

Neural mechanisms of language control in bilingual speech production

Di (Judy) Zhu

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Department of Cognitive Science

Faculty of Medicine, Health and Human Sciences

Macquarie University, Sydney, Australia



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GENERAL SUMMARY

Bilinguals have a remarkable ability to coordinate their languages during speech production; they can switch language with ease, but can also stay in a single language if required. What are the neural mechanisms underlying such language control? It has been proposed that bilingual control is supported by a range of cognitive processes (e.g. inhibition), with recent neuroimaging evidence pointing towards the engagement of executive-control brain regions during language switching. Building on these existing knowledge, the present thesis aimed to further investigate the exact manner in which language control takes place in the bilingual brain, focussing on three particular aspects: scope, timing, and demands for control under different circumstances.

Chapter 2 examined the scope of language control, by looking at whole-language and item-specific control side by side in a modified language-switching paradigm. The role of the pre-supplementary motor area (a key brain region for domain-general inhibitory control) was then probed using transcranial magnetic stimulation (TMS). An overall performance decrement following the disruption of this brain region revealed its essential role in general speech execution, while no reliable evidence was found for its specific involvement in either whole-language or item-specific control. Chapter 3 investigated the timing of language control, by dividing the language-switching process into two separate stages (preparation and production). Brain activities were recorded using magnetoencephalography (MEG), and reconstructed into source activities in pre-selected regions of interest. The findings suggested that different control processes took place during the preparation stage and production stage, supported by the left and right inferior frontal gyrus, respectively. Chapter 4 examined how the demands for language

control differed between natural and forced switching. The effects of language switching and mixing were compared across three different contexts, with varying levels of external constraint on language selection. The behavioural and MEG results indicated that freedom of language selection and consistent language choice for each given concept were both factors that contributed to making natural switching easier than forced switching.

Taken together, the findings in this thesis expand our current knowledge on the neural mechanisms of language control in bilingual speech production, particularly regarding whole-language and item-specific control, preparation and execution of a language switch, and reduction of control demands in natural switching. These new findings deepen our understanding of bilinguals' skilful language coordination in daily life.

DECLARATION

I certify that the research presented in this thesis entitled “Neural mechanisms of language control in bilingual speech production” is my own original work. The study in Chapter 2 builds on from some work in my Master of Research (MRes) thesis. Specifically, part of the data for this study were collected during the MRes project, and the method sections for this study (Sections 2.2.1 and 2.3.1) are from the MRes thesis with minor changes. I continued to collect data for this study in the first six months of my PhD project, and re-analysed all data using linear mixed-effects models and non-parametric permutation tests. The results and interpretations in Chapter 2 are different from those in the MRes, and all the discussion sections were re-written.

All other work presented in this thesis has not previously been submitted for a degree, nor has it been submitted as part of the requirements for a degree to any university or institution other than Macquarie University. This thesis is an original piece of research and it has been written by me. Any assistance that I have received has been appropriately acknowledged. All information sources and literature used are appropriately attributed in the thesis.

The research presented in this thesis was approved by the Macquarie University Human Research Ethics Committee (reference numbers: 5201400585, 5201300054).

Signed:

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CHAPTER 1

General Introduction

1.1 OVERVIEW

In the globalised world today, bilingualism (and multilingualism) has become a widespread phenomenon, seen in most countries and across age groups and classes of society (Grosjean & Li, 2013). Even though the exact figures are not known, it is widely assumed that at least half the world's population speak two or more languages (French & Jacquet, 2004). Owing to this, the past few decades have seen a tremendous growth of research in the cognitive psychology and neuroscience of bilingualism. The overarching aim of such research is to understand the cognitive processes and neural substrates underlying the coordination and processing of two (or more) languages within the same individual. A central topic in this field concerns bilinguals' remarkable ability to juggle two languages during speech production. In day-to-day life, bilinguals come across a variety of conversational contexts, which may require them to communicate in one or both of their languages. They seem to switch seamlessly between the two languages while conversing with other bilinguals who share both of the languages, and at the same time, they are able to restrict their speech to a particular language when required, without experiencing unwanted intrusions from the other language.

It is generally agreed that when a bilingual speaker intends to express a concept, relevant words from both languages are activated in parallel (e.g. Hermans, Bongaerts, De Bot, & Schreuder, 1998; Costa, Caramazza, & Sebastian-Galles, 2000; Colomé, 2001). This means that the two languages compete with each other during speech production. How does the bilingual then make sure that only words belonging to the desired language (and not the other language) are selected for output? Finkbeiner, Gollan, and Caramazza (2006) referred to this as the "hard problem" in bilingual lexical selection. Existing proposals on how bilinguals might handle this situation fall into three categories. The first category postulates that appropriate language selection is accomplished via inhibition of lexical nodes in

the non-target language (Green, 1998). This is the most influential view so far, and it has prompted a series of studies looking at evidence for inhibition in bilingual control (see Section 1.3 for a detailed review). The second category assumes that the intention to speak a particular language is encoded at the conceptual level, which is sufficient to ensure that lexical nodes in the target language are highly activated and therefore selected for output (La Heij, 2005). This means that bilingual lexical selection occurs in a qualitatively similar manner as to how monolinguals choose between words with closely-related meanings. The third category states that the lexical selection mechanism only considers words from the target language, thus eliminating possible competition from the non-target language (Costa & Caramazza, 1999; Costa, Miozzo, & Caramazza, 1999).

Aside from theoretical accounts, there is growing interest in the neural mechanisms underlying bilingual language control. Recent evidence suggests that bilinguals recruit executive control brain regions during speech production to help coordinate their two languages (see Section 1.4 for details). In connection to such findings, a popular view holds that the bilingual experience may enhance general executive function as a result of extensive practice in daily life (for reviews, see Kroll & Bialystok, 2013 and Bialystok, 2017)¹. In this thesis, I aim to further investigate the exact manner in which language control is carried out in the bilingual brain, via three experimental studies. The first study (Chapter 2) examines the scope of language control (i.e. whether it affects an entire language or only specific lexical items), and probes the causal role of a key brain region in the executive control network using non-invasive brain stimulation. The second study (Chapter 3) looks at the timing of language control by separating the control processes into two stages, and examining the brain activity at each stage using a highly time-resolved electrophysiological technique. The third study (Chapter 4) taps into the ecological validity of laboratory paradigms, comparing natural language switching with forced

¹ Note that this remains a topic of ongoing debate. For opposing views, see Paap, Johnson, and Sawi (2015) and Lehtonen et al. (2018).

language switching and examining how the control mechanisms differ between them. Together, these studies expand our understanding of the neural mechanisms of bilingual control, in terms of the scope and timing of language control as well as the demands for control under different circumstances. In this thesis, I look at *speech production* in particular, as this represents a situation where bilinguals can have volitional control over what language to use, rather than being driven by the input language (such as in reading or speech perception)².

In the remainder of this chapter, I will provide an overview of the relevant existing literature, focussing on language control in bilingual speech production. In Section 1.2, I will introduce one of the most popular experimental paradigms used to investigate bilingual control: the language-switching paradigm. All the experimental studies in this thesis adopt variations of this paradigm. In Section 1.3, I will discuss the role of inhibition in bilingual language control, with a particular focus on the behavioural evidence coming from the language-switching paradigm. In Section 1.4, I will summarise electrophysiological and neuroimaging findings on how language control is carried out in the bilingual brain. These findings demonstrate an important role of executive control brain mechanisms in language switching. In Section 1.5, I will consider the scope of language control and review existing evidence regarding the presence of control mechanisms at the whole-language level and item-specific level. This forms the background for the study presented in Chapter 2. In Section 1.6, I will look at the timing of language control and discuss previous findings on whether there are separate control processes in preparing for and executing a language switch. This provides the rationale for the work presented in Chapter 3. In Section 1.7, I will examine current evidence suggesting differential demands for language control between natural and forced

² I believe that the control mechanisms in production should be fundamentally different from those in perception, because such language control is triggered by an intention to speak a particular language (whether based on external cues or free choice), rather than by language input (see Mosca & de Bot, 2017, for a discussion).

language switching, possibly revealing why bilinguals switch languages spontaneously in everyday life even though this is usually found to take extra time and cognitive resources in the laboratory. This lays the foundation for the study presented in Chapter 4. In Section 1.8, I will introduce the neuro-stimulation and electrophysiological techniques used in this thesis. I will explain the advantages of these techniques and why they were chosen for the experimental studies. Finally, in Section 1.9, I will provide an outline of the structure of this thesis, along with an overview of the three experimental studies.

1.2 THE LANGUAGE SWITCHING PARADIGM

Language switching has been one of the most commonly used experimental tasks in studying bilingual language control. It offers a convenient and well-controlled approach to investigate how bilinguals coordinate their two languages during speech production. I adopt this task in all three experimental studies presented in this thesis.

In a typical language-switching paradigm, bilingual participants name target items (e.g. pictures or numerals) while switching between their first language (L1) and second language (L2). Participants' performance in this task is measured in terms of reaction times and error rates. Studies employing this paradigm usually include single-language and mixed-language blocks. In a single-language block, the same language is required on all trials. In a mixed-language block, the language requirement may vary from one trial to the next (either predictably or unpredictably). When there is a language change (i.e. a trial requiring a different language than its preceding trial), this trial is referred to as a *switch trial*; when the language requirement stays the same, it is called a *stay trial* (also known as *repetition trial* or *non-switch trial*). Two types of costs have been classically associated with the language-switching paradigm. *Switch cost* refers to slower

responses (or more errors) on switch trials compared to stay trials. *Mixing cost* refers to slower responses (or more errors) on stay trials in mixed-language blocks³ compared to single-language blocks. The former is assumed to reflect transient control processes, responsible for switching language from trial to trial, whereas the latter is assumed to reflect sustained control, enabling both languages to be produced in the same context while managing their interference on each other (see Christoffels, Firk, & Schiller, 2007; Wang, Kuhl, Chen, & Dong, 2009). Single-language blocks are usually used as the baseline for determining the mixing cost; however, a few studies have specifically looked at the effect of switching language between single-language blocks, which may reflect another form of sustained control⁴ (e.g. Misra, Guo, Bobb, & Kroll, 2012; Guo, Liu, Misra, & Kroll, 2011; Branzi, Martin, Abutalebi, & Costa, 2014; Branzi, Della Rosa, Canini, Costa, & Abutalebi, 2016).

Different design variations have been introduced into the language-switching paradigm over the years. Based on the way switches are elicited, these designs can be classified into two types. The first type of design, *cued switching*, has been adopted by the majority of language-switching studies so far (e.g. Meuter & Allport, 1999; Costa & Santesteban, 2004; Campbell, 2005; Christoffels et al., 2007; Philipp, Gade, & Koch, 2007; Schwieter & Sunderman, 2008; Verhoef, Roelofs, & Chwilla, 2009, 2010; Martin et al., 2013; Fink & Goldrick, 2015; Reynolds, Schlöffel, & Peressotti, 2016). In this design, the language requirement on each trial is indicated by a cue (e.g. colours, faces of interlocutors, auditory prompts), which is presented either simultaneously with the naming target or before the target is shown. Participants are required to name the picture or numeral using the language specified by the cue. Usually the language sequence is random and

³ In most cases, only stay trials are included in this comparison, because all trials in a single-language block are (by definition) “stay” trials. Occasionally, switch trials from mixed-language blocks are also included in the calculation (e.g. Gollan, Kleinman, & Wierenga, 2014; Kleinman & Gollan, 2016).

⁴ More detailed discussion about this in Section 1.5.

unpredictable for the participants, but predictable sequence (e.g. switching on every second trial) has also been used (Jackson, Swainson, Cunnington, & Jackson, 2001)⁵. Using the cued switching design, studies typically find significant switch costs, suggesting that switching language from one trial to the next involves additional processing compared to staying in the same language; significant mixing costs are also usually reported, showing that speech production is slower and more error-prone in a mixed-language context compared to a single-language context. It should be noted that these “costs” do not purely represent the time it takes to switch between languages (or to mix languages), as there may be other processes that also contribute to these costs. For example, the switch cost may reflect a combined effect of both cue-switching ⁶ and language-switching (Heikoop, Declerck, Los, & Koch, 2016).

The cued-switching design does not give bilinguals any freedom to choose what language to speak on each trial; they must follow the cue and perform “forced” language selection. In contrast, the *voluntary switching* design allows bilinguals to speak whichever language they like on each trial (e.g. Gollan & Ferreira, 2009; Gollan, Kleinman, & Wierenga, 2014; Zhang et al., 2015; Blanco-Elorrieta & Pylkkänen, 2017; de Bruin, Samuel, & Duñabeitia, 2018). Hence, it is up to the individuals whether they want to switch language or not. Compared to forced language switching, this type of design more closely resembles language use in real life. Typically, a bilingual would be more used to expressing certain concepts in one language and other concepts in the other language; therefore, such a design attempts to elicit language switching in a natural manner (i.e. based on the individual speaker’s lexical accessibility). When language switching occurs voluntarily, the switch cost is sometimes found to be smaller (Gollan et al., 2014,

⁵ The language cues are redundant in this case, since the required language sequence is fully predictable.

⁶ That is, the cue changing from one trial to the next may involve a cost in itself (e.g. to encode the new cue).

Exp. 2; Zhang et al., 2015), and the mixing cost can even turn into a *mixing benefit* (de Bruin et al., 2018; see also Gollan & Ferreira, 2009, who found a mixing benefit for the non-dominant language in unbalanced bilinguals). Further, Kleinman and Gollan (2016) introduced another variation to the voluntary switching design, which they called *bottom-up switching*. Here, participants could use whichever language they preferred when naming a picture for the first time, but they were then required to persist with the original language choice every time that same picture appeared subsequently. The purpose of this design was to ensure that participants truly used their preferred language to name the item on each trial, rather than switching language “for the sake of switching” (i.e. another artefact of the laboratory context). The switch cost was eliminated and the mixing cost was substantially reduced in bottom-up switching.

1.3 THE ROLE OF INHIBITION IN BILINGUAL LANGUAGE CONTROL

The most influential view so far on bilingual language control is the “inhibition hypothesis”. According to this hypothesis, bilinguals ensure appropriate language selection during speech production by inhibiting the non-intended language. In other words, speaking in one language involves suppression of the other language. This idea was first proposed in Green’s (1998) inhibitory control model (ICM).

Drawing on Norman and Shallice’s (1986) theory on the control of actions, Green considered language production “a form of communicative action” (Green, 1998, p. 68). In the ICM, language control is carried out by “language task schemas”, which are external to the lexico-semantic system. The intention to speak a particular language causes the supervisory attentional system to activate the corresponding language task schema (e.g. L1 production) and suppress the other one (e.g. L2 production); the schemas also compete with each other to gain control. Meanwhile, within the lexico-semantic system, each lexical node is associated with a language

tag, identifying which language it belongs to. The current language task schema then regulates the activation levels of lexical nodes according to these tags. Any highly activated lexical nodes belonging to the non-target language are reactively inhibited to avoid output in the undesirable language.

An important feature of the ICM is that more active lexical nodes receive stronger inhibition; this serves to ensure that competition from these lexical nodes is properly managed. For unbalanced bilinguals, lexical nodes belonging to the dominant language are more highly activated by default, so they need to be suppressed more strongly to allow non-dominant language production than vice versa. Green further proposes that the amount of time to overcome prior inhibition is proportional to the strength of that inhibition. Therefore, when a bilingual subsequently returns to dominant language production, it takes longer to recover from the strong inhibition previously applied on this language (compared to returning to the non-dominant language).

The inhibition hypothesis of bilingual control has since prompted many studies investigating different markers of inhibition in bilingual speech production. Below I will discuss the existing findings and their implications for the role of inhibition in bilingual control, with a particular focus on evidence from the language-switching paradigm.

1.3.1 Evidence for inhibition in language switching

The involvement of inhibition in bilingual language control is well supported by findings from the language-switching paradigm (see Section 1.2, for an overview of this paradigm). There are two main pieces of evidence which demonstrate the important role of inhibition in language switching.

The first piece of evidence, commonly called *asymmetrical switch cost* (or *switch cost asymmetry*), refers to the observation of a larger switch cost when bilinguals

switch into their dominant language, compared to switching in the other direction (Meuter & Allport, 1999). As mentioned above, Green's (1998) inhibition hypothesis predicts that it should take more time for bilinguals to switch back to speaking their dominant language after non-dominant language production than vice versa, due to the need to overcome stronger prior inhibition placed on the dominant language. The observation of switch cost asymmetry aligns perfectly with this prediction. Such asymmetry has now been replicated in many language-switching studies (e.g. Jackson et al., 2001; Costa & Santesteban, 2004, Exp. 1; Campbell, 2005; Philipp et al., 2007, Exp. 1; Schwieter & Sunderman, 2008; Wang et al., 2009; Linck, Schwieter, & Sunderman, 2012; Jin, Zhang, & Li, 2014; Fink & Goldrick, 2015)⁷, and has become widely accepted as a key behavioural evidence for inhibitory control. It is worth noting though that there are situations in which the switch cost asymmetry is not found, and alternative views exist on its interpretation, as I will explain below (see Section 1.3.2).

The second piece of evidence is related to the language dominance effect, which is a robust proficiency effect in the bilingualism literature. When bilinguals perform picture naming separately in their two languages, response times are faster in the dominant language than in the non-dominant language (see Runnqvist, Strijkers, Sadat, & Costa, 2011; Hanulová, Davidson, & Indefrey, 2011). However, when the two languages are mixed together, such as in a language-switching task, responses are sometimes found to be faster in the non-dominant language instead (e.g. Costa & Santesteban, 2004; Christoffels et al., 2007; Gollan & Ferreira, 2009; Verhoef et al., 2009; Verhoef, Roelofs, & Chwilla, 2010; Martin et al., 2013; Peeters & Dijkstra, 2018). This is referred to as the *reversed dominance effect* (also known as *global L1 slowing*). This observation is often interpreted as evidence of sustained inhibition

⁷ I have only included in this list studies that employed naming tasks (e.g. pictures/numerals), which are more relevant for this thesis. Asymmetrical switch cost has also been observed in tasks involving reading words aloud (e.g. Macizo, Bajo, & Paolieri, 2012, Exp. 1); however, this kind of task may be fundamentally different from naming, as word stimuli provide the lexical forms (to read out) rather than the concepts (to express).

placed upon the dominant language, serving to facilitate speech production in the non-dominant language within a mixed-language context (see Kroll, Bobb, Misra, & Guo, 2008; Gollan et al., 2014; Bobb & Wodniecka, 2013).

1.3.2 Alternative views on the asymmetrical switch cost

The asymmetrical switch cost in language switching is considered by many to be the key behavioural evidence demonstrating the role of inhibition in bilingual language control. However, a few alternative explanations have been proposed, challenging the interpretation of this phenomenon as necessarily indicating inhibition (for a similar debate in the task-switching literature, see Koch, Gade, Schuch, & Philipp, 2010). The first alternative view was put forward by Finkbeiner, Almeida, Janssen, and Caramazza (2006), who investigated the inhibition account of language control by employing both univalent and bivalent stimuli⁸ in a language-switching task. They observed asymmetrical switch cost for the bivalent stimuli, but no switch cost at all for the univalent stimuli; this led to the conclusion that the switch cost asymmetry did not reflect inhibition (otherwise it should apply to univalent stimuli too). To account for the observation in bivalent stimuli, the authors proceeded to show that a similar pattern of asymmetry could be obtained when participants switched between easy and difficult responses in a monolingual task. The switch cost was larger for the easy responses than the difficult responses, analogous to the pattern observed with dominant and non-dominant language. Thus, an alternative interpretation of the asymmetrical switch cost was proposed: when switching into the dominant (i.e. easy) language, the target response is generated too quickly (before the lexical selection mechanism finishes updating its task goal to speaking a different language); this initial response is therefore automatically rejected to avoid erroneous output, which leads to an apparently

⁸ Univalent stimuli were always named in the same language throughout the experiment, whereas bivalent stimuli were named in both languages.

slower response in the end (also see Finkbeiner & Caramazza, 2006, for further explanation).

Another possible account of the switch cost asymmetry was provided by Philipp et al. (2007). According to this account, the larger switch cost for the dominant language results from stronger activation of the non-dominant language on the previous trial, which persists into the current trial and creates more interference for dominant language production. This logic is actually in a similar vein as the inhibition hypothesis (except assuming persistent activation instead of inhibition), hence it can be considered as the other side of the same coin.

Finally, Verhoef et al. (2009) proposed yet another possible source of switch cost asymmetry. In this study, the naming target was presented at either 750ms or 1500ms after the language cue, allowing different amounts of preparation time. The short preparation interval gave rise to an asymmetrical switch cost, whereas long preparation interval resulted in a symmetrical switch cost. The disappearance of asymmetry was due to the response times on all trial types benefiting from the long preparation interval, except L1 stay trials. One explanation is that all but L1 stay trials were subject to competition from the non-target language. The authors argued that this unique advantage enjoyed by L1 stay trials made responses particularly fast, thus resulting in a larger switch cost for L1. However, it should be noted that these findings were not replicated in other studies where the preparation time was manipulated (e.g. Philipp et al., 2007; Fink & Goldrick, 2015).

Apart from these studies which provide alternative explanations for the switch cost asymmetry, there are other cases in which an asymmetry is missing. One such case occurs in bilinguals who are quite balanced between their languages. Costa and Santesteban (2004) asked highly proficient bilinguals to switch between their L1 and L2, and found the switch cost to be symmetrical. This observation is in line with the inhibition hypothesis - if the amount of inhibition depends on relative language dominance, then two languages with similar proficiency levels should be

suppressed to a similar extent. However, the surprising finding is that the switch cost was also symmetrical between L1 and a weaker L3, as long as the participants were highly proficient in their L1 and L2 (see also Martin et al., 2013). To explain this pattern, Costa and Santesteban proposed that highly proficient bilinguals develop a different type of language control strategy, which does not require inhibition.

Costa, Santesteban, and Ivanova (2006) went on to search for specific factors which may be responsible for the symmetrical switch cost observed in highly proficient bilinguals. They tested participants with varied similarity between their two languages, and participants who acquired their L2 at different ages. The switch cost remained symmetrical in each of these cases. To push it to the extreme, these authors asked highly proficient bilinguals to switch between their L3 and L4 (in which they had relatively low proficiency), and switch between their L1 and a newly learned (invented) language. In these cases, switch cost asymmetry was finally observed. These findings suggest that bilinguals may adopt different strategies depending on which languages they are switching between: while an inhibition-free strategy is probably more efficient for switching between the highly proficient L1 and L2, there may be a limit to utilising such a strategy when it comes to switching between less proficient languages.

A related case concerns bilinguals' language use pattern in everyday life; in particular, how often they switch between languages. Christoffels et al. (2007) observed symmetrical switch cost in bilinguals who were not very highly proficient, but switched frequently between their two languages in daily life. This suggests that extensive practice of language switching may alter a bilingual's language control strategy, perhaps making them behave more similarly to highly proficient bilinguals⁹.

⁹ Note, however, that the switch effect in the neural data was asymmetrical in this study, showing a switch advantage for the dominant language. See Section 1.4.1.1 for more details.

Another factor which may influence the existence of switch cost asymmetry is the way that switches are elicited. Gollan and Ferreira (2009) employed a task design where participants switched languages voluntarily rather than according to external cues. Specifically, bilinguals were instructed to use whichever language was easier for them on each trial. The switch cost was found to be symmetrical in this case, even for unbalanced bilinguals. A similar pattern of symmetrical switch cost has been observed in other studies adopting a voluntary design (e.g. Zhang et al., 2015; de Bruin et al., 2018). Furthermore, Kleinman and Gollan (2016) report that the switch cost disappeared altogether in bottom-up switching (i.e. when participants used the same language for each time the same picture was named). All these findings demonstrate that having the freedom to switch language (or not) can have a profound influence on the switch cost pattern, possibly reflecting differential amount (or types) of control required in these situations.

1.3.3 To inhibit or not to inhibit

Summarising the discussions above, the basis of asymmetrical switch cost is subject to a number of different interpretations; furthermore, under certain language switching conditions asymmetrical switch cost does not occur. These points raise questions about whether inhibitory control really plays an essential role in bilingual speech production. However, a lack of switch cost asymmetry does not necessarily rule out the presence of inhibition; rather, it might indicate that this phenomenon is not a very reliable marker of inhibition in language control (for detailed discussions on this, see Bobb & Wodniecka, 2013; Declerck & Philipp, 2015).

An important but perhaps often overlooked pattern in the literature is that, when switch cost asymmetry is missing, reversed dominance is often observed. This is true for most of the studies discussed above (e.g. Costa & Santesteban, 2004, Exp. 2~5; Costa et al., 2006, Exp. 1~2; Christoffels et al., 2007; Gollan & Ferreira, 2009; Verhoef et al., 2009; Martin et al., 2013; Peeters & Dijkstra, 2018; de Bruin et al.,

2018). One possible explanation is that the asymmetrical switch cost and reverse dominance are both caused by slowing down of responses in the dominant language in a mixed-language production context: when only the switch trials are slowed down, this results in a disproportionately large switch cost for the dominant language (i.e. giving rise to switch cost asymmetry); when both the stay and switch trials are slowed down, this does not increase the switch cost but instead cause a global slowing effect on the dominant language (i.e. reversed dominance effect). In other words, when switch cost asymmetry is not found, it is precisely due to the global slowing of the dominant language affecting both stay and switch trials in that language at the same time. As explained earlier, such overall slowing of dominant language production also constitutes strong evidence for the inhibition of the dominant language, which is believed to facilitate production of the non-dominant language in a mixed-language context (Kroll et al., 2008; Gollan et al., 2014; Bobb & Wodniecka, 2013). From this point of view, the reversed dominance effect complements switch cost asymmetry as evidence supporting the role of inhibition in bilingual language control. Currently, it is not clear what factors determine which of these patterns would be observed in a particular situation (I will provide a more in-depth discussion on this in Chapter 2, Section 2.4.1).

The role of inhibitory control in bilingual production is also supported by evidence from a range of other paradigms. For example, in the "n-2 language-repetition" paradigm, participants switch between three languages. Longer naming latencies are typically observed when the language required for the current trial is the same as the "n-2 trial" (e.g. German-English-German vs French-English-German). Such a pattern is taken as evidence for inhibition of the recently abandoned language, which persists into the current trial and therefore takes time to overcome (Philipp et al., 2007, Exp. 2; Philipp & Koch, 2009; Guo, Liu, Chen, & Li, 2013; Declerck, Thoma, Koch, & Philipp, 2015). In addition, the presence of inhibitory processes have been found in studies employing the picture-word interference paradigm and tasks tapping into the effect of cognate status (see Kroll et al., 2008, for a detailed

review). All together, these findings support the important role of inhibition in bilingual speech production in a variety of scenarios, not just in language switching.

1.3.4 Domain-general inhibitory control in language switching

In the sections above, I have discussed the role of inhibition in bilingual language control. But is this kind of inhibition related to domain-general inhibitory control? As a core component of the executive control system, inhibition is a prominent function in human cognitive control (Miyake et al., 2000; Diamond, 2006). A parsimonious position would assume that bilinguals make use of such existing control mechanisms to help them coordinate their two languages during speech production.

To investigate whether this is the case, studies have looked into the relationship between language-switching performance and domain-general inhibitory control. For example, Linck et al. (2012) measured each participant's inhibitory control ability using the Simon task, and they found that participants with better inhibitory control incurred smaller language-switch costs¹⁰. This suggests that domain-general inhibitory mechanisms play a role in language switching. In a different study, Liu, Rossi, Zhou, and Chen (2014) tested unbalanced bilinguals and divided the participants into two groups: high and low inhibitory control ability (measured by a modified Simon task). Participants with low inhibitory control ability showed the typical switch cost asymmetry in language switching, while those with high inhibitory control ability displayed symmetrical switch cost (see also Liu, Liang, Zhang, Lu, & Chen, 2017). This pattern demonstrates that the phenomenon of switch cost asymmetry (often considered as a marker of inhibition in language control, see above) is related to participant's generic inhibitory control ability.

