. F. I., & Allport, A. (1999). Bilingual Language Switching in Naming: Asymmetrical Costs of Language Selection. *Journal of Memory and Language*, *40*, 25–40.

Midgley, K., Holcomb, P., van Heuven, W., & Grainger, J. (2008). An electrophysiological investigation of cross-language effects of orthographic neighborhood. *Brain Research*, *1246*, 123–135.

Milham, M. P., Banich, M. T., & Barad, V. (2003). Competition for priority in processing increases prefrontal cortex's involvement in top-down control: An event-related fMRI study of the Stroop task. *Cognitive Brain Research*, *17*, 212–222.

Milham, M. P., Erickson, K., Banich, M. T., Kramer, A., Webb, A., Wszalek, T., & Cohen, N. J. (2002). Attentional Control in the Aging Brain: Insights from an fMRI Study of the Stroop Task. *Brain and Cognition*, *49*(3), 277–296.

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience*, *24*, 167–202.

Mohamed Zied, K., Phillipe, A., Pinon, K., Havet-Thomassin, V., Aubin, G., Roy, A., & Le Gall, D. (2004). Bilingualism and adult differences in inhibitory mechanisms: evidence from a bilingual Stroop task. *Brain and Cognition*, *54*(3), 254–256.

Montant, M., Schön, D., Anton, J.-L., & Ziegler, J. C. (2011). Orthographic Contamination of Broca's Area. *Frontiers in Psychology*, *2*(378), 1–10.

Moreno, E. M., & Kutas, M. (2005). Processing semantic anomalies in two languages: An electrophysiological exploration in both languages of Spanish-English bilinguals. *Cognitive Brain Research*, *22*(2), 205–220.

Moreno, E. M., Rodriguez-Fornells, A., & Laine, M. (2008). Event-related potentials (ERPs) in the study of bilingual language processing. *Journal of Neurolinguistics*, *21*(6), 477–508.

Morton, J. B., & Harper, S. N. (2007). What did Simon say? Revisiting the bilingual advantage. *Developmental Science*, *10*(6), 719–726.

Mägiste, E. (1984). Stroop tasks and dichotic translation: The development of interference patterns in bilinguals. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *10*(2), 304–315.

Naylor, L. J., Stanley, E. M., & Wicha, N. Y. Y. (2012). Cognitive and electrophysiological correlates of the bilingual Stroop effect. *Frontiers in Psychology*, *3*(81), 1–18.

Nee, D. E., Wager, T. D., & Jonides, J. (2007). Interference resolution: Insights from a meta-analysis of neuroimaging tasks. *Cognitive, Affective & Behavioral Neuroscience*, *7*(1), 1–17.

Nelson, J. R., Liu, Y., Fiez, J., & Perfetti, C. A. (2009). Assimilation and accommodation patterns in ventral occipitotemporal cortex in learning a second writing system. *Human Brain Mapping*, *30*(3), 810–820.

Newman, A. J., Bavelier, D., Corina, D., Jezzard, P., & Neville, H. J. (2002). A critical period for right hemisphere recruitment in American Sign Language processing. *Nature Neuroscience*, *5*(1), 76–80.

Newman, A. J., Tremblay, A., Nichols, E., Neville, H. J., & Ullman, M. T. (2012). The Influence of Language Proficiency on Lexical Semantic Processing in Native and Late Learners of English. *Journal of Cognitive Neuroscience*, *24*(5), 1205–1223.

Nichols, T., Brett, M., Andersson, J., Wager, T., & Poline, J.-B. (2005). Valid conjunction inference with the minimum statistic. *NeuroImage*, *25*(3), 653–660.

Niendam, T. A., Laird, A. R., Ray, K. L., Dean, Y. M., Glahn, D. C., & Carter, C. S. (2012). Meta-analytic evidence for a superordinate cognitive control network subserving diverse executive functions. *Cognitive, Affective & Behavioral Neuroscience*, *12*(2), 241–268.