¹⁰ This study tested trilingual participants. Inhibitory control ability predicted the language-switch cost when participants switched into their dominant L1 (from either L2 or L3), and when they switched from L1 into the weaker L3, but not when they switched into the relatively proficient L2 (from either L1 or L3).

Furthermore, Liu, Liang, Dunlap, Fan, and Chen (2016) found that training participants on domain-general inhibition skills resulted in improved performance in language switching, as evident in the disappearance of switch cost asymmetry after training. Similarly, Timmer, Calabria, and Costa (2019) trained bilinguals in a language-switching task, and observed switch cost reduction in non-linguistic tasks after training. Such cross-domain transfer of training effects offer further evidence that inhibition in bilingual control is carried out by domain-general mechanisms. It is important to note that there are also studies which have found different patterns of performance across language switching and non-linguistic task switching, which suggests that language control cannot be considered as fully subsidiary to the executive control system (e.g. Calabria, Hernández, Branzi, & Costa, 2012; Marne, Hernández, & Costa, 2015; Branzi, Calabria, Boscarino, & Costa, 2016). It may be the case that language control relies partially on domain-general inhibitory control, thus resulting in (limited) skill transfer across domains (Prior & Gollan, 2013; Weissberger, Wierenga, Bondi, & Gollan, 2012; Kang, Ma, Li, Kroll, & Guo, 2020).

In the next section, I will turn towards findings on the neural mechanisms of bilingual language control, which offer more support for the idea of domain-general mechanisms underpinning such control. These findings suggest the recruitment of not only inhibition, but also a range of other executive control processes, during bilingual speech production.

1.4 NEURAL MECHANISMS OF BILINGUAL LANGUAGE CONTROL

Propelled by growing interests in the neural mechanisms underlying bilingual language control, the past two decades have seen increasing applications of functional neuroimaging and electrophysiological techniques to this research area. Studies have investigated language control mechanisms in the bilingual brain, and how these are related to domain-general cognitive control. A variety of techniques

have been utilised, including electrophysiological techniques such as electroencephalography (EEG) and magnetoencephalography (MEG), neuroimaging techniques such as functional magnetic resonance imaging (fMRI) and positron emission tomography (PET), as well as non-invasive brain stimulation techniques such as transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS).

Most EEG studies of bilingual language control focussed on event-related potentials (ERPs) during language switching (e.g. Jackson et al., 2001; Christoffels et al., 2007; Verhoef et al., 2009, 2010; Martin et al., 2013; Liu et al., 2014; Jin et al., 2014; Chang, Xie, Li, Wang, & Liu, 2016; Peeters & Dijkstra, 2018; Liu, Zhang, Blanco-Elorrieta, He, & Chen, 2020), particularly modulation of the N2 component and the late positive component (LPC); some also looked at oscillatory activities (Liu et al., 2017). MEG studies, which are much rarer, have examined reconstructed brain activities in pre-defined regions of interest (e.g. Blanco-Elorrieta & Pylkkänen, 2016, 2017), as this technique enables more accurate source reconstruction than can usually be achieved with EEG (Cohen & Cuffin, 1983). These electrophysiological studies put a lot of emphasis on the timecourse of brain activity, making full use of the millisecond temporal resolution afforded by these techniques. On the other hand, fMRI studies focus more on brain activities in exact locations (e.g. Price, Green, & Von Studnitz, 1999; Hernandez, Martinez, & Kohnert, 2000; Hernandez, Dapretto, Mazziotta, & Bookheimer, 2001; Wang, Xue, Chen, Xue, & Dong, 2007; Abutalebi et al., 2008; Hernandez, 2009; Wang et al., 2009; Garbin et al., 2011; Abutalebi et al., 2012; Abutalebi et al., 2013; Ma et al., 2014; de Bruin, Roelofs, Dijkstra, & FitzPatrick, 2014; De Baene, Duyck, Brass, & Carreiras, 2015; Weissberger, Gollan, Bondi, Clark, & Wierenga, 2015; Reverberi et al., 2015). This technique offers the unique advantage of high spatial resolution and ability to examine activities in deeper brain structures, which may not be easily detectable by EEG and MEG. While the vast majority of studies so far have examined language control by passively recording participants' brain activity, a few recent studies have

combined non-invasive brain stimulation (tDCS or TMS) with EEG to investigate the causal role of particular brain regions in language switching (Li, Liu, Pérez, & Xie, 2018; Tong et al., 2019; Liu, Tong, et al., 2020; Pestalozzi, Annoni, Müri, & Jost, 2020).

The neural findings suggest that there may be a range of processes engaged in bilingual language control, largely supported by the brain mechanisms for domain-general executive control. Below I will review the existing evidence provided by each type of technique, focussing on the control processes recruited for language switching and mixing in bilingual production.

List of Abbreviations

EEG	electroencephalography
MEG	magnetoencephalography
fMRI	functional magnetic resonance imaging
fNIRS	functional near-infrared spectroscopy
PET	positron emission tomography
TMS	transcranial magnetic stimulation
tDCS	transcranial direct current stimulation
ERP	event-related potentials
ERF	event-related fields
N2	N2 component (in the ERP)
LPC	late positive component (in the ERP)
ROI	region of interest
BA	Brodmann area
ACC	anterior cingulate cortex
pre-SMA	pre-supplementary motor area
SMA	supplementary motor area
IFG	inferior frontal gyrus
DLPFC	dorsolateral prefrontal cortex
IPL	inferior parietal lobe

1.4.1 ERP studies of language switching

In ERP studies of bilingual language control, the most commonly examined components are the N2 and LPC in language switching. Currently, there are debates around what cognitive process is represented by each of these components, and whether they are or are not specifically related to inhibition.

1.4.1.1 *The N2 component*

The N2 component (also called N200) refers to a negative deflection in the ERP waveform, which usually occurs around 200 - 300 ms following stimulus onset. This component is generally associated with inhibitory control (e.g. Pfefferbaum, Ford, Weller, & Kopell, 1985; Jodo & Kayama, 1992; Eimer, 1993; Falkenstein, Hoormann, & Hohnsbein, 1999; Jackson, Jackson, & Roberts, 1999; van Boxtel, van der Molen, Jennings, & Brunia, 2001; Bruin & Wijers, 2002; Etchell, Sowman, & Johnson, 2012; Castro-Meneses, Johnson, & Sowman, 2016a), but has also been implicated in conflict monitoring (e.g. Nieuwenhuis, Yeung, Van Den Wildenberg, & Ridderinkhof, 2003; Donkers & Van Boxtel, 2004; Yeung, Botvinick, & Cohen, 2004). In language processing, the N2 component sometimes occurs later in time (e.g. Schmitt, Rodriguez-Fornells, Kutas, & Münte, 2001; Rodriguez-Fornells et al., 2005; Schiller, 2006). Early studies of language switching suggest that the N2 component may reflect inhibitory processes in bilingual control, which share a common underlying mechanism as motor inhibition; however, later studies have shown inconsistent evidence for this. Moreover, one commonly encountered issue is that it can be difficult to ascertain whether an N2-like component observed is equivalent to the N2 reported by previous studies, adding further complexities to its interpretation (e.g. Christoffels et al., 2007; Verhoef et al., 2010). The relevant findings will be discussed below.

In a cued language-switching study, Jackson et al. (2001) observed an asymmetrical switch effect in the N2 component in frontal sensors; switch trials elicited larger

amplitude than stay trials in the participants' L2 (but not L1). This was interpreted as reflecting stronger inhibition of the dominant language when bilinguals switched into their weaker language. Such inhibition then takes more time to overcome when switching back to the strong language (Green, 1998), consistent with the observation of a larger behavioural switch cost for L1 in this study. Similarly, Verhoef et al. (2010) reported a larger N2 component for switch trials compared to stay trials, and this again occurred in L2 but not L1. However, unlike the frontal scalp distribution of the N2 observed by Jackson et al. (2001), here the effect was found in posterior sensors only¹¹. The authors suggested that this pattern was more consistent with endogenous attentional control, serving to disengage from the no-longer-required language, rather than inhibition. Because L1 is the stronger language, more effort is needed to disengage from this language when switching from L1 to L2 (i.e. L2 switch trials), leading to the asymmetrical switch effect.

While the two studies above seem to show somewhat discrepant results, an even more confusing pattern arose in Christoffels et al. (2007). In this study, the N2 switch effect was asymmetrical, but characterised by a *smaller* amplitude on switch trials compared to stay trials in the L1, while no difference was found between stay and switch trials in L2. Considering this pattern together with a lack of switch cost asymmetry in the behavioural data, it seems that the participants in this study did not rely on inhibition to perform trial-to-trial switching. An interesting aspect of this study is that it not only assessed the switch effect, but also the mixing effect (i.e. mixed-language vs single-language blocks). Both the behavioural and ERP data show that language mixing has a greater impact on L1 than L2. This led the authors to propose that, in the mixed-language blocks, participants may have globally biased towards the weaker L2 to facilitate production in that language, essentially

¹¹ A switch-related negativity was also observed in the frontal sensors in this study. However, this negativity occurred later in time and the authors suggested that this also did not resemble the N2 effect reported by Jackson et al. (2001).

making L1 production harder and more effortful. As such, the N2 switch effect observed for L1 (during trial-to-trial switching) may be explained as reflecting additional conflict processing required for L1 production, as a result of such global biasing towards L2.

Aside from these different patterns of switch-related N2 modulation, there are studies that found no such effect at all; rather, the N2 was modulated by other factors. For example, Verhoef et al. (2009) report that a long preparation interval (between cue and target onset) gave rise to increased N2 amplitude compared to short preparation interval. This was the case for both stay and switch trials in L2, as well as for switch trials (but not stay trials) in L1. This pattern of N2 modulation was interpreted as evidence that all trial types involved language competition except L1 stay trials. Another example is Martin et al. (2013), who found a larger N2 component in early bilinguals compared to late bilinguals. This occurred as an overall effect between the two groups of participants (both groups switched between their L1 and L3 in this case, so the relative language strength was matched across groups). This effect shows that the N2 can be sensitive to the linguistic profile of the participants, suggesting possible differences in the language control mechanisms utilised by early and late bilinguals.

In sum, the existing findings relating to the N2 component in language switching show diverse patterns and are difficult to reconcile with each other. So far, it is not yet clear what exact process the N2 represents in language control. It seems that this ERP component cannot simply be considered as a marker of inhibition in bilingual production; rather, it may reflect diverse control processes depending on the specific situation.

1.4.1.2 The late positive component (LPC)

Another commonly reported ERP component in language switching is the LPC. Jackson et al. (2001) observed an overall switch effect on the LPC; switch trials elicited a larger amplitude LPC compared to stay trials. This is consistent with evidence suggesting that the LPC reflects engagement of executive control in order to carry out response selection in situations of high conflict (Liotti, Woldorff, Perez III, & Mayberg, 2000). The larger LPC on switch trials was interpreted as representing the process of overcoming prior inhibition of the currently required language, via reconfiguration of stimulus-response mappings. Interestingly, while the behavioural switch cost in this study was asymmetrical (i.e. larger for L1, presumably indicating more effort required to overcome the stronger inhibition of this language), the switch effect in the LPC was symmetrical between L1 and L2. In a later study, Martin et al. (2013) also found an enlarged LPC on switch trials compared to stay trials. Unlike in Jackson et al. (2001), here the switch effect in LPC was only present for switching into the L2 or L3, but not when switching into the L1 (i.e. asymmetrical). However, this pattern again did not match the accompanying behavioural results, which showed either a larger switch cost in L1 (for late bilinguals) or symmetrical switch cost (for early bilinguals). Such discrepancies between the behavioural and neural switch cost patterns bring into question whether the LPC truly reflects the process of overcoming prior inhibition, as Jackson et al. (2001) proposed.

Perhaps making things more complicated, Liu et al. (2014) observed a language effect on the LPC, rather than a switch effect. Specifically, the LPC increased in amplitude during L2 naming compared to L1 naming, for both stay and switch trials. This pattern occurred in unbalanced bilinguals with a high level of inhibitory control ability (as measured by the Simon task), whereas those with low inhibitory control ability showed no difference in the LPC between L1 and L2. Such observations suggest that the LPC modulation was related to inhibitory control; however, the larger amplitude on L2 trials seems more consistent with applying

(rather than overcoming) inhibition, i.e. stronger suppression of L1 to enable L2 production compared to the other way around.

Given these diverse patterns of LPC effects, we must be cautious when claiming what this ERP component really represents in language switching. Nonetheless, all of the results above demonstrate that more complex processing tends to produce larger LPC amplitude (e.g. switch trials compared to stay trials, non-dominant language compared to dominant language). Therefore, perhaps we can at least say that the LPC reflects some sort of control process which helps with handling demanding situations in bilingual language control.

1.4.1.3 Summary of ERP findings

In summary, the N2 and LPC seem to be modulated by different factors under different situations. At this stage, it is still unclear what specific control process is represented by each of these components. However, what is clear is that we cannot simply treat N2 as a marker of applying inhibition and LPC as an indication of overcoming inhibition (as originally proposed by Jackson et al., 2001), even though that would make for a very clean explanation. Aside from the N2 and LPC, other ERP components or time windows have also been analysed occasionally in language-switching studies. For example, Jin et al. (2014) examined the P2 component following language cue onset and observed an asymmetrical switch effect in fronto-central sensors, which was interpreted as reflecting endogenous language control. This switch effect was larger for the dominant L1, matching the pattern of switch cost asymmetry in their behavioural data. Chang et al. (2016) selected time windows for analysis based on visual inspection of the ERP waveforms. They found a switch effect in the time window of 270 - 400 ms following target onset, which was taken as evidence for control processes occurring at the lemma selection stage.

Together, the existing ERP findings suggest that a range of control processes may be at play during language switching, including but not limited to inhibition. The exact control mechanisms applied may be dynamically adjusted according to the demands of the current communicative context (see Green & Abutalebi, 2013, for a discussion of various control processes that may be engaged for bilingual language control in different interactional contexts).

1.4.2 MEG studies of language switching

Compared to EEG studies, MEG studies of bilingual language control are still very rare. In two MEG studies, Blanco-Elorrieta and Pylkkänen (2016, 2017) investigated the role of executive control brain regions in language switching. The first study examined whether the neural mechanisms recruited for language switching overlapped with those for task switching, while the second study looked at how the engagement of such mechanisms varied when bilinguals switched language under different circumstances (e.g. natural vs unnatural). Both of these studies examined language switching in speech production as well as comprehension. In the discussions below, I will focus on the findings related to production, as those are most relevant for the present thesis.

In these MEG studies, the main analyses focussed on reconstructed brain activities in regions of interest (ROI) associated with executive control. The included brain regions were the anterior cingulate cortex (ACC), dorsolateral prefrontal cortex (DLPFC), and inferior frontal gyrus (IFG); these were defined anatomically based on Brodmann areas (BA). There were some differences in the way that source reconstruction and subsequent statistical analyses were carried out in these two studies. Blanco-Elorrieta and Pylkkänen (2016) reconstructed the brain activity for each BA separately, and then performed cluster-based permutation tests within each BA, to identify *temporal* clusters which showed significantly different brain activities across conditions (i.e. stay vs switch trials). On the other hand, Blanco-

Elorrieta and Pylkkänen (2017) included all of the ROIs under a single mask (separately for left and right hemisphere), and then searched for *spatio-temporal* clusters within each mask, to identify both the time interval and more precise location in which the brain activities differed significantly across conditions.

In Blanco-Elorrieta and Pylkkänen (2016), Arabic-English bilinguals performed a language-switching and a category-switching task with highly similar stimuli and designs. Results showed that both types of switching recruited the DLPFC (and not the other two ROIs). Specifically, switch trials elicited increased activity in the DLPFC compared to stay trials, starting from around 400 ms after stimulus onset (the language cue was embedded in the stimulus, so the cue and target appeared simultaneously). The similar spatial profile shared by the language-switching effect and the category-switching effect supports the idea that bilingual control is carried out by domain-general control mechanisms¹³.

Blanco-Elorrieta and Pylkkänen (2017) used three types of language cues to investigate the extent of executive control engagement when language switching occurred in different contexts. Comparison was made between cued switching using artificial cues (colours) and more natural cues (pictures of monolingual interlocutors), as well as a third context using bilingual interlocutors who did not indicate any particular language (i.e. voluntary switching). In addition, the naming target was presented 300 ms after the cue, allowing cue-related and target-related brain activities to be examined separately. Following cue onset, there was only a main effect of context in the posterior ACC, showing different brain responses to the colour cues and the interlocutor cues. Following target onset, there was an

¹³ It is worth noting though, that language switching mostly recruited the right DLPFC whereas category switching mostly recruited the left DLPFC in this study. This may raise questions about whether they can be considered as sharing the same brain mechanisms. However, the authors pointed out that such disparity is also present in the existing fMRI findings (although results seem to be mixed regarding which hemisphere is involved in which domain of control). Given the reliable main effect of switch observed in both left and right DLPFC in this study, the authors suggested that these results are still supportive of overlapping mechanisms between language control and domain-general cognitive control.

effect of switching, which was modulated by context. Specifically, switch trials elicited increased activity in the left DLPFC and ACC between 100 - 160 ms (for colour and monolingual cues), and just in the left ACC between 143 - 295 ms (for colour cues only); no switch effect was observed in the voluntary switching context. The behavioural data exhibited a similar pattern, with the switch cost only being significant in the colour-cue context and not the other two contexts. Such a pattern suggests that language switching becomes less effortful (and requires less cognitive control) when it happens naturally. It should be noted that, since the interval between cue and target presentation was fixed and relatively short in this study, the neural switch effects can alternatively be interpreted as in response to the cue, starting around 400 ms after cue onset. This timing seems to be more consistent with the results from Blanco-Elorrieta and Pylkkänen (2016).

In summary, MEG findings reveal an important role of DLPFC and ACC in language switching. These results illustrate the engagement of executive-control brain regions in bilingual control, while also showing that such engagement is influenced by the demands of the current communicative context. In regards to the sensor space data, no reliable effects have been reported in the event-related fields (ERF). Therefore, it remains unclear whether there are language-switching effects in the ERF which may resemble the ERP effects discussed above (see Section 1.4.1). Additionally, since the participants in both of these studies were early and highly proficient bilinguals, language was not included as a factor in the analyses. Hence, there was no information on whether switch cost asymmetry and/or reversed dominance effect occurred in the behavioural data¹⁴ (which would point more specifically towards the involvement of inhibitory processes, see Section 1.3). These remain to be investigated in future studies.

¹⁴ In post-hoc analyses, Blanco-Elorrieta and Pylkkänen (2016) found that the *neural* switch effect in production (i.e. increased activity in the DLPFC) was symmetrical between the two languages.

1.4.3 Neuroimaging and neuro-stimulation studies of language switching

A growing amount of functional neuroimaging findings suggest that language control in bilinguals activates a broad range of brain areas, including cortical regions such as the anterior cingulate cortex (ACC), pre-supplementary motor area (pre-SMA), inferior frontal gyrus (IFG), dorsolateral prefrontal cortex (DLPFC), and inferior parietal lobe (IPL), as well as subcortical structures such as the caudate, thalamus, and cerebellum (see Abutalebi & Green, 2016 and Calabria, Costa, Green, & Abutalebi, 2018, for comprehensive reviews). These are nicely illustrated in Green and Abutalebi's (2013) neurocognitive model of bilingual language control (see also Abutalebi & Green, 2007, 2008, for the original version of this model). Below I will summarise the evidence that implicates each of these brain regions in bilingual control. As in previous sections, I will focus specifically on the findings from language switching in speech production (including the switch effect and mixing effect), as these are most relevant to the present thesis.

1.4.3.1 Brain regions recruited in language switching

The ACC and pre-SMA are among the most consistently reported brain regions in neuroimaging studies of language switching. These brain regions are well known for their important roles in general cognitive control; the ACC is typically associated with conflict monitoring (e.g. Carter, Botvinick, & Cohen, 1999; Van Veen, Cohen, Botvinick, Stenger, & Carter, 2001; Botvinick, Braver, Barch, Carter, & Cohen, 2001; Botvinick, Cohen, & Carter, 2004; Kerns et al., 2004), and the pre-SMA with response selection and inhibition (e.g. Nachev, Wydell, O'Neill, Husain, & Kennard, 2007; Xue, Aron, & Poldrack, 2008; Cai, George, Verbruggen, Chambers, & Aron, 2012; Swann et al., 2012). Activation of these brain regions in language switching and mixing has been reported in many studies. Some refer to the ACC (Wang et al., 2007; Abutalebi et al., 2008; Abutalebi et al., 2012), some refer to the pre-SMA (de Bruin et al., 2014; De Baene et al., 2015), while others refer to the "ACC/pre-SMA complex" (Garbin et

al., 2011; Abutalebi et al., 2013; Branzi, Della Rosa, et al., 2016)¹⁵. The activation patterns also diverge across studies. For example, Garbin et al. (2011) report increased activity in the ACC/pre-SMA only when bilinguals switched from L2 to L1, but not when they switched in the other direction; in contrast, de Bruin et al. (2014) observed pre-SMA activation only when participants switched into their L2 or L3, not when they switched into L1. Furthermore, Abutalebi et al. (2013) found that the ACC/pre-SMA was recruited on all switch trials, and such recruitment was symmetrical even between L1 and a weaker L3. Green and Abutalebi (2013) propose that the pre-SMA works together with the dorsal ACC to perform conflict monitoring in bilingual language control. At this stage, there does not seem to be a clear division between the roles of these two brain regions in bilingual control; however, a meta-analysis showed that the pre-SMA may be more universally engaged, possibly serving an additional role of initiating and executing speech during language switching (Luk, Green, Abutalebi, & Grady, 2012).

The left IFG, which includes Broca's area, is widely regarded as an important brain region for language processing and speech production in general (see Hagoort, 2014). It has also been implicated in the suppression of interference in working memory (Nee et al., 2012) and non-verbal task switching (Garbin et al., 2010), as well as response inhibition (Swick, Ashley, & Turken, 2008). In bilingual language control, activation of the left IFG has been observed in language mixing compared to single-language production (e.g. Hernandez et al., 2001; Abutalebi et al., 2008; Ma et al., 2014), and in a phonological judgment task involving language switching¹⁶ (Hosoda, Hanakawa, Nariai, Ohno, & Honda, 2012). Importantly, Hosoda et al. (2012) found that, while the switch effect was present in the left IFG for switching in both directions, it was significantly larger when participants

¹⁵ This apparent discrepancy stems partly from the varied definitions for these anatomical labels. Generally, the peak activation falls within an area known as the "rostral cingulate zone", which overlaps with the dorsal ACC and pre-SMA in various studies.

¹⁶ This may be considered as similar to language switching in a naming task, as the participants were explicitly instructed to perform (covert) naming in order to make the phonological judgment.

switched from L1 to L2 than vice versa. Such an asymmetrical effect suggests that switching into the weaker language relies more on this brain region. Consistent with this observation, Green and Abutalebi (2013) proposes that the left IFG works to resolve interference (especially from the dominant language) in order to suppress the prepotent but incorrect responses (see also Abutalebi & Green, 2016).

While the left IFG is more classically associated with language processing, its counterpart in the right hemisphere is known for playing a prominent role in domain-general inhibitory control (Jahfari et al., 2011; Aron, Robbins, & Poldrack, 2004, 2014). If bilingual speech production is mediated by inhibitory mechanisms in the brain, then it makes sense for this brain region to be involved. Indeed, de Bruin et al. (2014) report activation of the right IFG in a language-switching task. Importantly, this brain region (along with the pre-SMA) was recruited when trilinguals switched into their L2 or L3, but not when they switched into L1. Such findings suggest that switching into a weaker language requires more inhibition, which is consistent with the contention made by Green's (1998) ICM (see Section 1.3). An alternative proposal is that the right IFG participates in overcoming prior inhibition. This is based on findings from blocked naming, where language switching occurs between single-language blocks (as opposed to trial-to-trial switching). Branzi, Della Rosa, et al. (2016) observed increased activity in the right IFG (among other frontal and inferior parietal regions) for L1 naming when it took place after an L2 block¹⁷. Such activations were interpreted as a reflection of overcoming the strong inhibition previously applied on L1 during L2 production. The importance of the right IFG in bilingual language control is also recognised in Green and Abutalebi's (2013) model. Here, this brain region performs the role of salient cue detection (for similar proposals in the domain of general action control, see Hampshire, Chamberlain, Monti, Duncan, & Owen, 2010; Chatham et al., 2012).

¹⁷ The opposite pattern (i.e. decreased activity) was observed in these brain regions for L2 naming after L1.

Another frontal region reported to activate during language control is the DLPFC (e.g. Hernandez et al., 2001; Wang et al., 2007; Hernandez, 2009). This is a functionally-defined brain region, which usually lies on the middle frontal gyrus (for example, overlapping with BA 9, 10 and 46; see Blanco-Elorrieta & Pylkkänen, 2016). In general, the DLPFC is considered to be important for a range of executive functions, such as working memory, planning, task shifting, and response inhibition (e.g. Barbey, Koenigs, & Grafman, 2013; Tanji, Shima, & Mushiake, 2007; Vanderhasselt, De Raedt, Baeken, Leyman, & D'haenen, 2006; Castro-Meneses, Johnson, & Sowman, 2016b). In language switching and language mixing, the role of DLPFC is thought to be related to interference suppression and inhibition (Hernandez et al., 2001; Wang et al., 2007). Aside from imaging studies, more evidence for the involvement of DLPFC in language control comes from neuro-stimulation studies. Nardone et al. (2011) administered repetitive TMS to this brain region in a bilingual patient who was experiencing pathological language switching, and this enabled them to temporarily modulate the amount of pathological switching that occurred. Furthermore, perturbation of the DLPFC has also been reported to change the pattern of switch costs in healthy bilinguals¹⁸. Specifically, both anodal and cathodal tDCS led to disappearance of switch cost asymmetry (which was present in the sham condition), and cathodal stimulation in particular resulted in larger LPC amplitude when participants switched from L1 to L2 compared to the other direction (Li et al., 2018; Tong et al., 2019). These findings point to a causal role of the DLPFC in language switching.

Aside from the frontal brain regions discussed above, the parietal cortices are also considered to be part of the language control network in Green and Abutalebi's (2013) model, where they hold the role of maintaining task representations. Generally speaking, the IPL is known to be involved in attentional control (e.g. Coull,

¹⁸ Note that in the TMS study by Nardone et al. (2011), the modulatory effects were found following stimulation of the left (but not the right) DLPFC. However, in the tDCS studies conducted on healthy bilinguals, only the right DLPFC was stimulated.

Frackowiak, & Frith, 1998; Rushworth, Paus, & Sipila, 2001; Lee et al., 2013); it has also been associated with the control of multiple languages, based on early observations from lesion studies (Pötzl, 1925; Leischner, 1948). In recent neuroimaging studies of bilingual control, activation of the IPL has mostly been found when language switching occurred across blocks (e.g. when L1 naming took place after a block of L2 naming; see Guo et al., 2011; Branzi, Della Rosa, et al., 2016), and when mixed-language production was compared with single-language production (e.g. Ma et al., 2014). In addition, Wang et al. (2009) report the recruitment of left IPL in trial-to-trial switching; however, this effect only emerged in the by-language comparisons, not the overall comparison between stay and switch trials. Based on Mevorach, Humphreys, and Shalev's (2006) findings of dissociable roles for the left and right parietal cortices in dealing with conflicting stimuli, Abutalebi and Green (2007, 2008) propose that, in the case of bilingual control, the left IPL serves to bias language selection away from the non-target language, while the right IPL biases selection towards the currently required language.

Finally, a number of subcortical structures have been implicated in bilingual language control. Most notable among these is the caudate nucleus (especially in the left hemisphere¹⁹). Recruitment of this brain region has been reported for language switching (Garbin et al., 2011; Abutalebi et al., 2013) and language mixing (Abutalebi et al., 2008). Interestingly, both Garbin et al. (2011) and Abutalebi et al. (2013) observed an asymmetrical switch effect in the left caudate, such that stronger activation of this brain region occurred when participants switched from a more dominant to a less dominant language. This pattern is consistent with the proposed role of left caudate in controlling interference from irrelevant words (Ali, Green, Kherif, Devlin, & Price, 2010) or selecting the intended language in a bilingual context (Crinion et al., 2006)²⁰. Such functions of the left caudate are

¹⁹ But see Wang et al. (2007), who observed activation of the right caudate instead.

²⁰ Note that these two studies themselves are not about language switching in particular.

further supported by cases of involuntary language switching and mixing in bilingual patients who suffer from lesions in this brain region (Abutalebi, Miozzo, & Cappa, 2000; Mariën, Abutalebi, Engelborghs, & De Deyn, 2005). Apart from the caudate nucleus, other subcortical structures, such as the putamen and thalamus, as well as the cerebellum, are also being increasingly recognised as part of the brain network for bilingual language control (see Green & Abutalebi, 2013; Abutalebi & Green, 2016; Calabria et al., 2018). The exact roles of these brain regions in language switching and mixing await elucidation by future studies.

In summary, a great number of cortical and subcortical brain regions have been implicated in language switching. While there are some conflicting results across studies, there exists consensus on a few key brain regions involved in bilingual control. It is important to bear in mind that language control is a dynamic process; therefore, the recruitment of these brain regions (and the interactions between them) may vary depending on the demands of the specific communicative context (Green & Abutalebi, 2013). The engagement of language control mechanisms may also differ between individuals, based on factors such as language proficiency, age of acquisition for L2, and pattern of language use in daily life (see Calabria et al., 2018, for a discussion). In an effort to bring together the findings from different studies (e.g. to avoid apparent commonalities or discrepancies due to different labelling/locations of brain regions across studies), Sulpizio, Del Maschio, Fedeli, and Abutalebi (2020) recently conducted a meta-analysis, where they applied the activation-likelihood estimation method on the coordinates of peak activation reported in these neuroimaging studies. This analysis confirmed that bilingual language control involved widespread activation encompassing the various brain regions discussed above, with some small differences between early and late bilinguals.

1.4.3.2 Language control and domain-general executive control

The brain regions commonly recruited for bilingual language control, as discussed in the section above, largely overlap with the executive control brain network. A popular view holds that language control and general cognitive control are underpinned by similar neural mechanisms, and therefore, the bilingual experience enhances executive function as a result of extensive practice of language control in everyday life (see Kroll & Bialystok, 2013; Bialystok, 2017; but also see Paap et al., 2015; Lehtonen et al., 2018, for opposing views).

More direct evidence for the neural overlap between language control and executive control comes from studies which have compared these two domains of control directly in the same group of participants (Abutalebi et al., 2012; De Baene et al., 2015; Weissberger et al., 2015; Branzi, Della Rosa, et al., 2016; Blanco-Elorrieta & Pylkkänen, 2016). All of these studies tested highly proficient bilinguals, and the findings reveal mostly shared brain activations across the two domains, with some differences in certain brain regions. For example, Abutalebi et al. (2012) examined the ACC specifically, and found similar recruitment of this brain region when bilinguals performed a language-switching task and a non-linguistic conflict resolution task (i.e. the flanker task). Looking at the whole brain, De Baene et al. (2015) observed common activation of a range of frontal and parietal brain regions across language switching and non-linguistic task switching, while certain brain areas were specifically engaged for language switching (e.g. precentral and postcentral gyri, which are related to articulatory processing) and for task switching (e.g. dorsal premotor cortex, which is associated with action preparation). These differences across domains were attributed to factors such as the response modality (verbal responses in language switching vs manual button presses in task switching). Later studies were careful to control for such factors, using designs that elicit verbal responses in both language switching and task switching. These studies reveal shared brain activations across the two domains, mostly in the prefrontal cortex (Branzi, Della Rosa, et al., 2016; Blanco-Elorrieta & Pylkkänen, 2016), but also

in an extensive brain network involving many cortical and subcortical regions (Weissberger et al., 2015). Interestingly, Weissberger et al. (2015) also found some differences across the two domains, which were modulated by trial types. On stay trials, brain activities were larger in multiple locations for task switching compared to language switching; on the other hand, switch trials and single trials²¹ showed greater brain activities in a few select locations (cingulate gyrus and some subcortical structures) for language switching compared to task switching. Taken together, these findings demonstrate largely overlapping neural mechanisms between language control and general cognitive control. However, it is also likely that some domain-specific mechanisms exist.

1.5 THE SCOPE OF LANGUAGE CONTROL: WHOLE-LANGUAGE VS ITEM-SPECIFIC CONTROL

As set out in Section 1.1, the present thesis aims to provide a more detailed understanding of the neural mechanisms underlying bilingual language control, by approaching this topic from three particular angles. The first angle focusses on the scope of language control. During speech production, bilinguals may apply *global control* on each language, simultaneously regulating the activation levels of all lexical items in that language, or *local control*, specifically targeting individual lexical items that compete for selection (De Groot & Christoffels, 2006). Some models of bilingual production assume both levels of control to be present (e.g. Green, 1998; Schwieter & Sunderman, 2008; Declerck, Koch, & Philipp, 2015). According to De Groot and Christoffels, proactive regulation of the two languages on the global level may be complemented by reactive inhibition operating at the local level; the latter serves to catch and suppress any remaining highly-activated lexical items in the non-target language (despite the global suppression). In this

²¹ Stay and switch trials come from mixed-language/mixed-task blocks. Single trials come from single-language/single-task blocks.

way, global and local control work together to ensure that speech output occurs in the desired language. From a theoretical point of view, De Groot (2011) argues that local control alone would be sufficient to prevent the output of any words belonging to the non-target language, without needing any control mechanisms at the global level at all. Therefore, the construct of global control may be redundant.

A few experimental studies have so far examined global and local control in bilingual speech production. These studies adopted a variety of paradigms, and report mixed findings in regards to which level(s) of language control are at play (see Table 1-1, for a summary). Before discussing these findings in detail, I would like to first address an issue of terminology. The terms “global” and “local” are potentially confusing, as they have been used with different definitions than those of De Groot and Christoffels (2006). For example, Guo et al. (2011) referred to the effect of language mixing (i.e. mixed-language vs single-language blocks) as “local” control, and the block order effect among single-language blocks as “global” control. Furthermore, studies looking into the two levels of language control have used different names to denote these (e.g. Finkbeiner, Almeida, et al., 2006; Van Assche, Duyck, & Gollan, 2013 - see more details below). To avoid confusion, I will adopt the following terminology in this thesis: *whole-language control* refers to the simultaneous regulation of all lexical representations in a language (i.e. “global” as defined by De Groot & Christoffels, 2006), and *item-specific control* refers to targeted regulation of individual lexical representations that compete for selection (i.e. “local” as defined by De Groot & Christoffels, 2006).

The existing studies looking at whole-language and item-specific control generally do so by examining the effect of production in one language upon subsequent production in the other language²². These studies can be broadly classified into

²² This is the approach taken by most studies so far. One exception is Philipp and Koch (2009), who used the “n-2 language repetition” paradigm. This paradigm does not look at the effect of speaking

two categories. The first category looks at *transient* language control, i.e. the immediate after-effect of speaking a different language on the previous trial (such as can be seen in trial-to-trial switching). The second category examines *sustained* language control, i.e. the persisting after-effect of prior production in the other language (such as when changing language between single-language blocks)²³.

To investigate transient language control, one obvious approach is to examine the switch cost in the cued language-switching paradigm (see Section 1.2 for a detailed explanation). Finkbeiner, Almeida, et al. (2006) assessed the presence of whole-language inhibition (what they called “language suppression”) and item-specific inhibition (what they called “lexical suppression”) by asking bilinguals to name digits and pictures within the same experiment. A crucial aspect of the task design was that it included a mixture of univalent and bivalent stimuli. Specifically, participants were instructed to name the digits in their L1 or L2 according to colour cues (i.e. bivalent stimuli), but to name all pictures in L1 only (i.e. univalent stimuli). The authors reasoned that, if naming in one language involves suppression of the other language, then the time it takes to overcome that suppression should be reflected as slower responses whenever a language switch is required; importantly, this should be the case for both univalent and bivalent stimuli. In their first experiment, the pictures were common everyday objects (i.e. not semantically related to the digits), so a switch cost would indicate suppression of the non-target language as a whole on the previous trial. In their second experiment, the pictures were “dot patterns”, which elicited responses from the same numerical set as the digit stimuli; in this case, a switch cost would show up even if only individual competing lexical items in the non-target language were suppressed. The typical

a different language previously; rather, it looks at the effect of having recently abandoned the currently required language.

²³ For a similar distinction between transient and sustained language control, see Christoffels et al. (2007) and Wang et al. (2009). However, note that their definition of sustained control is equivalent to the language-mixing effect (i.e. mixed-language vs single-language blocks), whereas the type of sustained control discussed here refers to the after-effect of blocked naming in the other language.

(asymmetrical) switch cost was obtained for bivalent stimuli in both experiments; on the other hand, no switch cost was found at all for the univalent stimuli. This pattern led the authors to conclude that there was no inhibition operating at either the whole-language level or the item-specific level, and that the signature evidence for inhibition (i.e. asymmetrical switch cost) was simply an artefact of using bivalent stimuli in previous studies. However, there was a confound in this study, such that all univalent trials were accompanied by a task switch (from digit naming to picture naming). It is possible that a language-switching effect occurred for the univalent stimuli, but it was masked by the task-switching effect. More recently, Reynolds et al. (2016) showed that the asymmetrical switch cost is indeed present for both bivalent and univalent stimuli²⁴ when the confound of task switching is removed. Therefore, we cannot rule out the existence of whole-language or item-specific inhibition in trial-to-trial switching.

A slightly different method to examine transient language control makes use of the “n-2 language-repetition” paradigm. This paradigm involves switching between three languages, and the general finding is that naming latencies are longer when the language on the current trial is the same as the “n-2 trial” (e.g. German-English-German vs French-English-German). Such difference in naming latency (i.e. “n-2 repetition cost”) is taken as evidence for the inhibition of a recently abandoned language. In order to examine whether such inhibition acted on the entire language or only on specific stimulus-response sets, Philipp and Koch (2009) designed two different types of “n-2 repetition”. They observed no significant difference in the “n-2 repetition cost” whether the stimulus-response set was repeated or only the

²⁴ Their choice of “univalent stimuli” was a little different. Reynolds et al. (2016) used digits as bivalent stimuli, and number words as univalent stimuli. Number words can only be associated with the language they are written in, so these are *inherently* univalent. On the other hand, the picture stimuli used by Finkbeiner, Almeida, et al. (2006) were possible to name in both languages, but they were *artificially* made univalent by the task instruction, which specified that they should always be named in L1 in the context of this experiment.

language (i.e. not the stimulus-response set) was repeated. This suggests that the type of inhibition involved in this paradigm operates on the whole-language level.

In contrast to transient control in trial-to-trial switching, sustained language control is usually examined by looking at the block order effect across single-language blocks. In particular, comparison is made between production in one language with and without a prior block in the other language. Van Assche et al. (2013) used a verbal fluency task to investigate sustained whole-language and item-specific control. In this task, bilinguals were presented with letter prompts and asked to produce words beginning with those graphemes/phonemes in each language. Item-specific inhibition was assessed using repeated letter prompts across the two languages, while whole-language inhibition was assessed using different letter prompts for the two languages. A decrease in verbal fluency (i.e. fewer exemplars produced) was observed in the dominant language when exemplars were previously produced for the same letter prompts in the non-dominant language; this indicates the presence of item-specific inhibition²⁵. In contrast, for non-repeated letter prompts, such a verbal fluency decrease (which would indicate whole-language inhibition) was observed for Mandarin-English, but not Dutch-English, bilinguals. These findings suggest that item-specific inhibition may be more universally adopted by all bilinguals, whereas whole-language inhibition might be a strategy only used by some bilinguals (e.g. if their two languages are highly dissimilar).

Each of the studies above had their own way of eliciting whole-language and item-specific inhibition. Finkbeiner, Almeida, et al. (2006) contrasted the naming of semantically-related items (item-specific control) vs semantically-unrelated items (whole-language control) in a different language on the previous trial; Philipp and

²⁵ Note that whole-language inhibition could produce the same results, therefore this observation alone does not specifically point towards item-specific inhibition. However, given that some bilinguals in this study (Dutch-English) did not show evidence for whole-language inhibition at all (i.e. no decrease in verbal fluency for the non-repeated letter prompts), it is highly likely that this effect observed for the repeated letter prompts was due to item-specific inhibition.

Koch (2009) contrasted repeating the stimulus-response set (item-specific control) vs simply repeating the language (whole-language control) from the $n-2$ trial; Van Assche et al. (2013) contrasted production of exemplars with the same initial graphemes/phonemes (item-specific control) vs different initial graphemes/phonemes (whole-language control) after completing a previous block in the other language. Importantly, their definition of item-specific inhibition seems to be a broad one, i.e. such inhibition is assumed to act on all semantically-related or lexically-related items in the non-target language. Recent studies have converged towards a more conservative approach, which involves repeating the actual concepts to name in both languages (Misra et al., 2012; Guo et al., 2011; Branzi et al., 2014; Branzi, Della Rosa, et al., 2016). With this design, production of a set of names in one language is followed by producing their translation-equivalents in the other language. Since direct translation-equivalents are likely to be the most potent competitors in lexical selection, this kind of design should elicit the strongest form of item-specific inhibition. Similar to Van Assche et al. (2013), these studies all used blocked production (i.e. switching language between single-language blocks), which reflects a sustained form of language control.

In a series of two studies, Misra et al. (2012) and Guo et al. (2011) examined the behavioural and neural evidence for language inhibition in blocked picture naming. Misra et al. (2012) asked bilinguals to name a set of pictures firstly all in one language, and then all in the other language. The crucial manipulation was the order of the blocks (i.e. L1 or L2 first). Results showed that L2 naming became faster when it occurred following L1 (compared to occurring first), whereas no such benefit was observed for L1 when it followed L2. Since the same set of pictures were named in both languages, facilitation on L2 naming was as would be expected from repetition priming. On the other hand, the lack of a similar facilitation on L1 naming suggests that this dominant language might have been inhibited during prior L2 production, which negated the benefit of repetition priming. The accompanying ERP results also reveal a larger N2 component when L1 naming

followed L2, consistent with the presence of inhibitory control (e.g. Jackson et al., 2001). Guo et al. (2011) conducted an fMRI study using a similar design²⁷. Although they did not replicate the behavioural findings from Misra et al. (2012), a similar block order effect was seen in their imaging data. When L1 naming occurred after L2, this activated a broader brain network associated with cognitive control compared to the other way around. In both of these studies, the authors interpreted the asymmetrical block order effect as an indication of whole-language inhibition applied on L1 during L2 production, which took additional effort to overcome in the subsequent L1 block (i.e. slower responses or recruitment of more cognitive control). However, these findings can actually be explained by either whole-language or item-specific inhibition. Because all of the picture stimuli were repeated across the two languages, they would all be subject to item-specific inhibition, which then gives the same appearance as a whole-language inhibitory effect. Therefore, this type of design is unable to discern between whole-language and item-specific control.

In order to effectively distinguish between the two levels of control, Branzi et al. (2014) improved upon the above study design, such that only half of the picture stimuli were repeated from one block to the next (while the other half were replaced by new pictures). This allowed them to look at both repeated stimuli (eliciting item-specific control) and non-repeated stimuli (eliciting whole-language control), in a similar vein to Van Assche et al. (2013). For the repeated stimuli, the behavioural findings from Misra et al. (2012) were replicated, i.e. naming in L2 benefited from having named the same pictures in L1 first, whereas naming in L1 did not benefit from previously naming the same pictures in L2. However, ERP

²⁷ Guo et al. (2011) also included mixed-language blocks after the two single-language blocks, to examine the effect of *language mixing*. Although they referred to this as “local” switching effect, it is completely different from the concept of local / item-specific control under discussion here. As explained earlier, this is an issue of inconsistent terminology in this area.

waveforms showed a smaller N2 component²⁹ when L1 naming followed L2 (rather than the *larger* N2 as reported by Misra et al., 2012), questioning the interpretation of the lack of facilitation for L1 naming as reflecting inhibition of this language. Moreover, a larger P2 component was observed in this case, a pattern usually associated with more difficult lexical access (e.g. Strijkers, Costa, & Thierry, 2010). The authors interpreted such difficulty in L1 lexical access as a consequence of L2 activation, rather than L1 inhibition, in the prior block. For the non-repeated stimuli, naming in L1 was hindered by previous naming (of other pictures) in L2, whereas naming in L2 was not affected by previous naming (of other pictures) in L1; this asymmetrical effect on the two languages was analogous to that observed for the repeated stimuli (just removing the repetition priming). The ERP patterns for non-repeated stimuli were also the same as the repeated stimuli (i.e. smaller N2 and larger P2 component when L1 followed L2). The fact that repeated and non-repeated stimuli were affected in a similar way suggests that control mechanisms most likely acted on the whole-language level, although we cannot completely rule out the presence of item-specific control (see first point of discussion below).

In a subsequent fMRI study, Branzi, Della Rosa, et al. (2016) examined the brain regions responsible for whole-language and item-specific control. A number of prefrontal and inferior parietal regions were recruited when L1 naming followed L2, and these brain regions were engaged to a similar degree whether repeated or non-repeated stimuli were involved. Such a pattern was in agreement with Guo et al. (2011), who found that naming in L1 after L2 activated a broader brain network (including some prefrontal and inferior parietal areas) than vice versa. While it was not possible to determine whether control operated on the whole-language or item-specific level in Guo et al. (2011) (as all pictures were repeated across languages), the findings here suggest that control most likely operated on the

²⁹ This may be either an independent effect, or merely a consequence of the enlarged P2 component. Since the P2 component occurred prior to the N2 component, a larger P2 resulted in a more positive waveform in general, which could have contributed to the smaller N2 observed.

whole-language level (see first point of discussion below). In addition, the dorsal-ACC/pre-SMA complex was activated exclusively for naming repeated pictures in L2 after L1, which points to a specific role of this brain region in conflict monitoring at the item-specific level.

There are a few interesting points to consider in the studies reviewed above. Firstly, while non-repeated stimuli (between the two languages) were generally treated as indexing whole-language control and repeated stimuli as indexing item-specific control, the repeated stimuli should actually be impacted by both levels of control. More specifically, if naming in one language is hindered by prior naming of non-repeated stimuli in the other language, then this necessarily indicates the presence of whole-language control; on the other hand, if naming in one language is hindered by prior naming of the same stimuli in the other language, this could be due to either whole-language or item-specific control, or a combined effect of both. Therefore, in cases where naming of non-repeated stimuli is unaffected by prior naming in the other language (i.e. indicating an absence of whole-language control) but naming of repeated stimuli is hindered, we can be quite certain that this reflects item-specific control (e.g. the Dutch-English bilinguals in Van Assche et al., 2013). However, when both repeated and non-repeated stimuli show a similar effect (e.g. Branzi et al., 2014; the Mandarin-English bilinguals in Van Assche et al., 2013), it is difficult to know whether the effect observed in the repeated stimuli are due to the same cause as the non-repeated stimuli (i.e. whole-language control) or a different cause (i.e. item-specific control). The only tell-tale evidence would be if the effect is much larger for repeated stimuli compared to non-repeated stimuli, which would indicate that there is more going on for the repeated stimuli than just the whole-language control³⁰. Unfortunately, such information has not been provided by these existing studies.

³⁰ Note, however, that the absence of such a pattern would not necessarily mean that there is no item-specific control, as the effect arising from whole-language and item-specific control might not add up linearly.

Secondly, a common theme that emerges from the behavioural findings above is that only production in the dominant language seems to suffer from prior production in the non-dominant language³¹, but not the other way around. Specifically, in cases where non-dominant language production is facilitated by previously speaking in the dominant language (this only happens for repeated stimuli due to repetition priming, but not always), the dominant language does not enjoy a similar benefit (Misra et al., 2012; Branzi et al., 2014); in cases where non-dominant language production is unaffected by previously speaking in the dominant language (this can happen for either repeated or non-repeated stimuli), the dominant language is usually hindered by prior production in the non-dominant language (Van Assche et al., 2013; Misra et al., 2012). The neural findings also display a similar trend: when dominant language production follows non-dominant language, this usually recruits more indices of cognitive control than the other way around (e.g. Misra et al., 2012; Guo et al., 2011; Branzi et al., 2014; Branzi, Della Rosa, et al., 2016)³². Such hindrance of dominant language production (i.e. reflected by slower responses or recruitment of more neural resources) may be attributed to either inhibition of the dominant language or over-activation of the non-dominant language, which occurred during the prior non-dominant language block in order to enable easier production.

While most of the studies above assume the language control mechanisms to be inhibitory (Finkbeiner, Almeida, et al., 2006; Van Assche et al., 2013; Misra et al., 2012; Guo et al., 2011), Branzi et al. (2014) specifically considered the proposal of activation vs inhibition. Branzi et al. argued against the inhibitory account, as they found that naming in the dominant language after the non-dominant language resulted in a larger P2 component (associated with more effortful lexical access),

³¹ I will use the terms “dominant” and “non-dominant” when summarising findings across studies, as some bilinguals in these studies have switched dominance, such that their L1 has become the non-dominant language (e.g. the Mandarin-English bilinguals in Van Assche et al., 2013).

³² One exception is that there seems to be a specific mechanism for handling high-conflict situations in non-dominant language production (Branzi, Della Rosa, et al., 2016).

rather than a larger N2 component (associated with inhibitory control). However, according to the inhibitory account of language control (Green, 1998), the suppression of the dominant language should occur during the prior non-dominant language block; therefore, an enlarged N2 component should be expected in that block instead³³. Then, in the subsequent dominant language block, the prior inhibition of this language needs to be overcome, which is consistent with the observation of more difficult lexical access (i.e. larger P2 component). Therefore, the ERP findings by Branzi et al. (2014) are not incompatible with inhibitory mechanisms of language control.

Thirdly, it is interesting to draw a parallel between the asymmetrical block order effect (Misra et al., 2012; Guo et al., 2011; Branzi et al., 2014; Branzi, Della Rosa, et al., 2016) and the “asymmetrical switch cost” commonly found in trial-to-trial switching. If we do not simply view the former as the after-effect of production in one language upon subsequent production in another, but rather as the effect of switching language from one block to the next, then the “switch cost” (between blocks) is larger when switching into the dominant language, compared to switching into the non-dominant language. Such an observation suggests that the switch cost asymmetry not only exists in transient language control (i.e. switching from trial to trial; see Section 1.3 for a detailed review), but also in sustained control (i.e. changing languages between blocks, even if the production within each block occurs in a single language).

³³ The existing data cannot verify whether such N2 modulation occurred, as there is no valid comparison to make other than directly comparing the dominant and non-dominant language (i.e. N2 component should be larger in non-dominant language production overall), which may involve many other confounds between the two languages.

	Task	Duration of control	Reason for inhibition of currently-required language	In the "repeated" condition, what was repeated?	Repeated (item-specific control)	Non-repeated (whole-language control)	Neural findings (ERP / fMRI)
Finkbeiner et al., 2006	trial-to-trial switching	transient	production of other language on previous trial	response set	asymmetrical switch cost in bivalent stimuli; no switch cost in univalent stimuli (only tested L1)	asymmetrical switch cost in bivalent stimuli; no switch cost in univalent stimuli (only tested L1)	
Philipp & Koch, 2009	n-2 language repetition	transient	abandoning currently-required language on previous trial	response set	n-2 repetition cost	n-2 repetition cost	
Van Assche et al., 2013	verbal fluency	sustained	production of other language in previous block	initial grapheme/phoneme	non-dominant language not affected, dominant language suffered	non-dominant language not affected, dominant language suffered (English-Mandarin bilinguals); no effect on either language (Dutch-English bilinguals)	
Guo et al., 2011	blocked naming (+ mixed naming)	sustained	production of other language in previous block	actual concept	no effect on either language		L1: increased activity in right postcentral gyrus and a number of left hemisphere areas (middle frontal gyrus, middle temporal gyrus, precuneus, inferior parietal gyrus, and angular gyrus); L2: increased activity in right cuneus/precuneus only

Misra et al., 2012	blocked naming	sustained	production of other language in previous block	actual concept	L2 benefited, L1 not affected		L1: larger N2 component; L2: smaller N2 component
Branzi et al., 2014	blocked naming	sustained	production of other language in previous block	actual concept	L2 benefited, L1 not affected	L2 not affected, L1 suffered	L1: smaller N2 component, larger P2 component (<i>for both repeated and non-repeated stimuli</i>); L2: no change in N2 or P2 component (<i>for both repeated and non-repeated stimuli</i>)
Branzi et al., 2016	blocked naming (+ non-linguistic task)	sustained	production of other language in previous block	actual concept			L1: increased activity in prefrontal and inferior parietal regions in both hemispheres (<i>similar for both repeated and non-repeated stimuli</i>); L2: increased activity in dorsal anterior cingulate cortex / pre-supplementary motor area (<i>for repeated stimuli only</i>)

Table 1-1. Summary of existing studies which examined whole-language vs item-specific control in bilingual production. Most of these studies look at the after-effect of production in one language upon subsequent production in the other language (except Philipp & Koch, 2009). When describing the results, "L1" refers to naming in L1 after L2 (compared to naming in L1 first), and "L2" refers to naming in L2 after L1 (compared to naming in L2 first). A greyed-out box indicates that this particular aspect was not investigated in that study.

Summarising all the findings above, there is evidence supporting the existence of language control at the whole-language level as well as item-specific level in bilingual production. The exact nature of the observations seems to vary, especially across studies employing different experimental paradigms. In Chapter 2 of this thesis, I present a study which examines these two levels of control in the traditional cued-switching paradigm. The only study that previously attempted this was Finkbeiner, Almeida, et al. (2006), who argued against both levels of control based on an absence of switch cost for the univalent stimuli. However, that study involved a confound which may have masked the effect of language switching (see above). Moreover, the lack of switch cost might have been due to the broad assumption they adopted for item-specific inhibition. The study in Chapter 2 tests a more conservative version of item-specific inhibition (i.e. acting on translation-equivalents in the non-target language, rather than all semantically-related items), which aligns with the approach in recent studies (e.g. Branzi et al., 2016). In order to test this, the traditional cued-switching paradigm is modified so that both trial-to-trial switching and “within-item switching” (more details in Chapter 2) can be assessed in parallel. Such design overcomes previous issues by developing a new index for item-specific inhibition which is not subject to the effect of whole-language inhibition (see discussions above); therefore, the two levels of control can be clearly separated. In addition, this study investigates the involvement of domain-general brain mechanisms for inhibitory control, by perturbing the pre-SMA region using non-invasive brain stimulation. This technique provides us with the unique ability to temporarily “disable” a brain region and observe the consequence on participants’ performance, thus allowing the *causal* role of that brain region to be assessed (see Section 1.8 for more details).

1.6 THE TIMING OF LANGUAGE CONTROL: CUE- VS TARGET-RELATED PROCESSES

Aside from the scope of language control, another important aspect to look at is the timing of control. This is the second angle investigated by the present thesis. Can bilinguals proactively adjust the activation levels of their two languages, when preparing for upcoming production in a known language? Or do they have to wait till they know what concept to express, and then apply reactive control as necessary to resolve competition? Some models of bilingual production suggest the existence of proactive regulation on the whole-language level, complemented by targeted reactive control exerted on specific lexical items (see De Groot & Christoffels, 2006, for a review). Theoretically speaking, proactive whole-language adjustment is not necessary for ensuring appropriate language selection in the speech output (De Groot, 2011). However, when the opportunity arises (e.g. if preparation time is available), bilinguals might take advantage of that and apply proactive control so as to increase efficiency in later production, especially if they know a language switch will be required. Thus, proactive language control can be investigated by presenting the cue and target separately on each trial in a language-switching task, so that bilinguals have access to some preparation time after they see the language cue and before the actual naming target appears.