Novick, J. M., Kan, I. P., Trueswell, J. C., & Thompson-Schill, S. L. (2009). A case for conflict across multiple domains: Memory and language impairments following damage to ventrolateral prefrontal cortex. *Cognitive Neuropsychology, 26*(6), 527–567.

Novick, J. M., Trueswell, J. C., & Thompson-Schill, S. L. (2005). Cognitive control and parsing: Reexamining the role of Broca’s area in sentence comprehension. *Cognitive, Affective, & Behavioral Neuroscience, 5*(3), 263–281.

Parker Jones, ’O., Green, D. W., Grogan, A., Pliatsikas, C., Filippopolitis, K., Ali, N., Lee, H. L., et al. (2011). Where, When and Why Brain Activation Differs for Bilinguals and Monolinguals during Picture Naming and Reading Aloud. *Cerebral Cortex*, *22*(4), 892–902.

Penniello, M.-J., Lambert, J., Eustache, F., Petit-Taboué, M. C., Barré, L., Viader, F., Morin, P., et al. (1995). A PET study of the functional neuroanatomy of writing impairment in Alzheimer’s disease: The role of the left supramarginal and left angular gyri. *Brain,* 697–706.

Perani, D., & Abutalebi, J. (2005). The neural basis of first and second language processing. *Current Opinion in Neurobiology*, *15*(2), 202–206.

Perani, D., Abutalebi, J., Paulesu, E., Brambati, S., Scifo, P., Cappa, S. F., & Fazio, F. (2003). The role of age of acquisition and language usage in early, high-proficient bilinguals: An fMRI study during verbal fluency. *Human Brain Mapping*, *19*(3), 170–182.

Perani, D., Dehaene, S., Grassi, F., Cohen, L., Cappa, S. F., Dupoux, E., Fazio, F., et al. (1996). Brain processing of native and foreign languages. *NeuroReport*, *7*, 2349–2444.

Perani, D., Paulesu, E., Galles, N. S., Dupoux, E., Dehaene, S., Bettinardi, V., Cappa, S. F., et al. (1998). The bilingual brain: Proficiency and age of acquisition of the second language. *Brain, 121*, 1841–1852.

Perfetti, C. A., Liu, Y., Fiez, J., Nelson, J., Bolger, D. J., & Tan, L. H. (2007). Reading in two writing systems: Accommodation and assimilation of the brain’s reading network. *Bilingualism: Language and Cognition*, *10*(02), 131–146.

Perfetti, C. A., Liu, Y., & Tan, L. H. (2005). The lexical constituency model: Some implications of research on Chinese for general theories of reading. *Psychological Review*, *112*(1), 43–59.

Peterson, B. S., Kane, M. J., Alexander, G. M., Lacadie, C., Skudlarski, P., Leung, H. C., May, J., et al. (2002). An event-related functional MRI study comparing interference effects in the Simon and Stroop tasks. *Cognitive Brain Research*, *13*(3), 427–440.

Peterson, B. S., Skudlarski, P., Gatenby, J. C., Zhang, H., Anderson, A. W., & Gore, J. C. (1999). An fMRI study of Stroop word-color interference: evidence for cingulate subregions subserving multiple distributed attentional systems. *Biological Psychiatry*, *45*(10), 1237–1258.

Phillips, N. A., Klein, D., Mercier, J., & de Boysson, C. (2006). ERP measures of auditory word repetition and translation priming in bilinguals. *Brain Research*, *1125*(1), 116–131.

Phillips, N. A., Segalowitz, N., O'Brien, I., & Yamasaki, N. (2004). Semantic priming in a first and second language: evidence from reaction time variability and event-related brain potentials. *Journal of Neurolinguistics*, *17*(2-3), 237–262.

Portin, M., & Laine, M. (2001). Processing cost associated with inflectional morphology in bilingual speakers. *Bilingualism: Language and Cognition*, *4*(1), 55–62.

Potter, M., So, K., von Eckardt, B., & Feldman, L. B. (1984). Lexical and conceptual representation in beginning and proficient bilinguals. *Journal of Verbal Learning and Verbal Behavior*, *23*, 23–38.