The behavioural consequence of advance preparation in language switching has been examined in a number of studies. As participants are usually not required to produce any response following the language cue, the main variable measured behaviourally is how the switch cost magnitude (or its asymmetry) is modulated by the amount of preparation time. The most common observation is that the switch cost becomes smaller following a long cue-target interval (CTI) compared to a short one (e.g. Costa & Santesteban, 2004, Exp. 5; Declerck, Philipp, & Koch, 2013; Fink & Goldrick, 2015, Exp. 1; Ma, Li, & Guo, 2016; Mosca & Clahsen, 2016; Khateb, Shamshoum, & Prior, 2017). However, the opposite has also been reported, i.e. larger switch cost following a longer CTI (e.g. Philipp et al., 2007). Sometimes the

pattern is a little more complicated. For example, Lavric, Clapp, East, Elchlepp, and Monsell (2019) found that longer CTI resulted in reduced switch cost when the language cues were relatively opaque (e.g. segment of national anthem), but the same condition led to increased switch cost when the cues were more transparent (e.g. name of language). Further, the amount of preparation time also seems to affect the switch cost asymmetry. Verhoef et al. (2009) observed asymmetrical switch cost with short CTI, which became symmetrical with long CTI (but also see Fink & Goldrick, 2015, Exp. 2, where the switch cost remained asymmetrical even at long CTI). In sum, the CTI duration does seem to make a difference in the switch cost pattern observed; this suggests that bilinguals can apply some form of proactive control during the preparation time, although the effect of such preparation is not always consistent. In most cases, longer preparation leads to a switch cost reduction, but the switch cost is usually not completely eliminated³⁴; this suggests that there are also some control processes which can only be performed following target onset.

With regards to the neural mechanisms underlying bilingual control, imaging studies have so far identified a number of brain regions which are activated during language switching (see Section 1.4.3 for details). Green and Abutalebi (2013) proposed a model outlining how these brain regions may be interconnected and what control processes are performed by each brain region in language control. They distinguish between eight control processes, which may be engaged to different extents according to the demands of the interactional context. One can reasonably expect that some of these processes (such as goal maintenance and salient cue detection) would take place during preparation (i.e. following the language cue onset), and other processes (such as conflict monitoring and selective response inhibition) might occur when actual speech production is required (i.e. following the target onset). A study design with separate cue and target

³⁴ One exception might be Mosca and Clahsen (2016), who observed no significant switch cost in the long-preparation condition.

presentation makes it possible to disentangle the brain processes which can be completed in advance and those that can only take place after the concept activates relevant lexical nodes. If different control processes are involved at these two stages, then one can expect to observe different patterns of brain activations.

Aside from Verhoef et al. (2009), who explicitly investigated the effect of preparation (e.g. how the N2 ERP component following target presentation was modulated by CTI duration - see Section 1.4.1.1), most neural studies of preparation in language switching adopted a constant CTI and focussed on examining the brain activities occurring in response to the language cue and the naming target. In order to effectively distinguish between cue-related and target-related neural responses, these studies generally employed electrophysiological techniques, such as EEG or MEG, for their high temporal resolution. Brain activities following cue onset and/or target onset were examined to see whether they were modulated by switching (i.e. stay vs switch trials) or by language (i.e. L1 vs L2). A variety of design choices were made by these studies (e.g. types of language cues and stimuli, CTI durations, etc), and their findings are mixed (see Table 1-2, for a summary).

In a series of two ERP studies, Verhoef et al. (2009, 2010) examined the evoked brain activities time-locked to target presentation and cue presentation, respectively. They observed differential brain responses between stay and switch trials following cue onset, but not following target onset (either with a CTI of 750 or 1500 ms). This pattern seems to suggest that all of the switch-related control processes could be completed prior to the naming target becoming available. Two distinct ERP effects were identified in the cue window: an early posterior negativity (200 - 350 ms) on switch trials compared to stay trials, occurring in L2 only (i.e. asymmetrical between the two languages), and a late anterior negativity (350 - 500 ms) on switch compared to stay trials, occurring in both languages. The authors interpreted these effects as reflecting two separate processes of endogenous attentional control during language switching, where the early asymmetrical switch

effect corresponds to the disengagement of attention from the previously-used language (more effort required to disengage from the dominant L1 when switching into L2), and the late symmetrical switch effect corresponds to the engagement of attention towards the currently-required language.

Jin et al. (2014) employed a similar design as Verhoef et al. (2010), but with an auditory cue (left ear for Chinese, right ear for English). The cue lasted for 50 ms on each trial, and the target picture was presented at 700 ms after cue offset (i.e. 750 ms after cue onset). The ERPs occurring after cue onset and before target onset were examined. Based on visual inspection of the waveforms, the P2 component (160 - 200 ms) was selected for analysis. Larger P2 amplitude was observed on switch trials compared to stay trials in fronto-central sensors, and this occurred in L1 only (i.e. asymmetrical switch effect), matching the pattern of asymmetry in their behavioural data (larger switch cost in L1). The authors interpreted this cue-locked P2 effect as an indication of more endogenous control required when switching into the dominant L1. Interestingly, this seems to contradict the pattern of asymmetrical switch effect observed by Verhoef et al. (2010) following cue onset, where the switch effect was present in L2 only (suggesting more control required when switching into L2). However, such discrepancy may be due to the different ERP components examined in these two studies.

Taking a novel approach to specifically investigate the presence of inhibitory processes in language control, Liu et al. (2014) tested two groups of unbalanced bilinguals, with high and low abilities in domain-general inhibitory control (as assessed by the Simon task). In this study, the naming target was presented at 750 ms after the cue on each trial, and the ERPs following target onset were examined. In the group of participants with high inhibitory control ability, a language effect occurred in the LPC (450 - 650 ms), showing increased amplitude for L2 naming compared to L1 (on both stay and switch trials). This pattern was not found in the group with low inhibitory control ability. Such difference between the two groups

suggests that the language effect observed was related to inhibitory control, possibly reflecting stronger inhibition of the dominant L1 during L2 production than vice versa.

While each of the studies above looked at either cue-evoked or target-evoked brain responses, Chang et al. (2016) were the first to examine both the cue window and target window on each trial. This study included a condition where the cue was presented for 1000 ms before target onset, as well as a condition where the target was presented for 1000 ms before cue onset; below I will focus on the results from the cue-then-target condition, as it is more relevant for the present purpose. No significant switch effect or language effect was observed following cue onset; rather, a switch effect occurred between 270 - 400 ms following target onset. This effect was characterised by more negative ERPs on switch trials compared to stay trials, in both midline and left-hemisphere electrodes. Because the switch effect occurred only after the target was shown (even with a relatively long CTI of 1000 ms), it seems to suggest that control processes for language switching only take place at the production stage, not during advance preparation. This runs counter to the studies above which show switch effects in the cue window rather than the target window (Verhoef et al., 2009, 2010; Jin et al., 2014).

It is worth noting that both Chang et al. (2016) and Liu et al. (2014) interpreted their findings with regards to two stages of language control: language task schema competition and lemma selection. Such a differentiation is based on Green's (1998) proposal of two loci of language inhibition. However, these studies made different assumptions about *when* these two stages of control take place. Chang et al. (2016) regarded the time window following cue onset and the one following target onset (in the cue-then-target condition) as corresponding to the language task schema competition stage and the lemma selection stage, respectively. On the other hand, Liu et al. (2014) regarded the N2 time window and the LPC time window (both following target onset) as corresponding to the two stages of language control.

Interestingly, both studies reached the conclusion that control processes occurred during the later stage (i.e. lemma selection).

More recently, Lavric et al. (2019) set out with a specific aim to investigate whether preparation in language switching shared the same ERP signature as preparation in task switching. They did not restrict their analysis to the known spatial and temporal pattern they were looking for; therefore, the findings can be compared with other language-switching studies. This study employed a short CTI (100 ms) and a long CTI (1500 ms); to focus on preparation-related brain activities, cue-locked ERPs in the long-CTI condition were analysed. Switch trials (compared to stay trials) elicited a posterior positivity at 300 - 700 ms, followed by a fronto-central negativity at 1100 - 1500 ms after cue onset. The posterior positivity had similar timing and scalp distribution as the ERP signature of preparation in task switching (Karayanidis et al., 2010); moreover, its magnitude predicted the behavioural performance in the language-switching task, i.e. larger posterior positivity was observed on trials with faster responses and smaller switch costs, consistent with successful preparation. While these findings form a very coherent story within this study, they are again at odds with both Verhoef et al. (2010), who observed two switch-related ERP effects which were clearly different from the ones reported here, and Chang et al. (2016), who did not find a switch effect during preparation (i.e. after cue onset and before target onset).

Apart from these studies looking at ERPs in the preparation and execution of language switching, Liu et al. (2017) examined oscillatory brain activities following cue onset and target onset, when unbalanced bilinguals switched between their L1 and L2, and between L1 and a newly learned language (here I will focus on the results for L1-L2 switching). The authors made a distinction between evoked oscillations, which were obtained by performing time-frequency analysis on the averaged ERP across trials, and induced oscillations, which were obtained by performing time-frequency analysis on single-trial data and then averaging over

these. Following cue onset, evoked and induced oscillations in the theta and delta ranges were examined during the N2 time window (250 - 350 ms); following target onset, the same types of oscillatory activities were examined during the N2 (270 - 370 ms) and the LPC (450 - 650 ms) time windows. Similar to Liu et al. (2014), participants in this study were divided into two groups, with high and low abilities in domain-general inhibitory control (assessed by the Simon task), and any difference between the two groups was taken as evidence for the involvement of inhibitory processes. Such a difference first appeared in the N2 window following cue onset, where an interaction between group and language revealed greater power in the induced theta and delta oscillations on L2 trials compared to L1, occurring only in the group with high inhibitory control ability. A second difference between groups appeared in the LPC window following target onset, where a three-way interaction revealed greater power in evoked and induced theta oscillations on L2 switch trials compared to L1 switch (but no such difference between L2 and L1 stay trials), and this occurred only in the group with high inhibitory control ability. These findings suggest that inhibitory processes may be involved at both stages: preparing for L2 production requires stronger suppression of L1, regardless of whether a language switch is involved; the impact of switching then shows up at the production stage, where additional inhibition (likely at the individual-lemma level) is required for switching into L2 (compared to switching into L1).

Summing up the EEG studies above, some examined the ERPs during the preparation stage only (Verhoef et al., 2010; Jin et al., 2014; Lavric et al., 2019), while others examined the ERPs at the production stage only (Verhoef et al., 2009; Liu et al., 2014). Another study examined both but only detected effects at the production stage (Chang et al., 2016), and yet another study looked at oscillatory activities and detected changes in theta and delta power at both stages (Liu et al., 2017). These existing findings are inconsistent in regards to at what stage control processes take place during language switching. Moreover, even during the same stage, diverse

patterns of switch-related effects were observed. For instance, following presentation of the language cue, the patterns of modulation ranged from posterior followed by anterior negativity (Verhoef et al., 2010), fronto-central P2 modulation (Jin et al., 2014), to posterior positivity followed by (very late) fronto-central negativity (Lavric et al., 2019), or no effect at all (Chang et al., 2016). These studies also provide a range of different interpretations on what these effects represent (see Table 1-2). It is possible that each of these patterns was driven by a different underlying control process; given the dynamic nature of language control, some processes might be more required in certain situations than others (Green & Abutalebi, 2013), especially since these studies vary on a number of task design parameters. As discussed earlier (see Section 1.4.1), even for the relatively well-known ERP components in language switching, there is a lot of controversy around what control processes are associated with each of them, as the same component appears to be modulated by different factors under different circumstances. Hence, I will not attempt to map these effects onto specific control processes here. Perhaps one type of information that could offer more hints would be the locations in the brain where these activities originate from. Given that EEG does not usually provide the best data for source reconstruction (see Section 1.8), MEG may be a better choice for this purpose.

To my knowledge, the only MEG study so far that has looked at language switching with separate cue and target presentation was by Blanco-Elorrieta and Pylkkänen (2017)³⁵. These authors employed a short CTI of 300 ms, and examined the evoked brain activities following cue onset and target onset. The sensor data were used to reconstruct source activities in pre-defined regions of interest, including the DLPFC, ACC, and Broca's area, with the aim of tapping into executive control processes. A unique aspect of this study is that it compared the language-switch effect across

³⁵ The same group also conducted a similarly designed study on bimodal bilinguals (Blanco-Elorrieta, Emmorey, & Pylkkänen, 2018). However, here I will focus on investigations of switching between two *spoken* languages.

voluntary and forced switching contexts. Voluntary switching was elicited using bilingual interlocutors as cues (to whom the participants may respond in any language as they wish), while forced switching was achieved using either natural cues (monolingual interlocutors) or artificial cues (colours). Following cue onset, no switch effect was observed (only a main effect of context in posterior ACC). Following target onset, two clusters were identified which showed increased brain activities on switch trials compared to stay trials: the first cluster appeared in left DLPFC and ACC (100 - 160 ms), for colour cues and monolingual cues only; the second cluster appeared in left ACC (143 - 295 ms), for colour cues only. No switch effect was observed for voluntary switching. These findings suggest that executive control processes are only required when language selection is based on external cues, and more so if the cues are artificial. In addition, the lack of switch effect in the cue window seems to imply that language control processes took place at the production stage (rather than during preparation); however, such conclusion should be drawn carefully. As the CTI used in this study was very short (300 ms), the brain activities following target onset might actually be in response to the cue (especially given that the first cluster occurred as early as 100 - 160 ms after target onset, which seems too early for processes involving high-level cognitive control). Hence, this study does not offer a clear answer on whether language control takes place during preparation or production. However, the source location of the observed switch effects (left DLPFC and ACC) suggest that these effects may be related to control processes such as conflict monitoring and interference suppression.

While MEG can provide reasonably accurate source reconstruction, it is not as good as fMRI in terms of spatial resolution and sensitivity to activities of deeper brain structures. The drawback of fMRI, however, is its limited temporal resolution, which makes it difficult to separate the brain responses to the cue and to the target. To allow sufficient time for the haemodynamic response to take place, Reverberi et al. (2015) adopted a much longer CTI (9000 ms) than those used in the EEG/MEG

studies. The authors assessed the presence of switch effects and language effects following cue onset and target onset. The switch effect occurred mainly following the cue, where switch trials elicited increased brain activity in the precuneus, right superior lateral parietal lobe, and left middle temporal gyrus; following the target, such an effect was found in a small cluster in the medial prefrontal cortex. In contrast, language effects occurred only following target onset, with a number of brain regions implicated in executive control (IFG, ACC, insula, thalamus, and caudate) showing higher activation on L2 trials compared to L1, while brain regions overlapping with the default mode network (angular gyrus, precuneus, posterior cingulate cortex, and right lateral prefrontal cortex) were more engaged for L1 production compared to L2. It is interesting that even with such a long CTI, there are still control processes that could not be completed before target onset (as reflected by the language effects³⁶ as well as the small cluster showing switch effect following target presentation). The findings from this study point towards two separate stages of language control, with distinct neural mechanisms involved at each stage, possibly supporting different control processes. The preparation for a language switch did not seem to rely much on the typical executive control network but rather on brain regions associated with shifting attention (e.g. precuneus). Subsequently, at the production stage, executive control regions were recruited more on L2 trials, possibly to help with resolving competition, while L1 trials engaged the default mode network instead.

The use of a very long CTI in the study above comes with potential concerns about altering the type of preparatory control applied (see Ruge, Jamadar, Zimmermann, & Karayanidis, 2013, for a discussion of this in task switching). In a recent fMRI study, Branzi, Martin, Carreiras, and Paz - Alonso (2020) employed CTIs comparable to that used in electrophysiological studies of language switching. Two different

³⁶ While these effects could, in principle, be caused by differences in the specific features of the two languages, rather than due to cognitive control, the authors argued that this is unlikely to be the case.

CTI durations were included: 150 ms vs 1000 ms. The long CTI was aimed at encouraging preparation (i.e. eliciting proactive control), while the short CTI was aimed at preventing preparation (i.e. eliciting reactive control instead). As such, the comparison between long and short CTI provided a direct contrast between proactive and reactive control. This study focussed on the ventrolateral prefrontal cortex (VLPFC), which has been implicated in monolingual production, where the anterior and middle portion of it serve different roles in word retrieval. The authors report a similar segregation in the case of bilingual production, with the anterior VLPFC being involved specifically in proactive control (boosting the activation level of the target language) and the mid VLPFC (together with left inferior parietal lobe) being involved in both proactive and reactive control. The approach taken by this study offers another interesting way to look at two possible types of control in language switching. However, it should be noted that, in this particular design, the proactive and reactive control do not occur in succession on the same trial, but rather they occur on different trials and overlap in timing; hence, the distinction between them may reflect different strategies rather than "stages" of language control. This makes the study different from all of the studies reviewed above (which examine neural activities in the cue-locked and/or target-locked windows as two separate stages), and also different from studies investigating the effect of preparation (i.e. *target*-locked responses following long vs short CTI). Because of such differences, findings from this study are not really comparable with the other ones and therefore it is not included in the summary table below.

		Participants	Language cue	Stimuli	CTI (ms)	TRI (ms)	RT switch cost	Reversed dominance	Cue-locked neural effects	Target-locked neural effects	Interpretation of the neural effects (according to the authors)
Verhoef et al., 2009	ERP	Dutch-English (medium L2 proficiency; L2 AoA: 11yo)	National flag	48 pictures (half are cognates)	750, 1500	250	Short CTI: asymmetrical; long CTI: symmetrical	Yes		No switch effect in N2; language effect not examined	N/A
Verhoef et al., 2010		Dutch-English (medium L2 proficiency; L2 AoA: 11yo)	Colour patch	24 pictures (non-cognates)	750	250	Symmetrical	Yes	Posterior N2 (switch > stay), for L2 only; late anterior negativity (switch > stay), for both languages		Endogenous attentional control: posterior N2 reflects disengaging attention from previously-used language (more effort to disengage from L1); late anterior negativity reflects engaging attention to current target language (similar amount of effort for both languages)
Jin et al., 2014		Chinese-English (medium L2 proficiency; L2 AoA: 12yo)	Auditory (left/right ear)	56 pictures	750	250	Asymmetrical	No	Fronto-central P2 (switch > stay), for L1 only		Endogenous control (more control required when switching into L1)
Liu et al., 2014		Chinese-English (low L2 proficiency; L2 AoA: 8yo)	Colour patch	48 pictures	750	1250	Low-IC group: asymmetrical; high-IC group: symmetrical	Yes		LPC (L2 > L1), for high-IC group only	Inhibition during lexical selection (stronger inhibition of L1 required for L2 production)

Chang et al., 2016*	ERP (cont.)	Indonesian-Chinese (medium L2 proficiency; L2 AoA: after 10yo)	Colour patch	Digits 1-8	1000	0	Symmetrical	No	No switch effect; no language effect (in selected window, roughly N2)	Midline and left-hemisphere negativity (switch > stay)	Switch-related processes (possibly inhibition) during lemma selection
Lavric et al., 2019		German-English (quite highly proficient; L2 AoA: 9yo)	Auditory: name of language (transparent) vs national anthem (opaque)	96 pictures (+24 filler pictures)	100, 1500	0	Asymmetrical	Yes	Posterior positivity, followed by fronto-central negativity (switch > stay)		Posterior negativity reflects proactive top-down control, similar to that documented in task switching; late fronto-central negativity may reflect efforts to maintain language-set after preparation
Liu et al., 2017	EEG oscillations	Chinese-English (low L2 proficiency; L2 AoA: 11yo)	Colour patch	48 pictures	750	1250	Low-IC group: asymmetrical; high-IC group: symmetrical	Yes	In N2 time window (250-350ms): induced theta and delta power (L2 > L1), for high-IC group only	In LPC time window (450-650ms): evoked and induced theta power (L2 > L1, on switch trials only), for high-IC group only; evoked delta power (L2 > L1, on switch trials only)	Inhibition occurring mainly during lexical selection (switching into L2 requires stronger inhibition of L1 than vice versa), reflected by both evoked and induced theta oscillations (suggesting the involvement of both bottom-up and top-down processes)
Blanco-Elorrieta & Pykkänen, 2017	MEG	Arabic-English (highly proficient; L2 AoA: 5yo)	Colour patch; monolingual interlocutor; bilingual interlocutor	96 pictures	300	0			No switch effect; language effect not examined	Switch effects in left DLPFC and ACC (100-160ms cluster: colour and monolingual cues; 143-295ms cluster: colour cues only)	Executive control processes (e.g. conflict monitoring, interference suppression) - only required when language selection is based on external cues, especially if the cues are artificial

Reverberi et al., 2015	fMRI	German-English (quite highly proficient, L2 AoA: 9yo)	Abstract shape	120 pictures	9000	0	Symmetrical	No	Increased activity in precuneus, right superior lateral parietal lobe, and left middle temporal gyrus (switch > stay, symmetrical between L1 and L2); no language effect	Increased activity in IFG, ACC, insula, thalamus, and caudate (L2 > L1); angular gyrus, precuneus, posterior cingulate cortex, and right lateral prefrontal cortex (L1 > L2); small cluster in the prefrontal cortex (switch > stay)	Preparation: setting up and updating the goal to speak a different language (not relying on the typical language control network); execution: L2 production engages the language control network (e.g. to resolve competition), while L1 production activates the default mode network
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Table 1-2. Summary of existing language-switching studies in which the language cue and naming target were separated by a time interval. Here I only include studies that report the neural responses following cue onset and/or target onset. For behavioural studies which focus on the effect of preparation (i.e. long vs short interval), these have been nicely summarised in Mosca and Clahsen (2016, Table 4) and Khateb, Shamsoum, and Prior (2017, Table 1). A greyed-out box indicates that this particular aspect was not investigated in that study. CTI = cue-target interval; TRI = target-response interval (i.e. delayed response). The CTI and TRI in this table are calculated from cue/target onset (rather than offset). RT = reaction time. High-IC = high inhibitory-control ability; low-IC = low inhibitory-control ability (see main text for more details). L2 AoA = age of acquisition for L2 (mean age rounded to the nearest whole number). N2, P2 and LPC (late positive component) are ERP components. For other abbreviations (e.g. names of brain regions), see Section 1.4. *Chang et al. (2016) examined both cue-then-target and target-then-cue presentation (see main text); only the results from the cue-then-target condition are included in this table.

Summarising the findings discussed above, there is quite a lot of inconsistency as to whether bilinguals can prepare for upcoming production in a designated language, or only apply control at the production stage, or both. Furthermore, a variety of neural activity patterns have been observed at each stage, varying widely across studies. One possible explanation for such diverse patterns in the observed effects is that they represent different types of control processes; as a number of design choices varied from one study to another, it can be expected that the control processes involved may adapt to the demands of each specific situation. In the MEG study presented in Chapter 3, I take another look at the two possible stages of language control, aiming to bring together the best design elements from these previous studies (e.g. natural language cues, mapping two cues to each language to eliminate confound of cue switching, avoiding carry-over switch effect in the trial sequence, etc; see Chapter 3, Section 3.2.2 for more details).

As this investigation focusses on the (potentially distinct) control processes following cue onset and target onset, one critical decision is the CTI duration. In an MEG study, Blanco-Elorrieta and Pylkkänen (2017) found that switch effects occurred not following the cue but only following the target; however, most ERP studies report switch effects following the cue (Verhoef et al., 2010; Jin et al., 2014; Lavric et al., 2019; but see Chang et al., 2016). While there may be potential differences between the two techniques, it seems more likely that the absence of switch effect following cue was due to the short CTI (300 ms) used in the MEG study, such that the target was displayed even before the cue-related switch effects emerged. The study in Chapter 3 adopts a more commonly used CTI of 750 ms (see Table 1-2), which has been argued to be sufficient for optimal preparation (Rogers & Monsell, 1995; Verhoef et al., 2009).

Another possible factor which may have contributed to the discrepant findings in existing studies is the time windows chosen for analysis. Most of the studies above selected specific time windows based on a combination of previous reports and

visual inspection³⁷, making it difficult to draw direct comparisons across those results. Moreover, if effects are not detected in a selected time window, does that mean there is no effect at all? For example, Chang et al. (2016) was the only ERP study that looked at cue-locked brain activities but did not find a switch effect there - this could either be due to something special about digit naming (all other studies used picture naming), or due to the time window their analysis was restricted to. Likewise, the varied patterns of switch effect observed in the other ERP studies (e.g. Verhoef et al., 2010; Jin et al., 2014) may also result from the different time windows or components examined. In order to look at the full range of possible effects, the study in Chapter 3 does not restrict data analysis to pre-defined time windows, but rather searches for temporal clusters along the entire epoch.

1.7 THE DEMAND FOR LANGUAGE CONTROL: NATURAL VS FORCED SWITCHING

The third aspect of language control investigated in the present thesis is how the control demands (or mechanisms) differ between natural and forced switching. So far, most of the laboratory studies examined language switching under forced conditions (i.e. selecting language according to cues). These studies typically report some form of processing costs associated with language switching and mixing (longer reaction times, recruitment of more cognitive resources, etc). However, it is well known that bilinguals switch languages spontaneously in everyday conversations, even when there are no external instructions to do so. Such behaviour seems perplexing given the associated costs found in the laboratory. To shed some light on this phenomenon, an emerging line of research is looking into how switching language freely is different from being forced to switch. For example, when conversing with others who share the same languages, a bilingual might switch language because some words are more easily accessible for them in

³⁷ Only two of these studies examined the whole epoch (Blanco-Elorrieta & Pylkkänen, 2017; Lavric et al., 2019).

one language over another. Perhaps this type of switching demands less cognitive control? Or maybe it relies on a different set of control mechanisms? In this section, I will review the current behavioural and neural evidence on how language control in free switching differs from that in forced switching (see Table 1-3, for a summary).

Free language switching is examined using a paradigm which allows participants to choose what language to use on each trial. This is usually achieved via a small modification to the standard language-switching paradigm, where the language cues are omitted or neutral cues are provided (e.g. two national flags displayed simultaneously, bilingual interlocutors who can speak either language, etc). Compared to cued language selection, such freedom of language choice constitutes a closer resemblance to language use in real life, thus it may elicit more natural language switches based on lexical accessibility. Unlike the highly varied study designs employed for investigating the scope and timing of language control (see Sections 1.5 and 1.6), the paradigm used in studying free switching has been quite uniform. Therefore, I will discuss these studies in a more integrated manner in this section.

The main question investigated by these studies is whether free switching incurs processing costs (such as switch cost and mixing cost), just like cued switching does. Some studies examined free switching by itself (e.g. Gollan & Ferreira, 2009; Liu, Tong, et al., 2020), while others conducted direct comparisons between free and forced switching, either in a blocked fashion (e.g. Gollan et al., 2014; Kleinman & Gollan, 2016; de Bruin et al., 2018) or in a mixed fashion (Zhang et al., 2015). One study also looked at free and forced language switching in parallel with free and forced task switching, to examine the similarities and differences across the two domains (Gollan et al., 2014). Apart from the typical population of young adults, free language switching has also been studied in children (Gross & Kaushanskaya, 2015) and older adults (Gollan & Ferreira, 2009, Exp. 3). To investigate the neural

basis of free language switching, a variety of techniques have been employed, including fMRI (Zhang et al., 2015; Reverberi et al., 2018), MEG (Blanco-Elorrieta & Pylkkänen, 2017), and tDCS combined with EEG (Liu, Tong, et al., 2020).

Despite the relatively uniform paradigms adopted, it should be noted that there are some small variations in the type of “free switching” examined. While most of these studies adopt the *fully voluntary* design (where participants may use whichever language they like on each trial), additional restrictions are applied in some cases. For example, Gollan and Ferreira (2009, Exp. 2) asked bilinguals to name about half of the pictures in each language, so that the occurrences of the two languages were roughly equal. Similarly, Zhang et al. (2015) instructed participants to select each of the four trial types (L1 stay, L1 switch, L2 stay, L2 switch) in a relatively balanced fashion. A slightly more significant variation was introduced by Kleinman and Gollan (2016), where participants were given the freedom to choose language the first time they saw a picture, but had to maintain the same language choice for each subsequent appearance of that picture (this will be explained in more details below). Here, I use the term “free switching” as an overall name to denote any non-forced switching (i.e. whether fully voluntary or with additional constraints); on the other hand, the terms “forced switching” and “cued switching” are used interchangeably.

In the studies that directly compared free and forced language switching, the most obvious and consistent pattern observed is an overall voluntary advantage, i.e. faster reaction times overall in voluntary switching compared to cued switching (Gollan et al., 2014, Exp. 2; Kleinman & Gollan, 2016; de Bruin et al., 2018; Zhang et al., 2015; Blanco-Elorrieta & Pylkkänen, 2017). The only exception to this is Experiment 1 in Gollan et al. (2014), where voluntary responses were faster than cued in the non-dominant language, but *slower* than cued in the dominant language, resulting in no overall difference between voluntary and cued response times. This experiment only differed from their Experiment 2 in that the items were

not repeated; however, this may not be the responsible factor for the different results, as Blanco-Elorrieta and Pylkkänen (2017) also used non-repeated items but still obtained the voluntary advantage³⁸.

A more important question concerns whether the switch cost is reduced in free switching. In behavioural studies, fully voluntary switching usually incurs a significant switch cost (Gollan et al., 2014; Kleinman & Gollan, 2016; de Bruin et al., 2018; Gross & Kaushanskaya, 2015; but see Gollan & Ferreira, 2009, Exp. 2). When this cost is compared to that in cued switching (using a parallel design and looking for an interaction), the magnitudes are usually not significantly different (e.g. Gollan et al., 2014, Exp. 1; de Bruin et al., 2018). However, switch cost reduction in voluntary switching seems to emerge when participants adopt a more accessibility-driven strategy in lexical selection. For example, Gollan et al. (2014) examined voluntary vs cued switching, either with a large set of stimuli (total 192 pictures across all contexts) which were never repeated throughout the experiment (Exp. 1), or a small set of stimuli (8 pictures with high-frequency names) which were repeated many times³⁹ (Exp. 2). No significant switch cost reduction was observed for voluntary vs cued switching in the first case, and only a marginally-significant switch cost reduction was found in the second case. However, an important observation was made when participants in the second experiment were divided into two groups, based on how consistent they were in always naming the same picture in the same language. The group that maintained consistent language choice for most pictures (i.e. "bottom-up participants") showed a significant switch cost reduction compared to cued switching (with the voluntary switch cost itself being no longer significant); on the other hand, the group that did not maintain such consistency (i.e. "top-down

³⁸ Note that Blanco-Elorrieta and Pylkkänen (2017) used non-repeated items within each context (i.e. voluntary/cued switching), but the same set of items were used *across* contexts; on the other hand, Gollan et al. (2014, Exp. 1) had no repeated items across all contexts, i.e. each item only appeared once in the entire experiment. Therefore, there are still some differences between these two studies.

³⁹ Items were repeated 8 times within each context (cued/voluntary/single-language), i.e. 24 times across all contexts.

participants”) showed switch cost of similar magnitude to cued switching. These findings demonstrate that participants’ strategy in lexical selection is an important factor that influences the cost of switching, and cost-free language switches can be achieved if these switches occur naturally (rather than intentionally - which may be a consequence of the laboratory setting, even though participants are told to freely choose the language on each trial).

Given that participants who choose to maintain consistent language choices are able to switch language without a significant cost, it is possible that the same strategy might allow all bilinguals to switch more efficiently if they are explicitly instructed to follow such a strategy. Kleinman and Gollan (2016) investigated this using a design which they referred to as *bottom-up switching*, where bilinguals were free to choose their preferred language the first time they saw a picture, but had to continue to use the same language for each subsequent appearance of that picture. Language switching in the bottom-up block incurred no switch cost⁴⁰, which represented a significant cost reduction in comparison to both cued switching and voluntary switching (with a highly similar task and same set of stimuli). Performance within the bottom-up block was further analysed by dividing participants into two groups, based on whether they completed this block before or after the cued block⁴¹ (i.e. “cued-first” vs “bottom-up-first” bilinguals). The cued-first group showed significant switch cost in the bottom-up block, whereas the bottom-up-first group did not. These findings suggest that bottom-up switching is cost-free, so long as it does not occur following a cued-switching block. It remains unclear though whether the influence from prior cued switching is due to altering the participants’ strategy (i.e. they enter a top-down mode in the cued block, which persists into the subsequent bottom-up block), or due to contamination of the consistent item-language mappings (as all items are named in both languages in the cued block). These factors can be teased apart by using different items for the

⁴⁰ Not only “not significant”, but also with a Bayes factor favouring non-existent switch cost.

⁴¹ Block order was counterbalanced across participants in the overall study design.

bottom-up block and the cued block: if the block order effect remains in this case, then the cued block influenced participants' strategy; if the block order effect disappears, then it is the contamination of consistent item-language mappings that led to the switch cost.

Moving on to the neural basis of free language switching, studies have looked at whether free switching still recruits cognitive control. All the neural studies adopted a fully voluntary design, except a small additional constraint in Zhang et al. (2015) to select each trial type with roughly equal frequency. Some studies did not observe any neural switch effect in the voluntary context (Blanco-Elorrieta & Pylkkänen, 2017; Reverberi et al., 2018), suggesting that cognitive control may not be required when language switching occurs freely. Comparing voluntary switching directly to cued switching, Blanco-Elorrieta and Pylkkänen (2017) found switch-related activations in the left DLPFC and ACC during cued switching, which were not present during voluntary switching. It should be noted that the corresponding behavioural switch costs in these two studies were also not significant, even without encouraging participants to adopt a bottom-up strategy and with relatively large stimuli sets; such findings stand in contrast to the significant voluntary switch costs found in most behavioural studies employing the fully voluntary design (as mentioned above)⁴². In a neuro-stimulation study, Liu, Tong, et al. (2020) observed that increased cognitive control (induced by artificially elevating the excitability of right DLPFC) led to lower efficiency in voluntary switching, as indicated by overall slower responses and emergence of switch cost (which was not found in the sham session). These findings once again suggest that voluntary switching may not

⁴² One possible reason might be that these neural studies tend to perform simpler behavioural analyses (e.g. ANOVA on mean values), which may not be as sensitive as the more complex analyses commonly performed in the pure-behavioural studies (e.g. linear mixed-effects models). Such methodological difference may be one contributor to the discrepant findings here. In addition, the absence of voluntary switch cost in Blanco-Elorrieta and Pylkkänen (2017) could be due to the use of natural language cues (photos of interlocutors), as their cued-switching condition using similar natural cues also did not result in a switch cost (whereas another cued-switching condition using artificial cues in that same study did show a significant switch cost).

require any top-down control (and increased control actually results in interference rather than facilitation). Interestingly, a behavioural switch cost occurred with both anodal and cathodal tDCS; however, a switch effect in the ERP data was only present after cathodal stimulation. In contrast to all these findings above, Zhang et al. (2015) report a neural switch effect in voluntary switching in an fMRI study. This switch effect occurred in L1 only and was accompanied by increased activation in the bilateral superior and medial frontal gyri and the ACC when switching into L1 (vs staying in L1), and by increased activation of the left pre-central/post-central gyrus and IPL for the reverse comparison (i.e. staying in L1 vs switching to L1). Such patterns seem to suggest that voluntary switching does take effort; however, voluntarily *staying* also engages (different) neural resources. It is worth noting that the type of voluntary switching examined in this study is unlikely to be driven by lexical accessibility (i.e. bottom-up processes). This is because the stimuli set consisted of the digits 1-9, and a bilingual is unlikely to have different language preferences for different digits. Therefore, the voluntary switching condition may involve intentionally making a decision on what language to use, and the neural activations mentioned above could be reflecting such additional processing rather than voluntary switching per se. In addition, the behavioural switch cost in this study was smaller in voluntary compared to cued switching, suggesting that voluntary switching was nonetheless easier. Interestingly, while the switch effect in the fMRI data was asymmetrical (i.e. only observed in L1), the behavioural switch cost was symmetrical between the two languages.

Having discussed the behavioural and neural switch effects in free switching, I will now turn to the mixing effect (i.e. mixed-language vs single-language production). Fewer studies have examined this in a voluntary context, and so far only behavioural findings are available. As has been previously shown, forced language mixing is usually associated with a substantial mixing cost (e.g. Wang et al., 2009;

de Bruin et al., 2014; Ma et al., 2016)⁴³. In contrast to this, voluntary language mixing brings about some form of facilitation (i.e. faster responses or higher accuracy than restricting speech to a single language), either on both languages (de Bruin et al., 2018) or on the non-dominant language (Gollan & Ferreira, 2009; Gross & Kaushanskaya, 2015)⁴⁴. The only direct statistical comparison between free and forced mixing shows a significant cost reduction (de Bruin et al., 2018), turning a symmetrical mixing cost (in forced switching) into a symmetrical mixing benefit (in voluntary switching).

It should be noted that the definition of mixing cost is not always consistent. In the studies mentioned above, this cost was computed as the difference between single-language blocks and stay trials in the mixed-language blocks (Gollan & Ferreira, 2009; Gross & Kaushanskaya, 2015; de Bruin et al., 2018). This is the more commonly used approach, because all trials in a single-language block are technically “stay” trials, so they should be compared to the equivalent stay trials in mixed-language blocks. On the other hand, if single-language production is compared to all trials in mixed-language production (i.e. collapsed across stay and switch), that could result in a larger mixing cost (as switch trials are subject to additional processing costs, not just from language mixing). This less conservative definition of mixing cost has been used occasionally, for example, to highlight the additional efficiency of bottom-up switching (Kleinman & Gollan, 2016).

As mentioned above (in the discussion of switch costs), Kleinman and Gollan (2016) divided participants into two groups: “cued-first” and “bottom-up-first”. In the bottom-up block, mixing cost was significantly smaller for the bottom-up-first bilinguals compared to the cued-first bilinguals. This pattern was even more

⁴³ Sometimes the mixing cost is significant in the dominant language only (e.g. Christoffels et al., 2007; Jylkkä, Lehtonen, Lindholm, Kuusakoski, & Laine, 2018). Occasionally, a mixing cost in the dominant language together with a mixing benefit in the non-dominant language is observed (Guo et al., 2011).

⁴⁴ In Gross and Kaushanskaya (2015), mixing facilitation of non-dominant language is observed on naming accuracy, while no significant mixing cost is found for that language in reaction times.

pronounced when only looking at the second half of the bottom-up block, where a mixing cost was no longer observed for bottom-up-first bilinguals, but a significant mixing cost remained for the cued-first bilinguals. These observations suggest that the efficiency of bottom-up mixing can be influenced by prior performance of cued switching. As with the switch cost, it is unclear whether the influence from prior cued switching is due to alteration of the participants' strategy or contamination of the consistent item-language mappings.

	Type of switching	Participants	Language cue	Stimuli	Consistent item-language mappings? (within current block)	Overall RT in mixed blocks (free vs cued switching)	Switch effect (in RT, unless specified)		Mixing effect (in RT, unless specified)
Gollan & Ferreira, 2009	Voluntary	English-Spanish (English dominant)*	None	44 pictures (+ 44 for English-only block + 44 for Spanish-only block)	Yes (no repetition)		Symmetrical switch cost		Mixing cost in L1; mixing benefit in L2
						No switch cost		Symmetrical mixing cost	
	Voluntary - about equally often in the two languages	English-Spanish (English dominant)*					Switch benefit in L1; no switch effect in L2		Mixing cost in L1; mixing benefit in L2
Gollan et al., 2014	Cued (no repeated items)	English-Spanish (quite balanced)	National flag (both flags displayed = voluntary)	64 pictures for cued + another 64 for voluntary (+ 64 for single-language blocks)	Yes (no repetition)	(n/a)	Asymmetrical switch cost		Not explicitly reported, but their Fig.1 shows possible mixing cost in both languages
	Voluntary (no repeated items)			Overall no difference: Faster in L2; slower in L1		Switch cost (similar magnitude to cued switching), marginally asymmetrical		Not explicitly reported, but their Fig.1 shows mixing cost in L1 and possible mixing benefit in L2	
	Cued (repeated items)			8 pictures (same items across cued, voluntary, and single-language blocks)	No	(n/a)	Symmetrical switch cost	Top-down participants: switch cost	
			Bottom-up participants: switch cost						

Gollan et al., 2014 (cont.)	Voluntary (repeated items)	(cont.)	(cont.)	(cont.)	Up to participant choice	Faster (symmetrical)	Symmetrical switch cost (marginally smaller than in cued switching)	Top-down participants: switch cost (similar magnitude to cued switching)	
								Bottom-up participants: no switch cost in either language (significantly smaller than in cued switching)	
Kleinman & Gollan, 2016	Cued	Spanish-English (quite balanced)	National flag (both flags displayed = voluntary / bottom-up)	9 pictures	No	(n/a)	Symmetrical switch cost		Mixing cost
	Voluntary				Up to participant choice	Faster (symmetrical)	Symmetrical switch cost (no direct comparison with cued switching, but numerically similar)		Mixing cost (no direct comparison with cued switching, but numerically much smaller)
	Bottom-up (after cued block)				Yes	Faster (symmetrical)	Overall: No switch cost [Bayes] (significantly smaller than in cued switching & voluntary switching)	Switch cost	Mixing cost, even in second half of block
	Bottom-up (before cued block)				Yes		No switch cost (significantly smaller than above)	No switch cost (significantly smaller than above)	Mixing cost (significantly smaller than above); no mixing cost in second half of block
de Bruin et al., 2018	Cued	Spanish-Basque (quite balanced)	National flag	30 pictures for cued + another 30 for voluntary	No	(n/a)	Symmetrical switch cost		Symmetrical mixing cost
	Voluntary		None		Yes	Faster (symmetrical)	Symmetrical switch cost (similar magnitude to cued switching)		Symmetrical mixing benefit

Zhang et al., 2015 [^]	Cued	Chinese-English (unbalanced)	Letter prompt ('C' = Chinese, 'E' = English)	9 digits (forming 72 unique pairs)	No	(n/a)	RT: symmetrical switch cost fMRI: activation in bilateral SMA, IPL, middle cingulate cortex, left fusiform gyrus and precuneus, left pre-central/post-central gyrus (switch > stay, L1); right pre-central/post-central gyrus (stay > switch, L1); no switch effect in L2	
	Voluntary - about equally often in the four trial types: L1 stay, L1 switch, L2 stay, L2 switch		Letter prompt ('V' = voluntary)			Faster	RT: symmetrical switch cost (significantly smaller than in cued switching) fMRI: activation in bilateral superior and medial frontal gyri, ACC (switch > stay, L1); left pre-central/post-central gyrus and IPL (stay > switch, L1); no switch effect in L2	
Reverberi et al., 2018	Voluntary	German-English (quite balanced)	None	120 pictures	Up to participant choice		RT: No switch cost fMRI: no switch effect	
Blanco-Elorrieta & Pylkkänen, 2017	Cued	Arabic-English (quite balanced)	Colour patch; monolingual interlocutor	96 pictures	Yes (no repetition)	(n/a)	RT: switch cost for colour cues; no switch cost for monolingual cues MEG: switch effect in left DLPFC & ACC	
	Voluntary		Bilingual interlocutor			Faster	RT: no switch cost MEG: no switch effect (significantly smaller than in cued switching)	

Liu et al., 2020	Voluntary	Chinese-English (unbalanced)	None	72 pictures (distributed into 3 tDCS sessions)	Up to participant choice		RT: no switch cost (sham session); significant switch cost (anodal/cathodal tDCS on DLPFC) ERP: larger LPC (L2 > L1, switch trials only), for cathodal tDCS only	
Gross & Kaushanskaya, 2015	Voluntary	English-Spanish <i>children</i> (varied language profiles)	Auditory ('say' = English; 'diga' = Spanish; beep = voluntary)	42 pictures	Yes (no repetition)		Symmetrical switch cost	Mixing cost in L1; no mixing cost in L2. (Additionally, mixing benefit in L2 only, in naming accuracy)

Table 1-3. Summary of existing studies which investigated free switching in bilinguals. Some of these studies compared directly between free and forced switching, while others included free switching only. A greyed-out box indicates that this particular aspect was not reported in that study. **Green text** indicates switching/mixing benefit, or voluntary advantage over cued context; **red text** indicates switching/mixing cost, or absence of voluntary advantage. “No switch cost” = no significant switch cost found, unless otherwise labelled (e.g. Bayes); likewise for “no mixing cost”. Information on the (a)symmetry of switch effect and mixing effect are included whenever available. “L1” and “L2” in this table denote dominant and non-dominant language, respectively (rather than first and second language). RT = reaction time. tDCS = transcranial direct current stimulation. LPC = late positive component (in the ERP). For other abbreviations (e.g. names of brain regions), see Section 1.4. *Gollan and Ferreira (2009) made these classifications based on the participants’ performance in single-language blocks; according to self ratings, the “balanced” group was more dominant in Spanish. ^In the study by Zhang et al. (2015), cued and voluntary switching were not performed in separate blocks, but randomly mixed together; this differs from all other studies.

Summarising the findings discussed above, free switching is generally more efficient than forced switching, but in most cases the switch cost and mixing cost are not completely eliminated. Consistency of item-language mappings seems to play an important role in cost reduction, as shown by the additional efficiency observed in bottom-up switching (compared to fully voluntary switching), especially when this occurs without any prior cued switching (Kleinman & Gollan, 2016). To test whether such consistency alone is responsible for the reduction of switch cost and mixing cost (without requiring freedom of language selection), the study presented in Chapter 4 includes an “artificially-consistent context”, where participants follow language cues on each trial but consistent mappings are maintained throughout the experiment. In addition, while the bottom-up design by Kleinman and Gollan (2016) is effective at encouraging more accessibility-driven lexical selection, the task instruction itself requires participants to keep track of which language they are using for each item, thus adding extra constraints on the “free” switching and making it less natural. The monitoring demands required in this case could potentially elicit additional cognitive control. Therefore, the study in Chapter 4 makes a further improvement on this design by using strongly language-biased stimuli in the natural-switching context, such that bilinguals are very likely to adopt a bottom-up strategy even without explicit instruction. In other words, consistent mappings are achieved without participants needing to care about additional constraints. Furthermore, the neural basis of free language mixing (i.e. mixed vs single-language) has not yet been investigated in the current literature (see Table 1-3). To fill this gap, the study in Chapter 4 examines the mixing effect alongside the switch effect, and compare these across the natural context and artificially-consistent context described above, as well as the classic cued-switching context.

1.8 THE TECHNIQUES: TMS AND MEG

To investigate the neural mechanisms of language control, I make use of two techniques in the present thesis. In Chapter 2, I use TMS, a non-invasive neuro-stimulation technique, to assess the causal role of an inhibitory-control brain region in language switching. In Chapters 3 and 4, I use MEG, a highly time-resolved electrophysiological technique, to record brain activities while participants perform language-switching tasks in various contexts. In this section, I will briefly introduce these techniques and explain why they were chosen for the experimental work in this thesis.

TMS is a relatively well-established technique for non-invasively stimulating the human brain. This technique is based on electromagnetic induction, where a changing magnetic field, delivered through a coil placed on the surface of the scalp, generates electric current in the cortical region underneath, thus affecting the brain activity in that area (Barker, Jalinous, & Freeston, 1985). Traditionally, TMS has been used extensively for research in the motor domain (Rothwell et al., 1999); in recent years, it has found more wide-ranging applications in various areas of cognitive neuroscience. In particular, repetitive TMS protocols⁴⁵ that are capable of temporarily modulating brain activity (either excitatory or inhibitory) have gained considerable popularity (Sandrini, Umiltà, & Rusconi, 2011; Parkin, Ekhtiari, & Walsh, 2015). Low frequency repetitive stimulation (at around 1 Hz) generally produces an inhibitory effect, while higher frequency stimulation is likely to have an excitatory effect (Classen & Stefan, 2008). Recently, theta burst stimulation (TBS) has become more widely used; continuous TBS is thought to disrupt brain activity, while intermittent TBS has a facilitatory effect (Huang, Edwards, Rounis, Bhatia, & Rothwell, 2005). These kinds of stimulation are typically applied “offline”, i.e. not during task performance. The impact of the stimulation is then assessed by

⁴⁵ While repetitive TMS has many other useful applications, such as in the diagnosis and treatment of mental disorders, here I will focus on the particular area of application which is relevant for the present thesis (i.e. transient modulation of cortical activity).

comparing the participant's performance pre- and post-stimulation, or comparing between real and sham stimulation. Such methods to modulate cortical activity are extremely valuable, as they enable targeted perturbation in healthy participants, taking neuroimaging findings one step further.

Functional neuroimaging studies have so far provided a lot of useful information as to which parts of the bilingual brain are engaged during language switching (see Section 1.4.3, for a review). However, this type of information does not reveal whether the activities in these brain regions play a causal role or are simply correlated with language control. The TMS study presented in Chapter 2 focussed on one particular brain region, the pre-SMA, which has a well-known role in domain-general inhibitory control and is frequently reported to be active during language switching. An outstanding question is whether bilinguals rely on this brain region to carry out language inhibition during switching. The rationale of the study was as follows: if the pre-SMA plays an essential role in bilingual control, then disrupting its activity should result in a performance impact in the language-switching task. Thus, an ideal method to test this would be to transiently suppress pre-SMA activity, and then observe the consequences on participants' behavioural performance. This kind of approach can be considered as (non-invasively) creating brain lesions on demand in healthy participants, and is sometimes known as "virtual lesion" (see Weissman-Fogel & Granovsky, 2019).

Repetitive TMS is not the only method capable of achieving this goal. Another commonly used brain stimulation technique, tDCS, was also considered as an option. However, TMS was deemed to be more appropriate in this case, because it possesses the following advantages. Firstly, compared to standard tDCS, TMS provides better spatial precision, enabling stimulation of the exact target location⁴⁶ (Jiang, Truong, & Bikson, 2019). This advantage is amplified with the use of a neuro-

⁴⁶ Especially with a figure-of-8 coil (as used in Chapter 2), which provides more focality when delivering the magnetic pulses.

navigation system, which guides the placement of the magnetic coil for each participant according to their individual structural MRI scan (see Chapter 2, Section 2.3.1.2). Secondly, TMS is generally more effective at inhibitory stimulation (i.e. suppressing cortical excitability), especially using continuous TBS, which has a demonstrated suppressive effect backed by physiological evidence (Huang, Chen, Rothwell, & Wen, 2007). Moreover, the inhibitory effect of this protocol specifically on the pre-SMA has previously been reported (Dietrich, Müller-Dahlhaus, Ziemann, Ackermann, & Hertrich, 2015). Based on these reasons, repetitive TMS using the continuous TBS protocol was determined to be the most suitable choice for this study.

MEG is an electrophysiological technique which measures the magnetic fields generated by electrical activities in the brain (Cohen, 1968). One notable advantage of MEG over other techniques is its excellent temporal resolution, as magnetic fields travel extremely fast. Such availability of real-time neural activity with millisecond resolution is invaluable in studying the fast dynamics of brain activation and connectivity. While EEG shares a similar temporal resolution, other techniques which rely on indirect measures of brain activity (e.g. blood oxygenation levels) are much slower (Gross, 2019). The main advantage of MEG as compared to EEG is that magnetic fields can pass through the skull and scalp without much distortion, therefore source activities reconstructed from MEG data are generally more accurate than those derived from EEG data (Cohen & Cuffin, 1983). Whilst the spatial resolution of MEG source reconstruction cannot be compared to that of fMRI, a resolution in the range of millimetres can be achieved for cortical brain regions (Barnes, Hillebrand, Fawcett, & Singh, 2004). Another difference between MEG and EEG is that MEG is mainly sensitive to tangentially-oriented sources, but not radially-oriented sources in the brain (Cohen & Cuffin, 1991; Ahlfors, Han, Belliveau, & Hämäläinen, 2010). This may or may not be an advantage, depending on what type of currents one is aiming to detect. For example, if one is specifically interested in brain activities from tangential sources, MEG can help reveal these

more clearly than EEG measurements which contain a mixture of activities from tangential and radial sources (Cohen & Cuffin, 1983); on the other hand, if one is interested in radially-oriented currents, then MEG may not detect those at all. As such, MEG and EEG data provide complementary, rather than redundant, information about brain activities (e.g. Sharon, Hämäläinen, Tootell, Halgren, & Belliveau, 2007; Aydin et al., 2015).

In the study presented in Chapter 3 of this thesis, the main aim is to examine potentially distinct control processes during the preparation and execution of a language switch. For this reason, the language cue and naming target are presented 750 ms apart (see Section 1.6). Green and Abutalebi (2013) propose that these control processes may be supported by a number of different brain regions or circuits. Thus, it is important to simultaneously examine neural activities in multiple regions (at least as a first step before probing the causal role of any particular region). Since Green and Abutalebi's model associates each brain region with a proposed role in language control, it would be especially useful if sensor data can be converted accurately into source-space activities in these brain regions. Such information about the brain locations where certain patterns of activities arise can help elucidate the specific control processes represented by these patterns (see discussions in Section 1.6). MEG is an ideal choice for this study, as it satisfies all of the requirements above. Firstly, its high temporal resolution allows effective separation of brain responses to the cue and to the target⁴⁷, as well as providing detailed timecourses of brain activities with millisecond accuracy. Secondly, MEG (like most passive techniques) records from the whole head simultaneously, as opposed to being restricted to a particular region. Thirdly, as explained above, MEG is relatively superior in terms of enabling accurate source reconstruction compared

⁴⁷ The temporal resolution of MEG (or EEG) is a bit of an overkill for this purpose. However, other techniques (such as fMRI) would require a much longer interval or other modifications to the task design, in order to separate the brain responses to the cue and the target (see discussions in Section 1.6).

to EEG, which has a similar temporal resolution. Lastly, MEG studies of language switching are still very rare at this stage (see Section 1.4.2); since MEG and EEG are sensitive to neural sources of different orientations (see paragraph above), it is important to collect more data using MEG so that the patterns of brain activities can be compared across studies.

The study presented in Chapter 4 extends this investigation by looking at how the control demands differ between natural and forced language switching. For comparability, MEG was again used for this study and source activities were reconstructed for the same brain regions which were proposed to be part of the bilingual language control network (Green & Abutalebi, 2013).

1.9 THESIS STRUCTURE

This thesis aims to extend our current knowledge on the neural mechanisms of bilingual control, by focussing on the scope and timing of language control as well as the demands for control in different contexts. I present three experimental studies (Chapters 2 to 4), which provide detailed investigations into these aspects of language control in bilingual speech production. Each chapter is written in the form of an independent manuscript for publication. Chapter 2 has been published in *Brain Sciences* (Zhu & Sowman, 2020); Chapter 3 has been published in *Cognition* (Zhu, Seymour, Szakay, & Sowman, 2020); Chapter 4 is prepared for journal submission. Because all of these studies are centred around the same topic (i.e. neural mechanisms of bilingual language control), their backgrounds necessarily contain some overlapping information; however, each chapter is written with a distinct focus.

In **Chapter 2**, I start with a behavioural investigation on whole-language and item-specific inhibition in language switching (see Section 1.5 for background). These two levels of control are examined in parallel, and a behavioural index is established

for each of them. I then proceed to investigate whether the pre-SMA, an important brain region for domain-general inhibitory control, plays a causal role in either level of language inhibition. This is achieved by transiently disrupting this brain region using repetitive TMS and examining the impact on language-switching performance.

In **Chapter 3**, I investigate whether language switching can be prepared in advance, by including a time interval after presenting the language cue and before presenting the naming target (see Section 1.6 for background). In an effort to resolve the discrepancy among previous findings, this study is designed with the aim of bringing together the best design elements from existing studies (e.g. natural language cues, no confound of cue switching, etc). Neural responses are recorded using MEG and reconstructed into source activities in pre-selected regions of interest, allowing an examination of the control mechanisms taking place during the preparation stage (following cue onset) and the production stage (following target onset).