Poulin-Dubois, D., Blaye, A., Coutya, J., & Bialystok, E. (2011). The effects of bilingualism on toddlers' executive functioning. *Journal of Experimental Child Psychology*, *108*(3), 567–579.

Poulisse, N., & Bongaerts, T. (1994). First language use in second language production. *Applied Linguistics*, *15*(1), 36–57.

Power, J. D., Barnes, K. A., Snyder, A. Z., Schlaggar, B. L., & Petersen, S. E. (2012). Spurious but systematic correlations in functional connectivity MRI networks arise from subject motion. *NeuroImage*, *59*(3), 2142–2154.

Price, C. J., Green, D. W., & von Studnitz, R. (1999). A functional imaging study of translation and language switching. *Brain*, *122*, 2221–2235.

Prior, A., & Macwhinney, B. (2010). A bilingual advantage in task switching. *Bilingualism: Language and Cognition*, *13*(2), 253–262.

Protopapas, A., Archonti, A., & Skaloumbakas, C. (2007). Reading ability is negatively related to Stroop interference. *Cognitive Psychology*, *54*(3), 251–282.

Proverbio, A. M., & Adorni, R. (2009). C1 and P1 visual responses to words are enhanced by attention to orthographic vs. lexical properties. *Neuroscience Letters*, *463*(3), 228–233.

Proverbio, A. M., Adorni, R., & Zani, A. (2009). Inferring native language from early bio-electrical activity. *Biological Psychology*, *80*(1), 52–63.

Proverbio, A. M., Čok, B., & Zani, A. (2002). Electrophysiological measures of language processing in bilinguals. *Journal of Cognitive Neuroscience*, *14*(7), 994–1017.

Pugh, K., Mencl, W., Shaywitz, B., Shaywitz, S., Fulbright, R., Constable, R., Skudlarski, P., et al. (2000). The angular gyrus in developmental dyslexia: Task-specific differences in functional connectivity within posterior cortex. *Psychological Science, 11*(1), 51–56.

Pulvermüller, F., Assadollahi, R., & Elbert, T. (2001). Neuromagnetic evidence for early semantic access in word recognition. *European Journal of Neuroscience*, *13*(1), 201–205.

Pyers, J. E., Gollan, T. H., & Emmorey, K. (2009). Bimodal bilinguals reveal the source of tip-of-the-tongue states. *Cognition*, *112*(2), 323–329.

Ransdell, S., & Fischler, I. (1987). Memory in a monolingual mode: When are bilinguals at a disadvantage? *Journal of Memory and Language, 26*, 392–405.

Reynolds, M., & Besner, D. (2006). Reading aloud is not automatic: processing capacity is required to generate a phonological code from print. *Journal of Experimental Psychology. Human Perception and Performance*, *32*(6), 1303–1323.

Richardson, F. M., Seghier, M. L., Leff, A. P., Thomas, M. S. C., & Price, C. J. (2011). Multiple routes from occipital to temporal cortices during reading. *The Journal of Neuroscience, 31*(22), 8239–8247.

Ridderinkhof, K. R., Ullsperger, M., Crone, E. A., & Nieuwenhuis, S. (2004). The role of the medial frontal cortex in cognitive control. *Science*, *306*(5695), 443–447.

Ridderinkhof, K. R., van den Wildenberg, W. P. M., Segalowitz, S. J., & Carter, C. S. (2004). Neurocognitive mechanisms of cognitive control: the role of prefrontal cortex in action selection, response inhibition, performance monitoring, and reward-based learning. *Brain and Cognition*, *56*, 129–140.

Rodriguez-Fornells, A., De Diego Balaguer, R., & Münte, T. F. (2006). Executive control in bilingual language processing. *Language Learning*, *56*, 133–190.

Rodriguez-Fornells, A., Rotte, M., Heinze, H.-J., Nösselt, T., & Münte, T. F. (2002). Brain potential and functional MRI evidence for how to handle two languages with one brain. *Nature*, *415*(6875), 1026–1029.