In **Chapter 4**, I examine whether the demand for language control differs between free and forced language switching (see Section 1.7 for background). This taps into the ecological validity of laboratory paradigms, as bilinguals are known to spontaneously switch language in everyday conversations even though laboratory studies usually find that switching takes extra time and requires more cognitive resources. Three different production contexts are examined in this study, from completely natural switching without any constraints to fully cued switching, as well as a “intermediate level” where language selection is not free but each item is always mapped to the same language. The switch effect and mixing effect are compared across the three contexts, to determine whether natural switching is performed more efficiently than forced switching, and if so, what specific factors are responsible for such efficiency. The real-life scenarios represented by these contexts are also briefly discussed.

In **Chapter 5**, I summarise the main experimental findings and the overall contributions of this thesis. I dedicate a section to reflect on important methodological issues that should be considered when designing language-switching experiments, drawing on the lessons I've learned through conducting the three studies presented here. I also discuss the implications of the present findings on related topics and explore possible future research directions.

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CHAPTER 2

Whole-language and item-specific inhibition in language switching:
the role of domain-general inhibitory control

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Abstract

A prominent theory of bilingual speech production holds that appropriate language selection is achieved via inhibitory control. Such inhibition may operate on the whole-language and/or item-specific level. In this study, we examined these two levels of control in parallel, by introducing a novel element into the traditional cued-language-switching paradigm: half of the stimuli were univalent (each required naming in the same language every time it appeared), and the other half were bivalent (each required naming in different languages on different trials). Contrasting switch and stay trials provided an index for whole-language inhibition, while contrasting bivalent and univalent stimuli provided an index for item-specific inhibition. We then investigated the involvement of domain-general brain mechanisms in these two levels of language control. Neuroimaging studies report activation of the pre-supplementary motor area (pre-SMA), a key region in the executive-control brain network, during language-switching tasks. However, it is unclear whether or not the pre-SMA plays a *causal* role in language control, and at which level it exerts control. Using repetitive transcranial magnetic stimulation (TMS) to transiently disrupt the pre-SMA, we observed an essential role of this brain region in general speech execution, while evidence for its specific involvement in each level of inhibition remains inconclusive.

Keywords

bilingualism; language control; whole-language inhibition; item-specific inhibition; TMS; pre-SMA

2.1 INTRODUCTION

At least half of the world's population today are bilingual or multilingual (French & Jacquet, 2004). Knowing more than one language comes with the benefit of having access to information from a wider range of sources, and being able to communicate with more diverse groups of people. At the same time, it demands some kind of control mechanism to keep the languages separate and ensure they do not interfere with each other. How do bilingual individuals coordinate their two languages successfully, so that they can speak the desired language at any given time? How do they switch between languages with ease? An influential view was put forward by Green (1998), in his "inhibitory control model" of bilingual speech production. According to Green's model, appropriate language control is achieved via inhibition of the non-target language. That is, when bilinguals speak one language, they need to suppress the other language to avoid interference. Based on the assumption that lexical items in the more dominant language have a higher level of baseline activation, Green proposes that stronger inhibition needs to be placed on that language in order to enable speech production in the non-dominant language. On the other hand, production in the dominant language does not require that as much inhibition be applied to the non-dominant language. This leads to the prediction that it is relatively more difficult for bilinguals to return to their dominant language after speaking in their non-dominant language (than the other way around), due to the need to overcome stronger prior inhibition.

2.1.1 Behavioural markers of inhibition

Green's (1998) inhibition account of bilingual control finds support in the cued language switching paradigm (e.g. Meuter & Allport, 1999; Jackson, Swainson, Cunningham, & Jackson, 2001; Costa & Santesteban, 2004; Philipp, Gade, & Koch, 2007; Schwieter & Sunderman, 2008; Fink & Goldrick, 2015). In this paradigm,

bilingual participants name pictures or numerals in their first language (L1) or second language (L2), according to a cue given on each trial. The language requirement can either change from the previous trial (*switch trial*), or stay the same as the previous trial (*stay trial*). A robust finding is that reaction times (RT) are longer on switch trials compared to stay trials. This RT difference is commonly referred to as the *switch cost*. While the switch cost itself can be attributed to a number of factors, such as cue encoding (see Heikoop, Declerck, Los, & Koch, 2016), task shifting and goal updating (Abutalebi & Green, 2008), it is the finding of asymmetrical switch cost (especially in unbalanced bilinguals) that points towards the involvement of inhibitory processes in language switching.

Asymmetrical switch cost refers to the observation that the switch cost is larger when bilinguals switch into the dominant language, compared to switching into the non-dominant language (e.g. Meuter & Allport, 1999; Jackson et al., 2001; Costa & Santesteban, 2004, Exp. 1; Campbell, 2005; Costa, Santesteban, & Ivanova, 2006, Exp. 3 & 4; Philipp et al., 2007, Exp. 1; Schwieter & Sunderman, 2008; Fink & Goldrick, 2015; Zhu, Seymour, Szakay, & Sowman, 2020). This pattern aligns with Green's inhibition account of language control: production in the non-dominant language requires stronger suppression of the dominant language, so it takes more time to overcome such suppression when switching back into the dominant language. This phenomenon has been replicated in many studies (see above), but it is not universally observed. For example, the switch cost asymmetry seems to disappear when participants are given long preparation times for the language switch (e.g. Verhoef, Roelofs, & Chwilla, 2009; but see Philipp et al., 2007), when univalent stimuli⁴⁸ are employed (Finkbeiner, Almeida, Janssen, & Caramazza, 2006; but see Reynolds, Schlöffel, & Peressotti, 2016), when participants switch language voluntarily rather than according to cues (Gollan & Ferreira, 2009), or when testing early bilinguals who are highly proficient in both L1 and L2, even if the task requires

⁴⁸ A univalent stimulus elicits response in one language only, rather than both languages (see Section 2.1.4 for more details).

them to switch between their strong L1 and a much weaker L3 (Costa & Santesteban, 2004, Exp. 4; Martin et al., 2013). These findings raise questions about the reliability of the asymmetrical switch cost as a marker for inhibition (for detailed reviews, see Bobb & Wodniecka, 2013 and Declerck & Philipp, 2015).

Another common finding from the language switching paradigm is the *reversed dominance effect*, sometimes called *global L1 slowing*. This refers to the overall slower naming latencies observed in L1 compared to L2 (on both stay and switch trials), a surprising occurrence given that naming in L1 should normally be faster than in L2 (see Hanulová, Davidson, & Indefrey, 2011). The reversed dominance effect is often interpreted as evidence for sustained inhibition of L1, which serves to facilitate L2 speech production in a mixed-language context (Kroll, Bobb, Misra, & Guo, 2008; Gollan, Kleinman, & Wierenga, 2014; Bobb & Wodniecka, 2013). It is interesting to note that, in studies where a switch cost asymmetry is absent, a reversed dominance effect is often observed (e.g. Costa & Santesteban, 2004, Exp. 2~5; Costa et al., 2006, Exp. 1 & 2; Christoffels, Firk, & Schiller, 2007; Gollan & Ferreira, 2009; Verhoef et al., 2009, 2010; Martin et al., 2013; Peeters & Dijkstra, 2018)⁴⁹. It seems to be a matter of whether the L1 slowing affects both stay and switch trials (i.e. reversed dominance), or only the switch trials (i.e. asymmetrical switch cost). From this point of view, switch cost asymmetry and reversed dominance serve as complementary evidence supporting the presence of inhibitory processes in language switching.

2.1.2 The role of domain-general brain mechanisms

In the past two decades, researchers have begun to apply neuroimaging techniques to the study of bilingual language control. A growing amount of evidence now

⁴⁹ Note that this is a general observation but not a conclusive claim, as there exist studies which show neither of these effects (e.g. Calabria, Branzi, Marne, Hernández, & Costa, 2015; Prior & Gollan, 2011) and studies which show both (e.g. Schwieter & Sunderman, 2008).

shows that language switching engages the brain network for executive control (e.g. Hernandez, Dapretto, Mazziotta, & Bookheimer, 2001; Wang, Xue, Chen, Xue, & Dong, 2007; Abutalebi et al., 2008; Garbin et al., 2011; Abutalebi et al., 2012). This gives rise to the idea that the neural mechanisms underlying language control may be similar to those underlying generic action control (see Kroll & Bialystok, 2013). Based on such findings, Green and Abutalebi (2013) developed a neurocognitive model of bilingual language control, which proposes a brain network of cortical and subcortical structures tightly related to executive function (see also Abutalebi & Green, 2007, 2008).

In particular, the pre-supplementary motor area (pre-SMA) is often reported to be involved in language switching (Wang, Kuhl, Chen, & Dong, 2009; Garbin et al., 2011; Abutalebi et al., 2013; de Bruin, Roelofs, Dijkstra, & FitzPatrick, 2014; De Baene, Duyck, Brass, & Carreiras, 2015). However, the exact pattern of pre-SMA activation varies across studies. For example, Garbin et al. (2011) found that the pre-SMA was recruited only when bilinguals switched from their L2 into L1, not when switching in the other direction. In contrast, de Bruin et al. (2014) report the opposite pattern in trilingual participants: pre-SMA activation occurred when participants switched into their L2 (or L3), but not when they switched into L1. Furthermore, Abutalebi et al. (2013), who also tested trilingual participants, found that the pre-SMA was activated on all switch trials, regardless of which language the participants switched into. Such conflicting results leave open questions about exactly under what circumstances the pre-SMA is engaged and what its precise function is in language switching.

Outside of the linguistic domain, the pre-SMA is widely regarded as an important brain area in the inhibitory control network (Fedorenko, Duncan, & Kanwisher, 2013; Aron et al., 2007; Xue, Aron, & Poldrack, 2008). In recent years, it has been increasingly recognised for its role in response selection and conflict resolution across domains, especially in demanding tasks (for a review, see Nachev, Kennard,

& Husain, 2008). The pre-SMA is sometimes considered as part of a complex with the dorsal anterior cingulate cortex (ACC). It has been suggested that the pre-SMA may work together with dorsal ACC in carrying out conflict monitoring and error detection, in both language switching and non-linguistic tasks involving a high level of conflict (Abutalebi et al., 2012; De Baene et al., 2015). In Green and Abutalebi's (2013) neurocognitive model of bilingual language control, the role of performing conflict resolution belongs to the ACC/pre-SMA complex. However, a meta-analysis of fMRI studies on language switching (Luk, Green, Abutalebi, & Grady, 2012) identified significant activation in midline pre-SMA but not in the ACC, suggesting that the pre-SMA portion of this structure may be more universally engaged in bilingual control.

In summary, existing neuroimaging studies provide strong evidence for the involvement of pre-SMA in bilingual language control. However, findings vary on exactly when this brain region is engaged. Furthermore, functional neuroimaging is unable to discern whether the pre-SMA plays a causal role in language switching or simply co-activates with the language control network. In the present study, we take the approach of creating a "virtual lesion", by disrupting local brain activity in this region using non-invasive brain stimulation (see Weissman-Fogel & Granovsky, 2019). If this has an impact on language switching performance, then a causal relationship can be established between pre-SMA activity and language control. The role of the pre-SMA in language switching is generally regarded as conflict monitoring and resolution, without an exact specification of how such function is carried out (e.g. by biasing selection towards the target language, or by inhibiting the non-target language). Given that the pre-SMA acts as a key node in the brain network for domain-general inhibitory control, we hypothesise that it likely accomplishes conflict resolution via an inhibitory mechanism. In particular, we distinguish between two levels of inhibition in language switching (see below), and the pre-SMA may have a possible role in either or both of these. By examining whether each level of inhibition is affected by pre-SMA disruption, we might be

able to pinpoint the mechanism via which this brain region carries out language control.

2.1.3 Two levels of language inhibition

De Groot and Christoffels (2006) propose that bilingual language control may operate at two different levels: *whole-language control* affects all lexical representations in a language simultaneously, whereas *item-specific control* targets specific lexical representations that are competing for selection⁵⁰. If both levels of control are present, proactive regulation on the whole-language level may be complemented by reactive inhibition operating at the item-specific level. According to Green (1998), the intention to speak a particular language affects the activation levels of language task schemas (e.g. L1 production schema, L2 production schema). The active language task schema can then exert control on the whole-language level to bias selection towards lemmas in the target language. When a concept spreads activation to corresponding lemmas in both languages, the language task schema reactively inhibits any highly-activated lemmas belonging to the non-target language, to ensure that speech output occurs in the desired language (see Figure 2-1). De Groot (2011) argues that, in theory, item-specific control alone would be sufficient to prevent the output of any words belonging to the non-target language. Based on this view, whole-language control may be redundant.

⁵⁰ De Groot and Christoffels (2006) originally used the terms “global” and “local” to distinguish between these two levels of control. However, these terms have since been used with different definitions. For example, Guo, Liu, Misra, & Kroll, 2011 referred to the effect of language mixing (i.e. mixed-language vs single-language blocks) as “local” control, and the block order effect among single-language blocks as “global” control. To avoid potential confusion, here we adopt the terminology used by Van Assche, Duyck, and Gollan (2013), which are less prone to ambiguity: “whole-language” (i.e. global) vs “item-specific” (i.e. local) control.

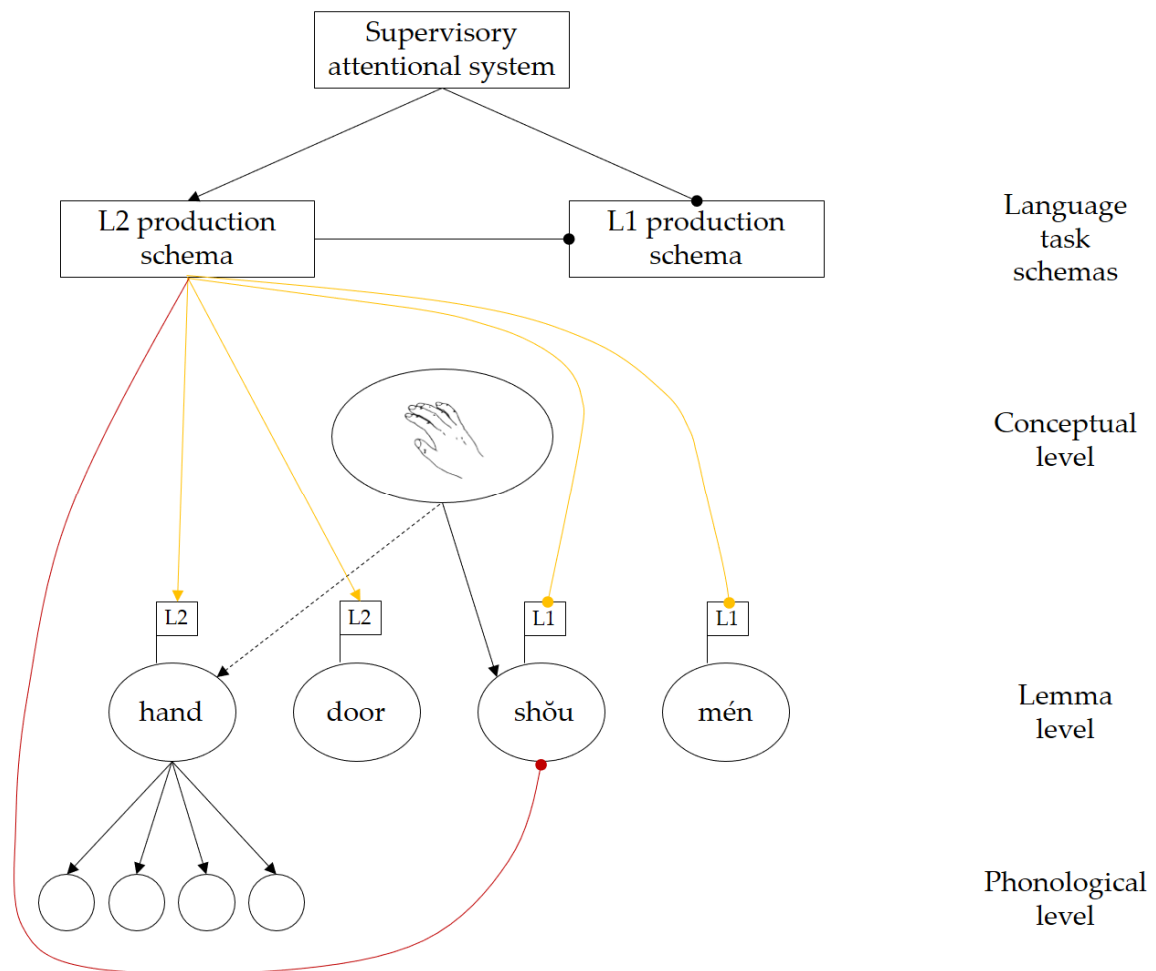


Figure 2-1. Whole-language and item-specific control in bilingual word production, based on Green (1998) and De Groot and Christoffels (2006). Yellow lines indicate whole-language control; red lines indicate item-specific control. Arrow heads indicate excitation; circle heads indicate inhibition.

In this example, the target language is L2 (English), and the non-target language is L1 (Mandarin). The intention to speak L2 is expressed by the supervisory attentional system, which activates the "L2 production schema" and suppresses the "L1 production schema". The L2 production schema then applies whole-language control to regulate the activation levels of lemmas in the two languages, in order to bias selection towards L2 lemmas. The L1 lemma "shǒu" (translation-equivalent of the target name "hand") receives strong activation from the concept, and thus becomes a strong competitor despite being suppressed at the whole-language level. To ensure correct selection of the L2 lemma "hand" for output, the L2 production schema reactively inhibits "shǒu" to resolve the competition.

Experimental studies have so far examined the two possible levels of language control in a variety of paradigms. Philipp and Koch (2009) asked participants to switch between three languages, and investigated the “n-2 language-repetition cost” which reflects inhibition of the recently-abandoned language. They found that the repetition cost was similar regardless of whether the stimulus-response set or only the language was repeated, suggesting that such inhibition occurred on the whole-language level. Van Assche et al. (2013) adopted a verbal fluency task, in which bilingual participants produced words beginning with certain graphemes/phonemes in each language, as specified by letter prompts. The task was conducted in a by-language blocked design. Difficulty of dominant language production when it occurred after the non-dominant language block was taken as evidence for inhibition of the dominant language. While item-specific inhibition (elicited by repeated prompts across languages) was found in both groups of bilinguals in that study, whole-language inhibition (elicited by non-repeated prompts) was only observed in Mandarin-English and not Dutch-English bilinguals, indicating that the latter might be an optional strategy. In blocked picture-naming tasks, the dominant language block suffered from slower responses following production of the non-dominant language, whether the picture stimuli were repeated across languages or not (Misra, Guo, Bobb, & Kroll, 2012; Branzi, Martin, Abutalebi, & Costa, 2014). Dominant language production also recruited more cognitive resources when it occurred after the non-dominant language, whether the stimuli were repeated or not (Guo et al., 2011; Branzi, Della Rosa, Canini, Costa, & Abutalebi, 2016). Such hindrance of dominant language production suggests the presence of sustained control on the whole-language level. In addition, Branzi et al. (2016) observed activation of the dorsal-ACC/pre-SMA complex exclusively for naming of repeated stimuli in the non-dominant language, pointing towards a particular role of this brain region in item-specific control.

Taken together, these findings support the existence of whole-language and item-specific control in bilingual speech production, with potentially different underlying

neural mechanisms. However, the presence of either or both levels of control in a particular situation seems to depend on the specific experimental paradigm used and the type of bilinguals tested. Given that, in the realm of language switching, a central piece of evidence for inhibitory control comes from the asymmetrical switch cost in the traditional cued-switching paradigm (i.e. trial-to-trial switching), it is important to examine the distinction between whole-language and item-specific inhibition within the context of this paradigm.

A previous attempt on this was made by Finkbeiner, Almeida, et al. (2006), who investigated (what they called) the “language suppression hypothesis” and “lexical suppression hypothesis”. These hypotheses encompass a similar idea as whole-language vs item-specific inhibition, but there are differences in the definitions. Specifically, the “lexical suppression hypothesis” suggests that naming a concept in one language suppresses all semantically-related names in the other language (to a certain degree); this broad assumption may be one reason why such suppression was not observed in that study. In accordance with more recent studies (e.g. Branzi et al., 2016), we adopt a conservative definition of “item-specific inhibition”, which looks specifically at suppression of translation-equivalents in the non-target language. Since direct translation-equivalents are likely to be the most potent competitors in lexical selection, this should elicit the strongest form of item-specific inhibition. In addition, Finkbeiner, Almeida, et al. (2006) argued against both whole-language and item-specific inhibition, based on an absence of switch cost for the univalent stimuli in their study; however, this pattern was likely due to a confound of task switching which accompanied all univalent trials (such that the effect of language switching was masked by the task switch)⁵¹. Therefore, in the present study we eliminate such confounds in the design. In the following section, we argue that the type of inhibition involved in trial-to-trial switching likely operates on the whole-language level, and we develop a comparable measure for

⁵¹ More recently, Reynolds et al. (2016) showed that the (typical) asymmetrical switch cost can indeed be obtained for univalent stimuli, when the confound of task switching is removed.

item-specific inhibition so that the two levels of control can be examined in parallel. To maximise the opportunity for observing both whole-language and item-specific inhibition in this study, we target Mandarin-English bilinguals as they have been previously shown to implement both levels of inhibition when another group of bilinguals did not (Van Assche et al., 2013).

2.1.4 The present study

The present study has two aims. The first aim is to examine whole-language and item-specific inhibition in the context of the traditional cued language-switching paradigm (Experiment 1). According to Branzi et al. (2016), whole-language control is reflected in the after-effect of naming *any* item in the other language, whereas item-specific control is reflected in the after-effect of naming the *same* item in the other language. We now consider what type of inhibition is involved in *trial-to-trial switching* (i.e. comparing switch trials to stay trials). On a switch trial, the response language changes from the preceding trial, which means that any inhibition previously applied on this language needs to be overcome (Green, 1998); on a stay trial, the response language stays the same as the previous trial, therefore no such processes are required. The difference between a switch trial and a stay trial rests on whether there is a language change, regardless of what individual lexical items are involved on these trials. Therefore, if there is any inhibition applied in this type of switching, it most likely operates on the whole-language level (for similar reasoning, see Finkbeiner, Almeida, et al., 2006, Exp 1). Note that the costs of carrying out other switch-related processes (e.g. cue encoding, task goal updating) may also contribute to the switch cost; however, if there is a cost associated with overcoming whole-language inhibition on switch trials, this should at least form one component in the switch cost. In particular, if the time it takes to overcome such inhibition differs significantly between the two languages (e.g. due to stronger

inhibition applied on the dominant language, as Green proposed), then we expect the switch cost to be asymmetrical.

To examine item-specific inhibition in a similar manner, we incorporate a novel element into the study design, which we shall refer to as *within-item switching*. This type of switching occurs when the same item is named in one language after being named in the other language. Under the hypothesis that item-specific inhibition is present in bilingual control, when an item is named in a particular language, its translation-equivalent should be strongly suppressed, therefore when the latter subsequently becomes the target label on another trial, it will take extra time to overcome that prior inhibition. To index the cost of such item-specific inhibition, we look at the difference between two types of stimuli: univalent and bivalent⁵². A *univalent stimulus* always requires a response in the same language every time it appears; a *bivalent stimulus* requires responses in different languages on different trials. Thus, univalent stimuli are analogous to “stay” trials (i.e. they stay in the same language as the last time this item was named, so there is no item-specific inhibition to overcome), while bivalent stimuli are analogous to “switch” trials (i.e. they change to a different language compared to the last time this item was named⁵³, so any item-specific inhibition applied previously now has to be overcome). As explained above, in trial-to-trial switching, the process of overcoming whole-language inhibition forms a part of the switch cost; by a similar logic, in within-item switching, the process of overcoming item-specific inhibition should be a component in the *valence cost* (i.e. difference between bivalent and

⁵² When we talk about “univalent” and “bivalent” here, it is in regards to the context of this experiment. Technically, all these stimuli are bivalent to the bilinguals, as they are able to name each picture in both languages. The definitions used here are consistent with Finkbeiner, Almeida, et al. (2006).

⁵³ In the present experimental design, this is not guaranteed on all bivalent trials. However, it is true most of the time, as bivalent items are always named in the other language when they appear on filler trials, and there are twice as many fillers as critical trials in the testing block (see Section 2.2.1.3 for details on the experimental design and how the trial sequence is generated). If bivalent items are guaranteed to change language every time they appear on a critical trial, that should produce an even larger valence cost; the present design simply means that we are observing a smaller version of this effect.

univalent items). If the time it takes to overcome item-specific inhibition differs significantly for labels in the two languages (again, due to stronger inhibition applied on labels in the dominant language), then we expect the valence cost to be asymmetrical.

There is scant opportunity to examine the valence cost in the current language-switching literature, as existing studies typically employ bivalent stimuli only. The few studies that have used both univalent and bivalent stimuli in a language-switching paradigm focussed on the question of whether the asymmetrical switch cost was uniquely found in bivalent stimuli (e.g. Finkbeiner, Almeida, et al., 2006; Reynolds et al., 2016), rather than directly looking into the difference between these two types of stimuli as an index for item-specific inhibition. In the present study, we ask bilinguals to perform a picture-naming task, in which univalent and bivalent stimuli are combined seamlessly. In this task, half of the stimuli are univalent, each consistently eliciting responses in the same language every time it appears; the other half are bivalent, each imposing varied language requirements throughout the experiment. Univalent and bivalent stimuli are mixed together and appear under exactly the same circumstances, therefore the valence of each stimulus remains implicit in the eyes of the participants. This ensures that there is no confound between these two types of stimuli, thus allowing them to be compared directly (but see Section 2.4.3 for a possible improvement). By enabling such comparison between univalent and bivalent stimuli (i.e. a measurement of item-specific inhibition) alongside the comparison between stay and switch trials (i.e. a measurement of whole-language inhibition) within the same experimental task, the two levels of inhibition can be examined simultaneously and compared side by side.

The second aim of this study is to investigate the involvement of domain-general inhibitory control in language switching (Experiment 2). The motivation behind this is to verify the relevant theoretical accounts in neurocognitive models of bilingual

language control (e.g. Abutalebi & Green, 2007, 2008; Green & Abutalebi, 2013), and to provide more concrete empirical basis for (or against) the view that language control relies on executive function. An increasing amount of neuroimaging evidence now suggests that language switching recruits the brain network responsible for domain-general inhibition, and chief among these brain areas is the pre-SMA. While neuroimaging findings can only reveal an association between pre-SMA activity and inhibitory control in language switching, the role of this brain region in language control will be further confirmed if a causal relationship can be established. In Experiment 2, we explore whether such a causal relationship exists, by externally disrupting the excitability of the pre-SMA region and then examining the consequence on bilinguals' language switching performance. This disruption is achieved using a non-invasive brain stimulation technique called transcranial magnetic stimulation (TMS).

We examine the role of pre-SMA in language control with respect to the proposed distinction between whole-language and item-specific inhibition. As explained above, the present experimental design affords the ability to inspect both types of inhibition within the same task, thus providing an excellent opportunity to assess whether they share the same underlying neural mechanism. Experiment 1 aims to establish the presence of whole-language inhibition (as indexed by the switch cost) and item-specific inhibition (as indexed by the valence cost) in a picture-naming task, and then the same task is used in Experiment 2 to investigate whether either or both levels of inhibition are causally dependent on domain-general inhibitory control. Distinguishing between these two levels of control in language switching and examining the involvement of pre-SMA in each of them will provide more fine-grained information as to what exactly this brain region is responsible for in bilingual language control. This can help shed light on the specific role of the pre-SMA in language switching and inform future updates to neurocognitive models of bilingual speech production.