Rodriguez-Fornells, A., van der Lugt, A., Rotte, M., Britti, B., Heinze, H.-J., & Münte, T. F. (2005). Second language interferes with word production in fluent bilinguals: brain potential and functional imaging evidence. *Journal of Cognitive Neuroscience*, *17*(3), 422–433.

Roelofs, A. (2003). Goal-referenced selection of verbal action: Modeling attentional control in the Stroop task. *Psychological Review*, *110*(1), 88–125.

Roelofs, A. (2006). Context effects of pictures and words in naming objects, reading words, and generating simple phrases. *Quarterly Journal of Experimental Psychology*, *59*(10), 1764–1784.

Roelofs, A. (2010a). Attention, temporal predictability, and the time course of context effects in naming performance. *Acta Psychologica*, *133*(2), 146–153.

Roelofs, A. (2010b). Attention and facilitation: converging information versus inadvertent reading in Stroop task performance. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *36*(2), 411–422.

Roelofs, A., van Turennout, M., & Coles, M. G. H. (2006). Anterior cingulate cortex activity can be independent of response conflict in Stroop-like tasks. *Proceedings of the National Academy of Sciences*, *103*(37), 13884–13889.

Rossion, B., Joyce, C. A., Cottrell, G. W., & Tarr, M. J. (2003). Early lateralization and orientation tuning for face, word, and object processing in the visual cortex. *NeuroImage*, *20*(3), 1609–1624.

Rousselet, G., Macé, M. J. M., & Fabre-Thorpe, M. (2004). Animal and human faces in natural scenes: How specific to human faces is the N170 ERP component? *Journal of Vision*, *4*, 13–21.

Rubia, K., Smith, A. B., Brammer, M. J., & Taylor, E. (2003). Right inferior prefrontal cortex mediates response inhibition while mesial prefrontal cortex is responsible for error detection. *NeuroImage*, *20*(1), 351–358.

Runnqvist, E., Strijkers, K., Sadat, J., & Costa, A. (2011). On the temporal and functional origin of l2 disadvantages in speech production: a critical review. *Frontiers in Psychology*, *2*(379), 1–8.

Rushworth, M. F., Ellison, A., & Walsh, V. (2001). Complementary localization and lateralization of orienting and motor attention. *Nature Neuroscience*, *4*(6), 656–661.

Ruz, M., & Nobre, A. C. (2008). Attention modulates initial stages of visual word processing. *Journal of Cognitive Neuroscience*, *20*(9), 1727–1736.

Rüschemeyer, S.-A., Zysset, S., & Friederici, A. D. (2006). Native and non-native reading of sentences: An fMRI experiment. *NeuroImage, 31*(1), 354–365.

Saalbach, H., & Stern, E. (2004). Differences between Chinese morphosyllabic and German alphabetic readers in the Stroop interference effect. *Psychonomic Bulletin & Review*, *11*(4), 709–715.

Sakurai, Y., Momose, T., Iwata, M., Sudo, Y., Ohtomo, K., & Kanazawa, I. (2000). Different cortical activity in reading of Kanji words, Kana words and Kana nonwords. *Cognitive Brain Research*, *9*(1), 111–115.

Scarborough, D. L., Gerard, L., & Cortese, C. (1984). Independence of lexical access in bilingual word recognition. *Journal of Verbal Learning and Verbal Behavior*, *23*(1), 84–99.

Schoonbaert, S., Holcomb, P. J., Grainger, J., & Hartsuiker, R. J. (2011). Testing asymmetries in noncognate translation priming: Evidence from RTs and ERPs. *Psychophysiology, 48*(1), 74–81.

Schroeder, U., Kuehler, A., Haslinger, B., Erhard, P., Fogel, W., Tronnier, V. M., Lange, K. W., et al. (2002). Subthalamic nucleus stimulation affects striato-anterior cingulate cortex circuit in a response conflict task: a PET study. *Brain*, *125*, 1995–2004.

Schwartz, A. I., & Kroll, J. F. (2006). Bilingual lexical activation in sentence context. *Journal of Memory and Language*, *55*(2), 197–212.

Schweizer, T. A., Ware, J., Fischer, C. E., Craik, F. I. M., & Bialystok, E. (2012). Bilingualism as a contributor to cognitive reserve: Evidence from brain atrophy in Alzheimer’s disease. *Cortex, 48*(8), 991–996.

Seeley, W. W., Menon, V., Schatzberg, A. F., Keller, J., Glover, G. H., Kenna, H., Reiss, A. L., et al. (2007). Dissociable intrinsic connectivity networks for salience processing and executive control. *The Journal of Neuroscience*, *27*(9), 2349–2356.

Segalowitz, S. J., & Zheng, X. (2009). An ERP study of category priming: Evidence of early lexical semantic access. *Biological Psychology*, *80*(1), 122–129.

Sereno, S. C., Rayner, K., & Posner, M. I. (1998). Establishing a time-line of word recognition: Evidence from eye movements and event-related potentials. *Neuroreport*, *9*(10), 2195–2200.

Shadmehr, R., & Holcomb, H. H. (1999). Inhibitory control of competing motor memories. *Experimental Brain Research*, *126*(2), 235–251.

Simon, G., Bernard, C., Lalonde, R., & Rebaï, M. (2006). Orthographic transparency and grapheme-phoneme conversion: An ERP study in Arabic and French readers. *Brain Research*, *1104*(1), 141–152.

Simon, G., Petit, L., Bernard, C., & Rebaï, M. (2007). N170 ERPs could represent a logographic processing strategy in visual word recognition. *Behavioral and Brain Functions*, *3*(21), 1–11.

Simon, J. R. (1969). Reactions toward the source of stimulation. *Journal of Experimental Psychology*, *81*(1), 174–176.

Siok, W. T., Spinks, J. A., Jin, Z., & Tan, L. H. (2009). Developmental dyslexia is characterized by the co-existence of visuospatial and phonological disorders in Chinese children. *Current Biology*, *19*(19), R890–892.

Small, D. ., Gitelman, D. ., Gregory, M. ., Nobre, A. ., Parrish, T. ., & Mesulam, M.-M. (2003). The posterior cingulate and medial prefrontal cortex mediate the anticipatory allocation of spatial attention. *NeuroImage*, *18*(3), 633–641.

Smithson, H. E., Khan, S. S., Sharpe, L. T., & Stockman, A. (2006). Transitions between color categories mapped with a reverse Stroop task. *Visual Neuroscience*, *23,* 453–460.

Snyder, A. Z., Abdullaev, Y. G., Posner, M. I., & Raichle, M. E. (1995). Scalp electrical potentials reflect regional cerebral blood flow responses during processing of written words. *Proceedings of the National Academy of Sciences*, *92*(5), 1689–1693.

Soares, C., & Grosjean, F. (1984). Bilinguals in a monolingual and a bilingual speech mode: The effect on lexical access. *Memory & Cognition*, *12*(4), 380–386.

Soveri, A., Rodriguez-Fornells, A., & Laine, M. (2011). Is There a Relationship between Language Switching and Executive Functions in Bilingualism? Introducing a within group Analysis Approach. *Frontiers in Psychology, 2*(183), 1–8.

Spalek, K., Hoshino, N., Damian, M. F., & Thierry, G. (2011). Phonological Co-activation of both languages in bilingual speech production. CNS 2011, San Francisco, California, April 2 – 5, 2011. [Poster].

Spieler, D. H., Balota, D. A., & Faust, M. E. (1996). Stroop performance in healthy younger and older adults and in individuals with dementia of the Alzheimer’s type. *Journal of Experimental Psychology: Human Perception and Performance*, *22*(2), 461–479.

Spinks, J. A., Liu, Y., Perfetti, C. A., & Tan, L. H. (2000). Reading Chinese characters for meaning: The role of phonological information. *Cognition*, *76*(1), B1–B11.