2.2 EXPERIMENT 1: WHOLE-LANGUAGE AND ITEM-SPECIFIC INHIBITION IN LANGUAGE SWITCHING

In this behavioural experiment, we aim to examine whole-language and item-specific inhibition side by side in a cued language-switching paradigm. We ask bilingual participants to perform a picture-naming task, in which they switch between English and Mandarin according to a cue on each trial. In this task, half of the pictures have consistent language mappings throughout the experiment (i.e. univalent items), and the other half have changing language requirements (i.e. bivalent items). With such a design, the cost of whole-language inhibition can be examined when the language requirement changes from one trial to the next (i.e. switch vs. stay trials), and the cost of item-specific inhibition can be assessed when the same picture elicits a response in one language after having been named in the other (i.e. bivalent vs. univalent items). Based on the hypothesis that both whole-language and item-specific control are at play during language switching, we predict the following: (1) an asymmetrical switch cost, which indexes the time it takes to overcome whole-language inhibition on switch trials, and (2) an asymmetrical valence cost, which indexes the time it takes to overcome item-specific inhibition on bivalent trials.

2.2.1 Materials and methods

2.2.1.1 Participants

Sixteen healthy adult Mandarin-English bilinguals participated in this study for course credits or monetary compensation. One participant was excluded from all analyses due to voice key issues during the experiment (see Section 2.2.1.5 for more details), so the final sample included fifteen participants (7 males; mean age 28.2 years). Bilinguals were required to be at least moderately proficient in both languages (a minimum self-rating of 4 out of 7, for each language). Participants

were free from speech or language impairments, and all had normal or corrected-to-normal vision. Informed consent was obtained from all participants. The study was approved by the human ethics committee of Macquarie University (#5201200035).

	Mean	SD
Age	28.2	5.8
Age of first exposure to Mandarin	1.9	2.9
Age of first exposure to English	10.0	3.0
Mandarin MINT score ^a	60.9	4.4
English MINT score ^a	53.4	6.3
Mandarin listening ability ^b	6.6	0.9
Mandarin speaking ability ^b	6.4	0.9
Mandarin reading ability ^b	6.7	0.8
Mandarin writing ability ^b	6.5	0.9
English listening ability ^b	5.5	0.9
English speaking ability ^b	5.0	0.8
English reading ability ^b	5.9	0.5
English writing ability ^b	5.0	0.6
Percent Mandarin use currently ^c	47.1	24.9
Percent English use currently ^c	48.9	20.6
Percent Mandarin use during childhood ^c	75.2	35.4
Percent English use during childhood ^c	8.4	9.6
Switching frequency currently ^d	4.2	1.2
Switching frequency in childhood ^d	2.1	1.5

Table 2-1. Characteristics of included participants in Experiment 1.

^a Maximum possible score in the MINT test is 68 for each language.

^b Language proficiency based on self-ratings on a 7-point scale: 1 = little to no knowledge, 7 = like a native speaker.

^c Percentages for Mandarin and English use did not add up to exactly 100 percent, as some participants reported also speaking another variant of Chinese.

^d Switching frequency based on self-ratings on a 6-point scale: 1 = never, 2 = very infrequently, 3 = occasionally, 4 = two to three times per conversation, 5 = several times per conversation, 6 = constantly.

Demographic information and language proficiency self-ratings were collected from all participants using a language history questionnaire (either completed at the end of the experiment, or online in their own time). The Multilingual Naming Test (MINT; Gollan, Weissberger, Runnqvist, Montoya, & Cera, 2012), a 68-item picture-naming test available in both English and Mandarin, was administered to each participant to obtain a more objective measurement of their language proficiency. The naming test was always given after the participant had completed the experimental task, to avoid any possible influence on their performance. A summary of participant characteristics is presented in Table 2-1.

These participants acquired Mandarin at an early age in a home setting or at the beginning of primary school, and they started learning English half way through primary school or from the beginning of high school. Three of the participants were slightly more dominant in English, while the rest were slightly more dominant in Mandarin⁵⁴. The participants switched languages quite regularly in everyday life. It is worth noting that most Mandarin speakers also speak another variant of Chinese, so it was not practical to recruit “pure” Mandarin-English bilinguals. However, we only included participants for whom Mandarin and English were their two strongest languages.

2.2.1.2 Materials

We selected eight black-and-white line drawings from the set of stimuli used in a previous language-switching study (Kleinman & Gollan, 2016). The following items were included⁵⁵: *hand-shǒu*, *door-mén*, *tree-shù*, *horse-mǎ*, *pencil-qiānbǐ*, *bone-gǔtóu*, *king-guówáng*, *grapes-pútao*. Each picture was to be named in English,

⁵⁴ It would be better if we had a balanced number of Mandarin-dominant and English-dominant bilinguals. However, this was not achievable due to recruitment constraints.

⁵⁵ The Mandarin names are presented here in hànǚ pīnyīn (the romanisation system for spelling out Mandarin sounds).

Mandarin or both in the experiment. Pictures were selected such that naming ambiguity (i.e. more than one possible name for a picture) was minimised in both languages, and no within-language or cross-language homophones existed among the sixteen possible target names. All target names in English were either one- or two-syllable words that were 4-6 letters long, and all target names in Mandarin were one- or two-character words (in Mandarin, one character is one syllable). We ensured that there was minimal semantic relatedness between any two pictures, so that the sequence of pictures could be fully randomised without the risk of any semantic interference effects on naming latencies.

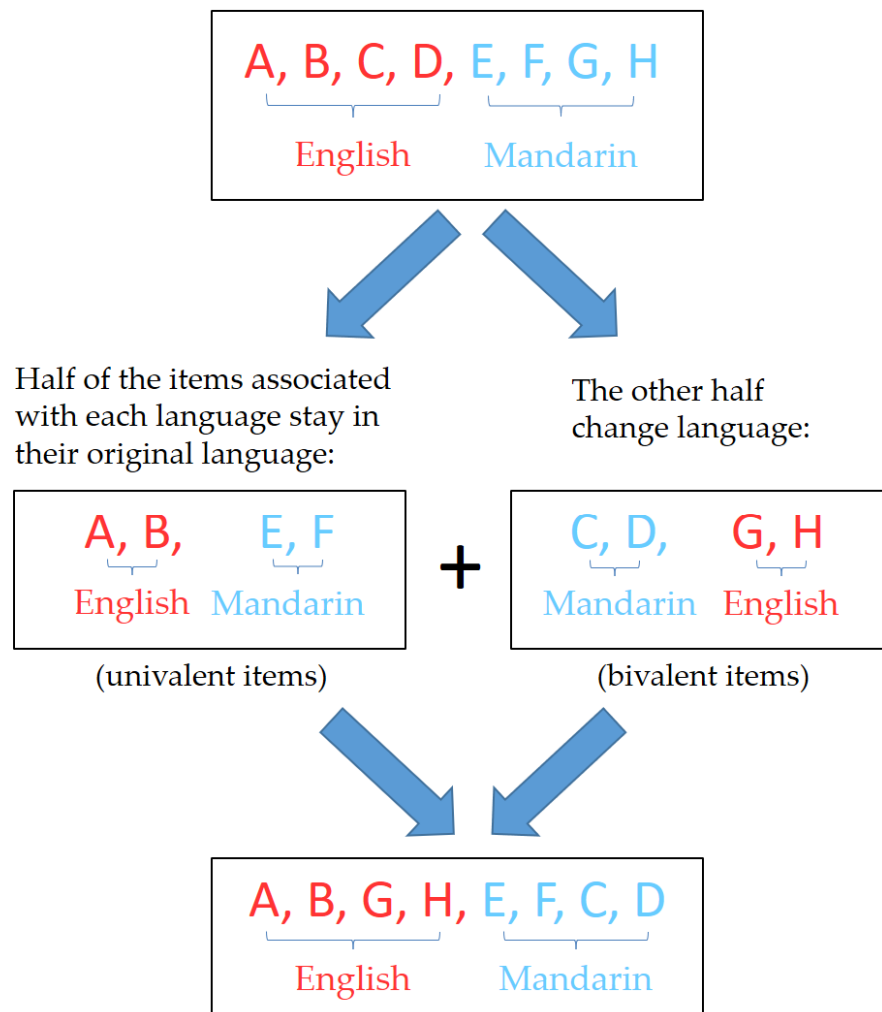
2.2.1.3 Design and procedure

The picture-naming task was designed to allow a direct comparison between univalent and bivalent items (to examine item-specific inhibition), and between stay and switch trials (to examine whole-language inhibition). The task consisted of a training block and a testing block. Each univalent item maintained consistent language requirement throughout the two blocks, while each bivalent item was trained on one language and tested in the other. Item-language pairings were randomly generated for each participant when the experiment started, such that four out of the eight pictures were associated with English and the other four with Mandarin. Next, out of the four pictures associated with each language, two were randomly selected to be univalent and the other two were assigned to be bivalent. In the training block, the original item-language pairings were followed. In the testing block, those pictures that were assigned to be bivalent changed their language requirement (i.e. if it was originally trained in English, it now required naming in Mandarin, and vice versa), while the univalent pictures stayed in their original language (see Figure 2-2). The language requirement on each trial was specified using a language cue, which appeared simultaneously with the picture stimulus. The language cue was either “*What is this?*”, indicating the response was

to be given in English, or the Chinese equivalent “*这是什么?*”, indicating a response in Mandarin was required. These language cues were designed to elicit responses in each language more naturally (compared to some commonly used cues, such as background colours or national flags), so as to minimise any cue-processing and related costs.

Participants were tested individually in a sound-attenuated room. Each session lasted approximately 35-45 minutes. The experiment was programmed in, and controlled by the Presentation software (Neurobehavioral Systems, Version 18.3). Stimuli were displayed on a Samsung SyncMaster SA950 (27 inch) monitor, connected to a Dell Optiplex 9010 PC (3.2GHz Intel i5-3470 CPU, 8GB RAM). Participants were seated comfortably in a chair 80cm away from the monitor. Vocal responses were recorded through a microphone, and a voice key was set up in Presentation to detect response onset. The microphone amplifier volume was adjusted individually for each participant to optimise the functioning of the voice key. Before the picture-naming task commenced, participants were given verbal and onscreen instructions, which asked them to name the pictures as quickly and accurately as possible according to the language cue on each trial. Instructions were followed by a short practice block, which consisted of the same stimuli used in the experiment proper. Each stimulus appeared twice in the practice block. The purpose of the practice block was to allow participants to familiarise themselves with the task, as well as to make sure they had no trouble naming each picture. After a short break, participants initiated the training block themselves by pressing a key when they were ready. A short break was given after the training block, and then participants initiated the testing block, again by pressing a key themselves.

Training
Block:



Testing
Block:

Figure 2-2. Illustration of the procedure used in Experiment 1 to achieve balanced assignments of language and valence to the picture stimuli. A total of eight pictures were used in this experiment. Here each letter (e.g. 'A') represents one picture item. Items associated with English are shown in red; items associated with Mandarin are shown in blue. Univalent items maintained consistent language requirement in the two blocks, while bivalent items were trained and tested in opposite languages. Item-language pairings for the training block were randomly generated for each participant, such that four out of the eight pictures were associated with English and the other four with Mandarin (*top row*). Next, out of the four pictures associated with each language, two were randomly selected to be univalent and the other two were assigned to be bivalent. The language requirement for each bivalent item was changed (*middle row*). This produced the set of item-language associations to be used in the testing block (*bottom row*).

In the training block, each picture stimulus appeared 12 times. Pictures were presented in a random order for each participant, with the constraints that each picture appeared an equal number of times on stay trials and switch trials, and that no two consecutive trials had the same picture. In the testing block, trials were presented in the form of triads (i.e. groups of three), similar to the quartet structure used by Finkbeiner, Almeida, et al. (2006). In the triad structure, each (critical) trial was preceded by two filler trials. These two fillers always required responses in the same language, which served to ensure that each critical trial had a run-length of two (i.e. a switch trial would not directly follow another switch trial, which could result in a "stacked" effect). Thus, an example of a stay trial could be English -> English -> English, and a switch trial could be Mandarin -> Mandarin -> English. Each target picture stimulus appeared 12 times on critical trials (six stay trials and six switch trials), resulting in a total of 96 critical trials. As language and valence were already assigned earlier to all picture items in a random and balanced manner, this created critical trials that were fully balanced across language, valence, and transition type (stay vs. switch), eliminating possible bias due to factors other than the variables of interest. In addition, the same eight picture stimuli were used on the filler trials, so each picture appeared 24 times as a filler. The fillers appeared no different to critical trials from the participants' perspective, but were not included in the data analysis. The triads were constructed in such a way that there was no repetition of pictures within each triad, and then all the triads were presented to the participant in a random sequence. The use of filler trials allowed dynamic sequences to be generated for each participant on the fly, and further ensured participants would not be able to make predictions about the upcoming trial (as fillers were indistinguishable from critical trials). To avoid the naming of bivalent items on filler trials potentially overriding the training effect (and to maintain the bivalency throughout the testing block), filler trials used the original item-language

pairings consistent with the training block. Thus, opposite languages were required on filler and critical trials for bivalent items⁵⁶.

The trial structure is shown in Figure 2-3. Each trial started with a fixation cross which appeared at the centre of the screen for 350 ms. This was followed by a blank screen for 150 ms, before the language cue and picture stimulus appeared simultaneously on screen. The picture was displayed at the centre of the screen, while the language cue was located above it. Sound recording started as soon as the stimulus appeared. The trial was terminated upon the voice key being triggered by a response, or 3 seconds after stimulus onset if no response was detected. The inter-trial interval lasted 850 ms, during which a blank screen was displayed, and then the next trial started. The vocal response on each trial was saved as an individual wave file for later verification.

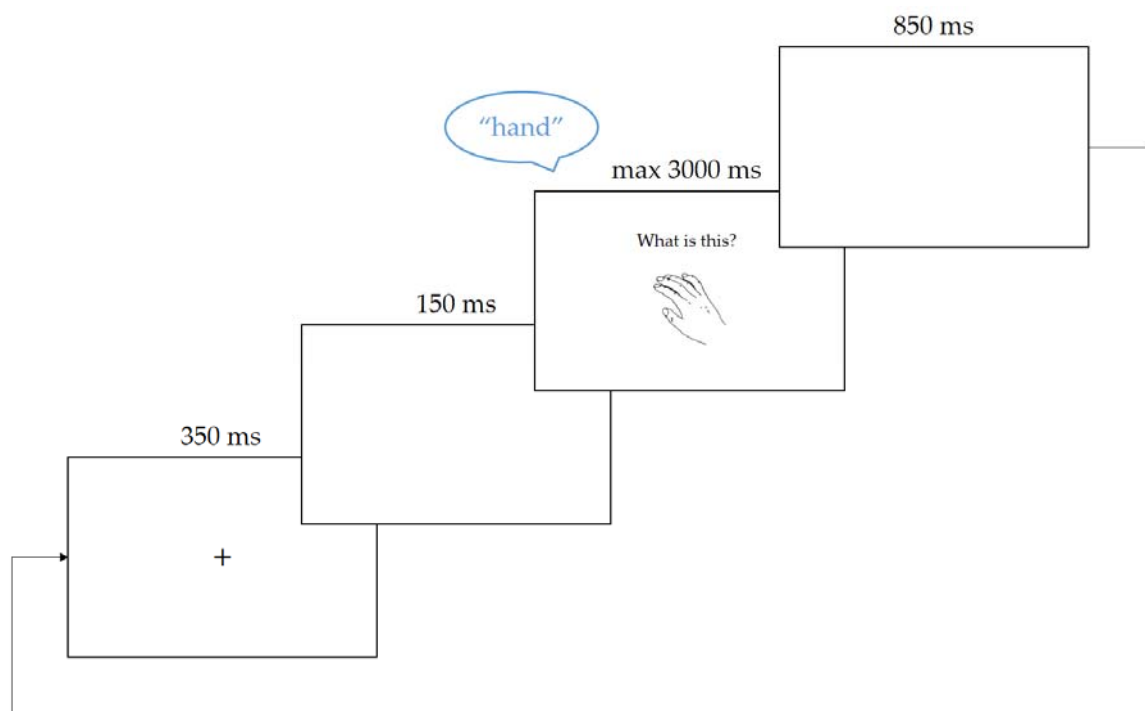


Figure 2-3. An example of a naming trial, showing the sequence of frames and the display of language cue ("What is this?") and target stimulus (the picture of the hand). This example trial requires the response "hand" in English.

⁵⁶ Note that the filler trials alone may be sufficient to create the bivalency, which means the training block may be redundant.

2.2.1.4 Offline processing

The voice key in Presentation was triggered when the input speech volume from the microphone reached a certain threshold. This was intended to serve two purposes in the experiment: ending the current trial when a response is detected, and automatically reporting a reaction time (RT) value for each trial. While the speech detection was good enough for ending trials, the RT output (in milliseconds) did not reach the expected level of accuracy (i.e. the detected RTs did not consistently align with response onset across all trials). In order to obtain more accurate RT values, all of the wave files were processed offline using in-house software for speech onset detection. The detection output for each wave file was visualised as a graph and visually inspected to ensure accuracy. Any inaccurately detected RTs were identified and those trials were subsequently excluded from the RT analysis.

Error coding was performed manually for all trials by checking the sound recording against the target response. The definition of "error" used here was a broad one, which included incorrect responses as well as all verbal disfluencies (e.g. partial responses, stuttering, and utterance repairs). If the participant started giving the correct response but hesitated before having sounded out the complete word, or if they started to make a mistake but quickly corrected themselves, these were all counted as error trials. In other words, only straight-forward correct responses were scored as correct. The reasoning is that those disfluencies represent cases of high conflict (which we are interested in for the same reason that we are interested in error trials), and determining which of these trials should be classified as correct and which as error often must involve subjective interpretation of the response given.

One participant was excluded from all data analyses due to heavy breathing triggering the voice key on a large number of trials. Even though this did not affect the RT values (as speech onsets were correctly detected by the post-processing

procedure described above), the early triggering of voice key meant that the trial ended (and stimulus disappeared) before an actual response was produced. This could affect the RT for the current trial in unknown ways. Moreover, the early ending of trials resulted in shortened inter-trial interval (which started as soon as each trial ended), and it appeared that there was insufficient time following these trials for the participant to get ready for the upcoming trial.

2.2.1.5 Data analysis

All error trials were excluded from the RT analysis. We also excluded the trials identified earlier with inaccurately detected RTs, and trials with RTs outside 2.5 SD of each participant's mean. Statistical analyses were performed in R (Version 3.4.4; R Core Team, 2018) using the "lme4" package (Bates, Maechler, Bolker, & Walker, 2015). The RT and error data were submitted to 2 x 2 x 2 linear mixed-effects models with the following factors: "valence" (univalent vs bivalent items), "transition type" (stay vs switch trials), "language" (L1 vs L2), and the interactions between them were included as fixed effects; "participant" and "item" were included as random effects (random intercepts only, as the inclusion of random slopes did not improve model fit). For any follow-up tests conducted to unpack interactions, the p -values were adjusted using Bonferroni correction. Effects were categorised as significant at $p < .05$ and marginally significant at $p < .1$.

The analysis of RT data was conducted using both the raw values and log-transformed values. The latter was an attempt to satisfy the "normality of residuals" assumption of the linear model; however, the resulting model did not seem to meet this requirement (Shapiro-Wilk test: $p < .0001$; Kolmogorov-Smirnov test: $p < .0001$). It has been argued that log-transformation does not always achieve such purpose, in which case it may be more appropriate to apply statistical methods that do not come with these assumptions (Feng et al., 2014). Therefore, we also conducted permutation tests to estimate the p -values for the model terms. This is

a popular non-parametric method which does not assume any particular underlying data distribution (see Kherad-Pajouh & Renaud, 2010). The permutation tests were conducted on RT data using the “permanova.lmer” function in the R package “predictmeans” (Luo, Ganesh, & Koolaard, 2014). All versions of analysis (raw RT, log-transformed RT, and permutation tests) agreed in terms of which effects were significant and which were not, but the exact statistical values differed. We report the raw RT version in the in-text description below and include all versions of results in Appendix A.

2.2.2 Results

Following the trial exclusion procedure described above, approximately 10.7% of trials were excluded from the RT analysis. Mean reaction time and error rate in each condition are shown in Table 2-2. Statistical analyses were performed on single-trial RT and error data.

(A) Reaction times (ms)					(B) Error rates			
	<i>Univalent</i>		<i>Bivalent</i>		<i>Univalent</i>		<i>Bivalent</i>	
	<i>L1</i>	<i>L2</i>	<i>L1</i>	<i>L2</i>	<i>L1</i>	<i>L2</i>	<i>L1</i>	<i>L2</i>
Stay	694	661	883	769	1.1%	1.7%	16.7%	11.7%
Switch	714	685	888	802	3.9%	1.7%	21.1%	13.9%

Table 2-2. Mean reaction times and error rates in each condition in Experiment 1: “valence” (univalent vs bivalent items) x “response language” (L1 vs L2) x “transition type” (stay vs switch trials).

The RT analysis revealed significant main effects of valence, transition type, and response language. Bivalent items were named more slowly than univalent items (mean difference 165 ms; $\chi^2(1) = 215.7919$, $p < .0001$). Responses were slower on switch trials compared to stay trials (19 ms; $\chi^2(1) = 6.6664$, $p = .0098$). Naming in L1 took longer than in L2 (60 ms; $\chi^2(1) = 27.7909$, $p < .0001$). Importantly, there

was a significant interaction between valence and language, such that the RT difference between bivalent and univalent items (i.e. valence cost) was larger in L1 (218 ms) than in L2 (116 ms): $\chi^2(1) = 9.1807, p = 0.0024$. Follow-up tests revealed that the valence cost was significant within each language (L1: $t = 12.203, p < .0001$; L2: $t = 8.477, p < .0001$). The p -values in follow-up tests were adjusted for multiple comparisons using Bonferroni correction. No other interactions were significant in the RT analysis.

The error analysis showed significant main effects of valence and response language. Participants made more errors on bivalent items compared to univalent items (mean difference 13.6%; $\chi^2(1) = 56.2991, p < .0001$), and they made more errors when responding in L1 compared to L2 (3.3%; $\chi^2(1) = 5.0815, p = .0242$). The main effect of transition type was not significant in the error analysis, nor were any of the interactions between factors.

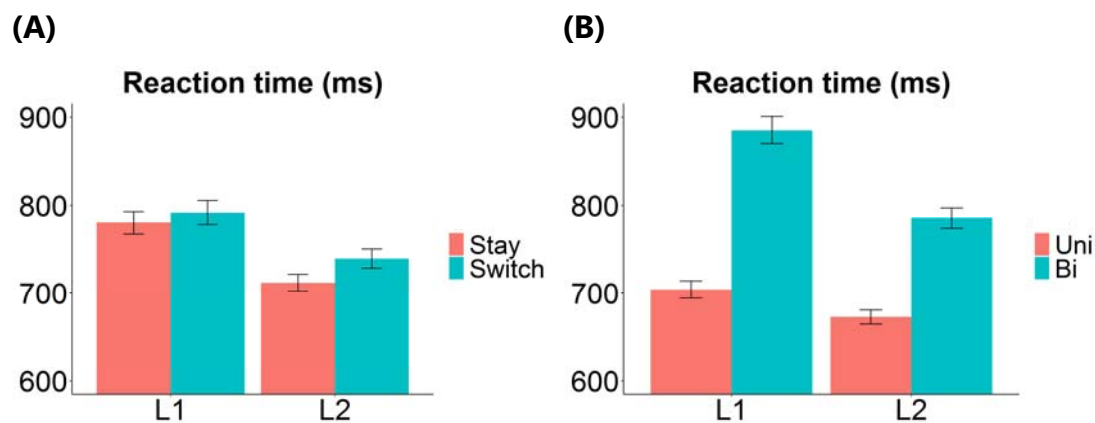


Figure 2-4. Switch cost and valence cost in Experiment 1. **(A)** Reaction time as a function of “response language” (L1 vs L2) and “transition type” (stay vs switch trials). The switch cost was symmetrical between the two languages. **(B)** Reaction time as a function of “response language” (L1 vs L2) and “valence” (univalent vs bivalent items). The valence cost was significantly larger in L1 compared to L2. Error bars indicate one standard error above and below the means. Uni = univalent items; Bi = bivalent items.

2.2.3 Discussion

In this experiment, we aimed to examine whole-language inhibition (via trial-to-trial switching) and item-specific inhibition (via within-item switching) side by side in a cued language-switching task. The main effects of transition type and valence were significant, demonstrating that switch trials were more difficult than stay trials, and naming bivalent items was more difficult than naming univalent items. As explained earlier (see Section 2.1.4), the presence of switch cost and valence cost alone does not necessarily mean there is inhibition involved - the switch cost may capture other processes related to switching (e.g. cue encoding, task goal updating), and the valence cost may reflect other differences between univalent and bivalent items (e.g. the target labels for univalent items might benefit more from repetition priming, since they are repeated more frequently than the target labels for bivalent items⁵⁷). A key marker for inhibition would be identified if these costs were asymmetrical between the two languages.

Here we observed an asymmetrical valence cost, where the RT difference between bivalent and univalent items was found to be larger in L1 (Figure 2-4 B). The valence cost was nonetheless significant in L2. The most straight-forward explanation for the asymmetry is that stronger item-specific inhibition was applied on the competing L1 labels when bivalent items were named in L2 than vice versa; as a result, it took longer to overcome the prior item-specific inhibition when bivalent items were to be named in L1 again. Other possible components of the valence cost are unlikely to generate such an asymmetry. For example, differential amount of repetition priming may cause univalent items to be named faster and more accurately than bivalent items, but such repetition should benefit L1 and L2 equally

⁵⁷ This is a potential limitation in the present experimental design. Because a univalent stimulus is always named in the same language, its appearance on filler trials and in the training block results in a lot more repetitions of the target label. On the other hand, a bivalent stimulus is named in one language when it appears on critical trials, and in the other language when it appears on filler trials and in the training block, therefore the latter does not contribute to repetitions of the target label. We discuss this issue in more details in Section 2.4.3.

(i.e. the valence effect should not interact with language); alternatively, it may benefit the L2 more (as that is the less practiced language), in which case the valence cost should be larger for L2. These possibilities are inconsistent with our observation of a larger valence cost in L1.

Interestingly, we observed symmetrical switch cost between the two languages (Figure 2-4 A). This suggests that either whole-language inhibition did not occur in trial-to-trial switching, or the strength of the whole-language inhibition was similar between L1 and L2. Given that our participants were relatively proficient in their L2 (compared to most studies where switch cost asymmetry was found), the latter is likely to be true. Moreover, we observed a reversed dominance effect, i.e. L1 naming was overall significantly slower than L2 naming (on both stay and switch trials). Such a pattern is usually found in cases where the switch cost asymmetry is absent (e.g. Costa & Santesteban, 2004; Christoffels et al., 2007; Gollan & Ferreira, 2009; Verhoef et al., 2009; Martin et al., 2013), and it is often interpreted as evidence for sustained inhibition of L1 in a mixed-language production context (Kroll et al., 2008; Gollan et al., 2014; Bobb & Wodniecka, 2013). Note though that the reversed dominance effect here may be driven entirely by the bivalent items (see Figure 2-4 B), so it should be interpreted with caution. We defer further discussions about this to Section 2.4.1.

2.3 EXPERIMENT 2: DOMAIN-GENERAL INHIBITORY CONTROL IN LANGUAGE SWITCHING

In Experiment 1, we examined whole-language and item-specific inhibition in a picture-naming task with cued language switching. We set out to investigate whether both types of inhibition were involved in this task, and if so, to find a behavioural index for each. We observed an asymmetrical valence cost as predicted, suggesting that item-specific inhibition was present and the amount of

inhibition applied on L1 labels were stronger than on L2 labels. On the other hand, symmetrical switch cost was observed between the two languages. While this could be explained by a complete lack of whole-language inhibition, it is more likely that the inhibition on both languages were simply of similar strength (see discussions in Section 2.2.3). In this case, whole-language inhibition would still be a component in the switch cost.