Stowe, L. A., & Sabourin, L. (2005). Imaging the processing of a second language: Effects of maturation and proficiency on the neural processes involved. *International Review of Applied Linguistics in Language Teaching*, *43*(4), 329–353.

Stroop, J. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology: General*, *18*, 643–662.

Sumiya, H., & Healy, A. F. (2004). Phonology in the bilingual Stroop effect. *Memory & Cognition, 32*(5), 752–758.

Swick, D., & Turken, A. U. (2002). Dissociation between conflict detection and error monitoring in the human anterior cingulate cortex. *Proceedings of the National Academy of Sciences*, *99*(25), 16354–16359.

Taft, M., & van Graan, F. (1998). Lack of Phonological Mediation in a Semantic Categorization Task. *Journal of Memory and Language*, *224*(38), 203–224.

Taha, H., Ibrahim, R., & Khateb, A. (2012). How Does Arabic Orthographic Connectivity Modulate Brain Activity During Visual Word Recognition: An ERP Study. *Brain Topography*. doi:10.1007/s10548-012-0241-2.

Tan, L. H., Laird, A. R., Li, K., & Fox, P. T. (2005). Neuroanatomical correlates of phonological processing of Chinese characters and alphabetic words: A meta-analysis. *Human Brain Mapping*, *25*(1), 83–91.

Tan, L. H., Liu, H. L., Perfetti, C. A., Spinks, J. A., Fox, P. T., & Gao, J. H. (2001). The neural system underlying Chinese logograph reading. *NeuroImage*, *13*(5), 836–846.

Tan, L. H., & Perfetti, C. A. (1997). Visual Chinese Character Recognition: Does Phonological Information Mediate Access to Meaning? *Journal of Memory and Language*, *37*(1), 41–57.

Tan, L. H., Spinks, J. A., Eden, G. F., Perfetti, C. A., & Siok, W. T. (2005). Reading depends on writing, in Chinese. *Proceedings of the National Academy of Sciences*, *102*(24), 8781–8785.

Tan, L. H., Spinks, J. A., Gao, J. H., Liu, H. L., Perfetti, C. A., Xiong, J., Stofer, K. A., et al. (2000). Brain activation in the processing of Chinese characters and words: A functional MRI study. *Human Brain Mapping*, *10*(1), 16–27.

Tanaka, J. W., & Curran, T. (2001). A Neural Basis for Expert Object Recognition. *Psychological Science*, *12*(43), 43–47.

Tao, L., Marzecová, A., Taft, M., Asanowicz, D., & Wodniecka, Z. (2011). The efficiency of attentional networks in early and late bilinguals: the role of age of acquisition. *Frontiers in Psychology*, *2*(123), 1–19.

Thierry, G., Martin, C. D., Downing, P., & Pegna, A. J. (2007). Controlling for interstimulus perceptual variance abolishes N170 face selectivity. *Nature Neuroscience*, *10*(4), 505–511.

Thierry, G., & Wu, Y. J. (2004). Electrophysiological evidence for language interference in late bilinguals. *NeuroReport*, *15*(10), 1555–1558.

Thierry, G., & Wu, Y. J. (2007). Brain potentials reveal unconscious translation during foreign-language comprehension. *Proceedings of the National Academy of Sciences*, *104*(30), 12530–12535.

Thompson-Schill, S. L., Bedny, M., & Goldberg, R. F. (2005). The frontal lobes and the regulation of mental activity. *Current Opinion in Neurobiology*, *15*(2), 219–224.

Thompson-Schill, S. L., D’Esposito, M., Aguirre, G. K., & Farah, M. J. (1997). Role of left inferior prefrontal cortex in retrieval of semantic knowledge: A reevaluation. *Proceedings of the National Academy of Sciences*, *94*, 14792–14797.

Thompson-Schill, S. L., Kurtz, K. J., & Gabrieli, J. D. E. (1998). Effects of Semantic and Associative Relatedness on Automatic Priming. *Journal of Memory and Language*, *38*(4), 440–458.

Thornburgh, D., & Ryalls, J. (1998). Voice onset time in Spanish-English bilinguals: Early versus late learners of English. *Journal of Communication Disorders*, *31*, 215–229.

Tokowicz, N., Michael, E. B., & Kroll, J. F. (2004). The roles of study-abroad experience and working-memory capacity in the types of errors made during translation. *Bilingualism: Language and Cognition*, *7*(3), 255–272.

Tsao, Y. C., Wu, M. F., & Feustel, T. (1981). Stroop Interference: Hemispheric Difference In Chinese Speakers. *Brain and Language*, *378*, 372–378.

Tzelgov, J., Henik, A., & Leiser, D. (1990). Controlling Stroop interference: Evidence from a bilingual task. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *16*(5), 760–771.

Ullsperger, M., & von Cramon, D. Y. (2006). How does error correction differ from error signaling? An event-related potential study. *Brain Research*, *1105*, 102–109.

Unsworth, N., & Engle, R. W. (2007). The nature of individual differences in working memory capacity: Active maintenance in primary memory and controlled search from secondary memory. *Psychological Review*, *114*(1), 104–132.

van Assche, E., Duyck, W., & Hartsuiker, R. J. (2012). Bilingual word recognition in a sentence context. *Frontiers in Psychology*, *3*(174), 1–8.

van Hell, J. G., & Dijkstra, T. (2002). Foreign language knowledge can influence native language performance in exclusively native contexts. *Psychonomic Bulletin & Review*, *9*(4), 780–789.

van Hell, J. G., & de Groot, A. M. B. (2008). Sentence context modulates visual word recognition and translation in bilinguals. *Acta Psychologica*, *128*(3), 431–451.

van Heuven, W., Conklin, K., Coderre, E. L., Guo, T., & Dijkstra, T. (2011). The Influence of Cross-Language Similarity on within- and between-Language Stroop Effects in Trilinguals. *Frontiers in Psychology*, *2*(374), 1–15.

van Heuven, W., & Dijkstra, T. (2010). Language comprehension in the bilingual brain: fMRI and ERP support for psycholinguistic models. *Brain Research Reviews*, *64*(1), 104–122.

van Heuven, W., Dijkstra, T., & Grainger, J. (1998). Orthographic neighborhood effects in bilingual word recognition. *Journal of Memory and Language*, *39*(3), 458–483.

van Heuven, W., Schriefers, H., Dijkstra, T., & Hagoort, P. (2008). Language conflict in the bilingual brain. *Cerebral Cortex*, *18*(11), 2706–2716.

van Veen, V., & Carter, C. S. (2002). The anterior cingulate as a conflict monitor: fMRI and ERP studies. *Physiology & Behavior*, *77*(4-5), 477–482.

van Veen, V., & Carter, C. S. (2005). Separating semantic conflict and response conflict in the Stroop task: a functional MRI study. *NeuroImage*, *27*(3), 497–504

Vargha-Khadem, F., Watkins, K. E., Price, C. J., Ashburner, J., Alcock, K. J., Connelly, A., Frackowiak, R. S., et al. (1998). Neural basis of an inherited speech and language disorder. *Proceedings of the National Academy of Sciences*, *95*(21), 12695–12700.

Verbruggen, F., Aron, A. R., Stevens, M. A., & Chambers, C. D. (2010). Theta burst stimulation dissociates attention and action updating in human inferior frontal cortex. *NeuroImage*, *107*(31), 13966–13971.

Vingerhoets, G., Van Borsel, J., Tesink, C., van den Noort, M., Deblaere, K., Seurinck, R., Vandemaele, P., et al. (2003). Multilingualism: an fMRI study. *NeuroImage*, *20*(4), 2181–2196.

Wager, T. D., Sylvester, C.-Y. C., Lacey, S. C., Nee, D. E., Franklin, M., & Jonides, J. (2005). Common and unique components of response inhibition revealed by fMRI. *NeuroImage*, *27*(2), 323–340.

Wang, Y., Kuhl, P. K., Chen, C., & Dong, Q. (2009). Sustained and transient language control in the bilingual brain. *NeuroImage*, *47*(1), 414–422.

Wang, Y., Xue, G., Chen, C., Xue, F., & Dong, Q. (2007). Neural bases of asymmetric language switching in second-language learners: An ER-fMRI study. *NeuroImage*, *35*(2), 862–870.

Wartenburger, I., Heekeren, H. R., Abutalebi, J., Cappa, S. F., Villringer, A., & Perani, D. (2003). Early setting of grammatical processing in the bilingual brain. *Neuron*, *37*(1), 159–170.

Watkins, K. E., Vargha-Khadem, F., Ashburner, J., Passingham, R. E., Connelly, A., Friston, K. J., Frackowiak, R. S. J., et al. (2002). MRI analysis of an inherited speech and language disorder: structural brain abnormalities. *Brain*, *125*, 465–478.

Weber-Fox, C., & Neville. (2001). Sensitive periods differentiate processing of open-and closed-class words: An ERP study of bilinguals. *Journal of Speech, Language, and Hearing Research*, *44*, 1338–1353.

Weber-Fox, C., & Neville, H. (1996). Maturational constraints on functional specializations for language processing: ERP and behavioral evidence in bilingual speakers. *Journal of Cognitive Neuroscience*, *8*(3), 231–256.

Weekes, N. Y., & Zaidel, E. (1996). The effects of procedural variations on lateralized Stroop effects. *Brain and Cognition*, *31*(3), 308–330.

West, R. (2003). Neural correlates of cognitive control and conflict detection in the Stroop and digit-location tasks. *Neuropsychologia*, *41*(8), 1122–1235.

West, R., & Alain, C. (1999). Event-related neural activity associated with the Stroop task. *Cognitive Brain Research*, *8*(2), 157–164.

West, R., & Alain, C. (2000). Effects of task context and fluctuations of attention on neural activity supporting performance of the Stroop task. *Brain Research*, *873*(1), 102–111.

West, R., Jakubek, K., Wymbs, N., Perry, M., & Moore, K. (2005). Neural correlates of conflict processing. *Experimental Brain Research*, *167*(1), 38–48.

Wong, A. C. N., Gauthier, I., Woroch, B., DeBuse, C., & Curran, T. (2005). An early electrophysiological response associated with expertise in letter perception. *Cognitive, Affective & Behavioral Neuroscience, 5*(3), 306–318.

Wright, B., & Wanley, A. (2003). Adults’ versus children's performance on the Stroop task: Interference and facilitation. *British Journal of Psychology*, *94*, 475–485.

Wu, Y. J., & Thierry, G. (2010). Chinese-English bilinguals reading English hear Chinese. *The Journal of Neuroscience*, *30*(22), 7646–7651.

Wu, Y. J., & Thierry, G. (2011). Unconscious translation during incidental foreign language processing. *NeuroImage*, *59*(4), 3468–3473.

Xu, Y., Pollatsek, A., & Potter, M. C. (1999). The activation of phonology during silent Chinese word reading. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *25*(4), 838–857.

Ye, Z., & Zhou, X. (2009). Conflict control during sentence comprehension: fMRI evidence. *NeuroImage*, *48*(1), 280–290.

Yeung, N., Botvinick, M. M., & Cohen, J. D. (2004). The Neural Basis of Error Detection: Conflict Monitoring and the Error-Related Negativity. *Psychological Review*, *111*(4), 931–959.

Zelazo, P. D., Craik, F. I. M., & Booth, L. (2004). Executive function across the life span. *Acta Psychologica*, *115*(2-3), 167–183.

Zhang, T., van Heuven, W., & Conklin, K. (2011). Fast Automatic Translation and Morphological Decomposition in Chinese-English Bilinguals. *Psychological Science, 22*(10), 1237–1242.