In this experiment, we investigate the neural mechanisms underlying whole-language and item-specific inhibition. In particular, we are interested in whether one or both of them engages domain-general inhibitory control. De Groot and Christoffels (2006) propose that these two types of control operate at different times and serve distinct purposes in lexical selection; therefore, it is likely that they operate via different neural mechanisms. We examine a particular brain area known for its role in domain-general inhibitory control: the pre-SMA. This brain region has frequently been found to activate during language switching, which suggests its possible involvement in performing inhibition in language control. However, it remains unclear whether the pre-SMA plays a *causal* role in language inhibition, and if so, what its precise function is. Using the same picture-naming task as Experiment 1, we investigate these questions by perturbing the pre-SMA via a repetitive TMS protocol and observing the effect on whole-language and item-specific inhibition. As explained in Section 2.1.4, whole-language inhibition forms a component of the switch cost, while item-specific inhibition forms a component of the valence cost. If the pre-SMA plays a causal role in either type of inhibition, then TMS should modulate the corresponding type of cost (or the asymmetry of it). This would allow us to pinpoint which level of language control relies on the pre-SMA, and infer more precisely the role of this brain region in language switching. Based on previous findings from a different paradigm, we predict that the pre-SMA has a more prominent role in item-specific control (Branzi et al., 2016).

2.3.1 Materials and methods

2.3.1.1 *Participants*

Sixteen healthy adult Mandarin-English bilinguals (5 males; mean age 24.6 years) participated in this study for course credits or monetary compensation. All participants were right-handed; they were free from any neurological disorders and met the safety requirements for undergoing MRI and TMS. Participants were not taking any psychiatric medication, and all had normal or corrected-to-normal vision. Each participant gave informed consent before taking part in the experiment. The study was approved by the human ethics committee of Macquarie University (#5201400585).

Individual high-resolution T1-weighted brain MRI images were obtained for each participant for the purpose of localising the target area for TMS. Each participant was then tested in two separate TMS sessions, which were scheduled at least one week apart. The TMS sessions were all scheduled in the afternoon, and the two sessions for the same participant always took place around the same time of day (with at most one-hour difference between the starting time) to minimise possible influence of circadian rhythm on the efficacy of TMS (Sale, Ridding, & Nordstrom, 2008). Testing order was fully counterbalanced in regards to TMS order (pre-SMA stimulation in first session, or control site in first session).

Demographic information and language proficiency self-ratings were collected from all included participants via a language history questionnaire. The MINT test (Gollan et al., 2012) was also administered to each participant to obtain a more objective assessment of their proficiency in each language; this test was always done at the end of the second TMS session, to avoid having any possible influence on their performance during the experimental tasks. A summary of participant characteristics is presented in Table 2-3.

	Mean	SD
Age	24.6	4.9
Age of first exposure to Mandarin	1.5	2.3
Age of first exposure to English	8.6	3.8
Mandarin MINT score ^a	60.8	4.5
English MINT score ^a	47.4	8.4
Mandarin listening ability ^b	6.8	0.7
Mandarin speaking ability ^b	6.6	0.9
Mandarin reading ability ^b	6.8	0.5
Mandarin writing ability ^b	6.5	0.9
English listening ability ^b	5.4	0.9
English speaking ability ^b	4.9	1.1
English reading ability ^b	5.4	0.9
English writing ability ^b	4.9	1.0
Percent Mandarin use currently ^c	61.2	21.9
Percent English use currently ^c	35.4	17.1
Percent Mandarin use during childhood ^c	81.9	22.9
Percent English use during childhood ^c	10.6	11.0
Switching frequency currently ^d	3.8	1.1
Switching frequency in childhood ^d	2.0	1.1

Table 2-3. Characteristics of included participants in Experiment 2.

^a Maximum possible score in the MINT test is 68 for each language.

^b Language proficiency based on self-ratings on a 7-point scale: 1 = little to no knowledge, 7 = like a native speaker.

^c Percentages for Mandarin and English use did not add up to exactly 100 percent, as some participants reported also speaking another variant of Chinese.

^d Switching frequency based on self-ratings on a 6-point scale: 1 = never, 2 = very infrequently, 3 = occasionally, 4 = two to three times per conversation, 5 = several times per conversation, 6 = constantly.

2.3.1.2 Target localisation

The pre-SMA is a small cortical region located on the medial frontal cortex (very close to the midline between the two hemispheres of the brain). The fMRI studies that identified activation of this area in language switching simply referred to it as

“pre-SMA” (without stating whether it is the left or right side), and a meta-analysis summarised this as “midline pre-SMA” (Luk et al., 2012). However, a precise target location is required for TMS, as stimulating on the midline (i.e. on top of the medial longitudinal fissure) would likely result in ineffective stimulation of either the left or right pre-SMA. The right pre-SMA was chosen in this study because it is more commonly accepted as part of the inhibitory control network (see Cai, George, Verbruggen, Chambers, & Aron, 2012).

A high-resolution T1-weighted structural brain MRI scan (slice thickness: 1 x 1 x 1 mm) was obtained for each participant (Macquarie Medical Imaging, Macquarie University Hospital, Sydney). The images were firstly reoriented as necessary such that the head was upright and the anterior commissure (AC) and posterior commissure (PC) were on the same horizontal line. The pre-SMA was then located anatomically, using a procedure similar to that described by Tremblay and Gracco (2009). We adapted this procedure to locate the right rather than the left pre-SMA. A vertical line was drawn 10mm anterior to the AC, forming a coronal plane which intersects the cerebral cortex at the top. The right pre-SMA was identified as a point along the intersection on the medial most portion of the right superior frontal gyrus (SFG). The coordinates of this point were noted and a white spherical blob was drawn onto the MRI at this position using an in-house Matlab script (Figure 2-5).



Figure 2-5. The position of right pre-SMA marked on the individual MRI scan.

Localisation of TMS target on the participant was guided by a frameless stereotaxic system (Visor2, ANT Neuro, Enschede, Netherlands; <http://www.ant-neuro.com>). The MRI images for each individual participant were loaded into the navigation system and a 3D model of the head and brain was reconstructed from these images. The target location was then marked in the system at the location of the white blob drawn earlier. During each TMS session, an MRI coregistration procedure was performed to link the 3D model to the participant's head in real space. The participant wore a headband with reflective spherical markers, which were tracked by the navigation system. The navigation system then guided the placement of the coil over the predefined target location.

The vertex, which served as the control site, was defined as the halfway point between the nasion and inion (Cai et al., 2012). This location was determined with tape measurement and the desired coil position was marked for later use. For both stimulation sites, the coil was held with the handle pointing in the posterior direction. The same MRI coregistration procedure and tape measurement were carried out during both the experimental session and control session to make the two sessions appear identical from the participant's perspective, and participants were told that two areas of interest were being investigated. During the debriefing at the end of the entire study, participants reported similar sensations from TMS during both sessions, and some expressed surprise upon learning that one of these sessions was the control condition. When asked to guess which session was experimental and which was control, they were unable to tell (more than half gave the incorrect answer).

2.3.1.3 TMS Procedure

Magnetic stimulation was delivered using a Magstim Rapid2 stimulator (Magstim Co., Whitland, UK), with a hand-held 70-mm figure-of-eight coil. Resting motor threshold (RMT) was determined individually for each participant. The RMT was

defined as the minimum intensity applied on the right primary motor cortex (M1) to elicit three visible twitches on the contralateral first dorsal interosseous (FDI) muscle out of five consecutive stimuli. Participants were instructed to keep their hand muscles relaxed while the RMT was determined.

Continuous theta-burst stimulation (cTBS; Huang, Edwards, Rounis, Bhatia, & Rothwell, 2005) was used to achieve transient suppression of the right pre-SMA. This is a repetitive TMS protocol capable of inducing a reduction of cortical excitability thought to be mediated by long-term-depression-like mechanisms (Huang, Chen, Rothwell, & Wen, 2007). Suppressive effects of cTBS on pre-SMA excitability has previously been demonstrated (e.g. Dietrich, Hertrich, Ackermann, Ziemann, & Müller-Dahlhaus, 2015). In the cTBS protocol, each burst consisted of 3 pulses delivered at 50Hz, and the bursts were repeated at 5Hz. As such, a total of 600 pulses were delivered over a period of 40 seconds. In accordance with previous studies (e.g. Chiou, Sowman, Etchell, & Rich, 2014), stimulation intensity for each individual was calculated as 80% of their RMT⁵⁸.

2.3.1.4 Behavioural task

The behavioural task was the same picture-naming task used in Experiment 1, with identical materials and procedure. After the RMT was determined and MRI coregistration was performed, the participant was given verbal and onscreen instructions for the task and completed the first part of picture naming (i.e. the training block). The coregistration accuracy was checked (by validating the nasion position) immediately before TMS to ensure the navigation markers worn on the participant's head did not move relative to the head (in one case where the

⁵⁸ The participants in this study had rather high RMT in general (this may be race-related, see Yi et al., 2014). Due to capacity limit on the stimulator, the maximum output intensity achievable in the cTBS protocol was 51%. For participants whose calculated intensity exceeded this limit, they were stimulated at 51%. We discuss this further in Section 2.4.3.

validation failed, the coregistration procedure was carried out again before TMS). Then, cTBS was delivered for 40 seconds and the participant was instructed to rest for 5 minutes without talking. This waiting time was based on observations on the after-effects of cTBS over M1, where the modulation of motor evoked potentials (MEP) was found to be most reliable at 5 minutes post-stimulation (Vernet et al., 2014). After the 5-minute waiting time, the participant was instructed to proceed to the second part of picture naming (i.e. the testing block).

To make the results from the two TMS sessions more comparable and to ensure there was no contradicting training effects during the two sessions, the same item-language pairings and item-valence assignment were maintained for each individual. In the first TMS session, the pairings were randomly generated just as in Experiment 1; in the second session, the previously generated pairings were used instead of new pairings being created.

2.3.1.5 Data analysis

The procedures for offline RT detection, error coding, and trial exclusions were identical to Experiment 1. Each participant underwent two test sessions in this experiment (TMS stimulation on pre-SMA and vertex), so a new factor was introduced into the analysis. RT and error data were submitted to $2 \times 2 \times 2 \times 2$ linear mixed-effects models: "TMS location" (pre-SMA vs control site), "valence" (univalent vs bivalent items), "transition type" (stay vs switch trials), "language" (L1 vs L2), and the interactions between these were included as fixed effects; "participant" and "item" were included as random effects (random intercepts only, as the inclusion of random slopes did not improve model fit). Effects were categorised as significant at $p < .05$ and marginally significant at $p < .1$.

As with Experiment 1, the analysis of RT data was conducted using both the raw values and log-transformed values. Since the "normality of residuals" assumption

of the linear model was not satisfied even after log transformation, we again conducted permutation tests as an additional check. The results from the analyses of raw RT and log-transformed RT agreed on all effects, except a marginal interaction which was only present in the raw RT version. In the permutation tests, this interaction was found to be marginally significant (i.e. agreeing with the raw RT results). In the section below, we report the statistical values from the raw RT analysis, and we include all versions of results in Appendix B.

2.3.2 Results

Following the trial exclusion procedure described in Experiment 1, approximately 16.3% of trials were excluded from the RT analysis. Mean reaction time and error rate in each condition are shown in Table 2-4. Statistical analyses were performed on single-trial RT and error data.

(A) Reaction times (ms)

	Control site				pre-SMA			
	<i>Univalent</i>		<i>Bivalent</i>		<i>Univalent</i>		<i>Bivalent</i>	
	<i>L1</i>	<i>L2</i>	<i>L1</i>	<i>L2</i>	<i>L1</i>	<i>L2</i>	<i>L1</i>	<i>L2</i>
Stay	598	588	759	727	606	602	778	756
Switch	616	611	744	731	628	618	791	773

(B) Error rates

	Control site				pre-SMA			
	<i>Univalent</i>		<i>Bivalent</i>		<i>Univalent</i>		<i>Bivalent</i>	
	<i>L1</i>	<i>L2</i>	<i>L1</i>	<i>L2</i>	<i>L1</i>	<i>L2</i>	<i>L1</i>	<i>L2</i>
Stay	3.1%	1.0%	23.4%	24.0%	3.1%	0.5%	34.9%	17.7%
Switch	4.2%	3.1%	32.8%	26.0%	5.2%	2.1%	27.1%	26.0%

Table 2-4. Mean reaction times and error rates in each condition in Experiment 2: "TMS location" (control site vs pre-SMA) x "valence" (univalent vs bivalent items) x "response language" (L1 vs L2) x "transition type" (stay vs switch trials).

The RT analysis revealed significant main effects of TMS location, valence, transition type, and response language. Perturbation of the pre-SMA resulted in longer naming latencies compared to control site stimulation (mean difference 21 ms; $\chi^2(1) = 10.2989, p = .0013$). Bivalent items were named more slowly than univalent items (149 ms; $\chi^2(1) = 516.1176, p < .0001$). Responses were slower on switch trials compared to stay trials (13 ms; $\chi^2(1) = 5.8391, p = .0157$). Naming in L1 took longer than in L2 (12 ms; $\chi^2(1) = 9.4246, p = .0021$). As in Experiment 1, there was a significant interaction between valence and language, such that the RT difference between bivalent and univalent items (i.e. valence cost) was larger in L1 (156 ms) compared to L2 (143 ms): $\chi^2(1) = 5.1166, p = .0237$. Follow-up tests revealed that the valence cost was significant within each language (L1: $t = 17.558, p < .0001$; L2: $t = 14.878, p < .0001$). There was also a marginally significant interaction between valence and TMS location, with the valence cost being larger when pre-SMA was perturbed (160 ms) compared to control site (137 ms): $\chi^2(1) = 3.5719, p = .0588$. Follow-up tests revealed that the valence cost was significant in each condition (pre-SMA: $t = 17.740, p < .0001$; control site: $t = 14.952, p < .0001$). The p -values in follow-up tests were adjusted for multiple comparisons using Bonferroni correction. No other interactions were significant in the RT analysis.

The error analysis showed significant main effects of valence, transition type, and response language. Participants made more errors on bivalent items compared to univalent items (mean difference 23.7%; $\chi^2(1) = 233.9853, p < .0001$), more errors on switch trials than stay trials (2.3%; $\chi^2(1) = 3.9657, p = .0464$), and more errors when responding in L1 compared to L2 (4.2%; $\chi^2(1) = 10.5175, p = .0012$). There was also a 3-way interaction between TMS location, transition type and language: $\chi^2(1) = 7.0611, p = .0079$. Follow-up tests showed that there was no switch cost asymmetry (i.e. 2-way interaction between transition type and language) either when the pre-SMA was perturbed ($z = 1.430, p = .1528$) or when the control site was perturbed ($z = 0.398, p = .6909$). No other main effects or interactions were significant in the error analysis.

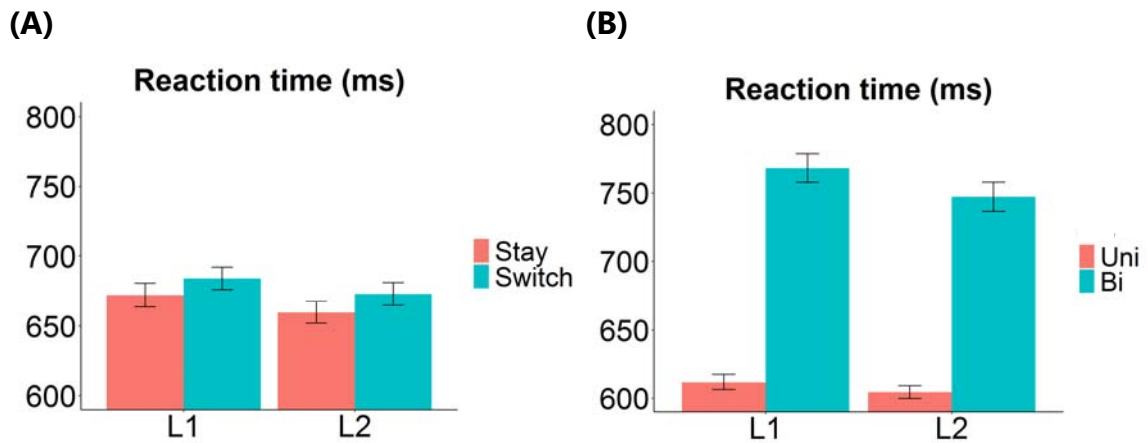


Figure 2-6. Switch cost and valence cost in Experiment 2. **(A)** Reaction time as a function of “response language” (L1 vs L2) and “transition type” (stay vs switch trials). The switch cost was symmetrical between the two languages. **(B)** Reaction time as a function of “response language” (L1 vs L2) and “valence” (univalent vs bivalent items). The valence cost was asymmetrical (larger in L1). Error bars indicate one standard error above and below the means. Uni = univalent items; Bi = bivalent items.

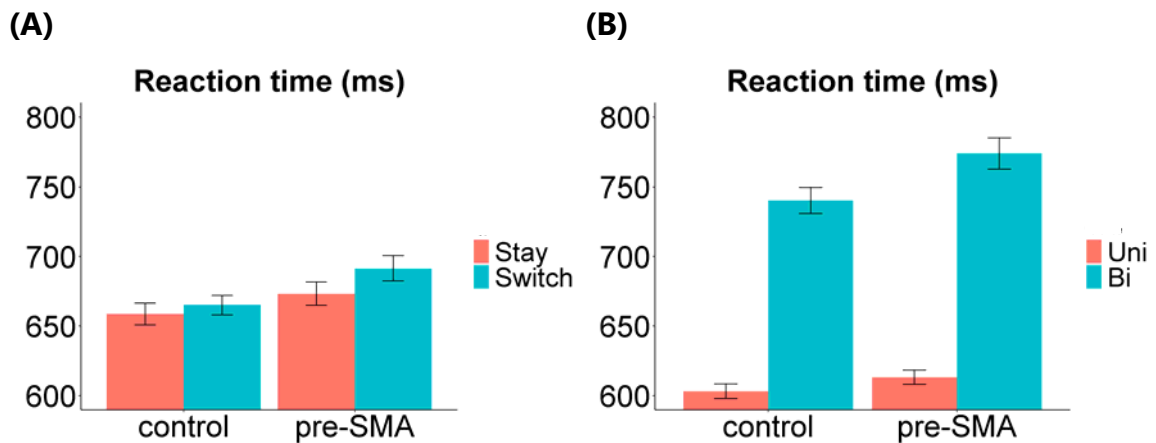


Figure 2-7. The effect of TMS stimulation on the switch cost and valence cost in Experiment 2. **(A)** Reaction time as a function of “TMS location” (control site vs pre-SMA) and “transition type” (stay vs switch trials). TMS did not significantly modulate the switch cost. **(B)** Reaction time as a function of “TMS location” (control site vs pre-SMA) and “valence” (univalent vs bivalent items). The valence cost was larger when TMS was applied on the pre-SMA (marginally significant interaction). Error bars indicate one standard error above and below the means. Uni = univalent items; Bi = bivalent items.

2.3.3 Discussion

The purpose of this experiment was to investigate the involvement of domain-general inhibitory control in language switching. In particular, we examined whether the pre-SMA had an essential role in whole-language and/or item-specific inhibition. Using the same behavioural task as Experiment 1, bilingual participants named pictures and switched between English and Mandarin according to the language cue on each trial. Participants' performance from two TMS sessions (pre-SMA and vertex perturbation) were compared to see if the disruption of pre-SMA activity had any impact on language switching. The cTBS protocol was intended to induce a reduction of cortical excitability at the stimulation site, resulting in a suppressive effect on that brain region. The use of a control site (vertex) as baseline allowed a direct examination of the consequence of target site (pre-SMA) stimulation, without the risk of the observed effect being an artefact (e.g. merely a generic effect of applying TMS).

All the findings from Experiment 1 were replicated here, including the behavioural indices for whole-language and item-specific inhibition. The main effects of both valence and transition type were significant, signifying the presence of a switch cost and a valence cost. The valence cost was asymmetrical between the two languages (larger in L1), suggesting that there was stronger item-specific inhibition applied on L1 labels compared to L2 labels (Figure 2-6 B). While the switch cost was symmetrical, we again observed a reversed dominance effect (Figure 2-6 A), which is an indication of sustained inhibition of L1 (see Section 2.2.3 for detailed discussions on these interpretations).

The disruption of pre-SMA activity using TMS had an overall impact on participants' performance. Naming on all trials was slowed by the perturbation of pre-SMA (compared to control site). This observation aligns with the reported involvement of this brain region in word selection and speech execution in general (Alario, Chainay, Lehericy, & Cohen, 2006; Van Heuven, Schriefers, Dijkstra, & Hagoort,

2008; Price, 2010). We attempted to pinpoint the role of the pre-SMA in bilingual control by assessing how its disruption affected the switch cost and the valence cost. According to the rationale laid out earlier, if the pre-SMA plays a causal role in item-specific inhibition (which is indexed by a component in the valence cost), then TMS should modulate the valence cost or its asymmetry between the two languages. Similarly, if the pre-SMA plays a causal role in whole-language inhibition (which is indexed by a component in the switch cost), then TMS should modulate the switch cost or its (lack of) asymmetry. We discuss the relevant findings below.

There was a marginally significant interaction between TMS location and valence, with the valence cost being larger when the pre-SMA was perturbed (Figure 2-7 B). This indicates a possible role of the pre-SMA in item-specific inhibition, which is consistent with Branzi et al. (2016), who suggest that the dorsal-ACC/pre-SMA complex is specifically recruited to handle increased monitoring demands in item-specific control. If this interaction is real, what did the disruption of pre-SMA actually affect? The fact that the valence cost increased (rather than reduced) with pre-SMA disruption demonstrates that this intervention did not simply make the item-specific inhibition weaker (if it did, the weaker inhibition should take less time to overcome, resulting in a smaller valence cost). Instead, the present findings suggest that pre-SMA perturbation may have affected another process represented by the valence cost (alongside overcoming item-specific inhibition). It has been shown that disrupting the activity of pre-SMA can slow down the inhibition process such that it takes more time to complete successfully (Obeso, Robles, Marron, & Redolar-Ripoll, 2013). Therefore, after TMS was delivered over this brain region, it might have taken longer to achieve the appropriate level of item-specific inhibition on each bivalent trial to prevent erroneous output, resulting in an increased valence cost. In addition, the asymmetry of the valence cost was not affected by pre-SMA disruption, showing that competing L1 labels (on L2 bivalent trials) were still suppressed more strongly than vice versa, and the strong

suppression took longer to overcome subsequently. It is important to note that the interaction was only marginally significant, therefore the interpretation above should be taken with caution.

There was no interaction between TMS location and transition type in the naming latencies. In other words, the switch cost did not show a significant change when TMS was applied on the pre-SMA compared to the control site (Figure 2-7 A). A 3-way interaction was found between TMS location, transition type and language in the error analysis, showing a trend of eliminating switch cost asymmetry when the pre-SMA was perturbed. However, follow-up tests revealed no significant switch cost asymmetry either under pre-SMA disruption or control site disruption, so the interaction was likely driven by the change of direction in the switch cost (i.e. it was slightly larger in L1 under control site perturbation, and slightly larger in L2 under pre-SMA perturbation). This pattern was only observed in the error data.

In summary, we observed an essential role of the pre-SMA in general speech production, but did not find strong evidence for a causal role of this brain region in either whole-language or item-specific inhibition. While there is some indication of its involvement in these two levels of control (i.e. marginally significant modulation of RT valence cost, and modulation of switch cost asymmetry in error data), this is inconclusive evidence and should therefore be interpreted with caution.

2.4 GENERAL DISCUSSION

The present study aimed to answer two questions about language control in bilingual speech production. The first question was in regards to whether both whole-language and item-specific inhibition were involved in language switching. We examined these in parallel in a modified language-switching paradigm (Experiment 1). Item-specific inhibition (indexed by the valence cost) was more

pronounced in the dominant language, indicating stronger inhibition of the individual labels in L1 than L2; whole-language inhibition (indexed by the switch cost) was symmetrical between the two languages. The valence cost was much larger in magnitude compared to the switch cost, suggesting that the strength of item-specific inhibition may be greater than whole-language inhibition⁵⁹.

The second question concerned whether brain mechanisms for domain-general inhibitory control played an essential role in whole-language and/or item-specific inhibition. We employed a repetitive TMS protocol to disrupt the functioning of the pre-SMA, a prominent region in the inhibitory control brain network (Experiment 2). Such disruption led to an overall slowing of naming latencies, suggesting a general role of the pre-SMA in speech execution. However, we did not find reliable evidence for its causal involvement in either whole-language or item-specific inhibition in the coordination of two languages. Given the lack of reliable modulation of either the switch cost or the valence cost by pre-SMA perturbation, we will focus on patterns in the behavioural results in the discussions below.

2.4.1 Item-specific inhibition and the reversed dominance effect

One interesting phenomenon in the current language switching literature is that the involvement of inhibition is underpinned by two distinct pieces of evidence, which occur in a somewhat complementary manner (see Section 2.1.1). Specifically, some studies report an asymmetrical switch cost (e.g. Meuter & Allport, 1999; Jackson et al., 2001; Costa & Santesteban, 2004, Exp. 1; Philipp et al., 2007; Schwieter & Sunderman, 2008; Fink & Goldrick, 2015), while others report a reversed dominance effect (e.g. Costa & Santesteban, 2004, Exp. 2~5; Costa et al., 2006, Exp. 1 & 2; Gollan & Ferreira, 2009; Verhoef et al., 2010; Peeters & Dijkstra,

⁵⁹ Note that this difference could also be caused by other components in the switch cost and valence cost (see Section 2.4.3), so we cannot say with certainty that it reflects a strength difference between whole-language and item-specific inhibition.

2018). The observation of either of these patterns is generally taken as evidence for the presence of inhibitory processes in language switching. However, at this stage there is no clear theory about why (or when) one or the other pattern would emerge in a particular situation. In the present study, the inclusion of two different types of stimuli (univalent and bivalent) provides a unique opportunity to look into possible differences in the mechanisms underlying the asymmetrical switch cost and reversed dominance effect, especially in regards to the level of control these mechanisms operate at. This might help provide a preliminary answer as to why some studies observe one pattern while other studies observe the other pattern.

In both of the experiments reported here, we found a significant interaction between stimulus valence (univalent vs bivalent) and language (L1 vs L2). In the analyses and discussions so far, we have interpreted this interaction as a reflection of differential amount of item-specific inhibition applied on L1 and L2 labels. In other words, the “valence cost” was different between the two languages. Now we present an alternative angle to look at this interaction: the reversed dominance effect (i.e. global slowing of L1) was different between univalent and bivalent items. Post-hoc analyses conducted separately on bivalent and univalent stimuli (with Bonferroni correction) show that the L1 slowing affected bivalent items ($t = 3.709$, $p = .0004$) but not univalent items ($t = 0.854$, $p = .7867$). Given the usual interpretation of the reversed dominance effect as evidence for sustained L1 inhibition in a mixed-language production context to facilitate L2 output (Kroll et al., 2008; Gollan et al., 2014; Bobb & Wodniecka, 2013), the fact that such inhibition of L1 only impacted the bivalent items makes an interesting suggestion: the global slowing⁶⁰ observed was due to inhibition of individual lexical items rather than the entire lexicon. If the sustained inhibition affected L1 as a whole, then bivalent and univalent items should be slowed down by a similar degree. The present findings suggest otherwise: items that had previously been named in L2 suffered extra

⁶⁰ The term “global” here means “both stay and switch trials”. It is not referring to “the whole language”.

slowing when being subsequently named in L1, whereas items that had never been named in L2 before (within the context of this experiment) did not suffer from slowing when named in L1.

Following this logic, we predict that it should not be possible to obtain a reversed dominance effect using univalent stimuli (i.e. if stimuli are never repeated, or if each stimulus maintains a fixed language association every time it appears). Consistent with this prediction, all of the language-switching studies that have observed a reversed dominance effect so far have utilised bivalent stimuli. Notably, Kleinman and Gollan (2016) compared cued switching (bivalent with forced language selection), bottom-up switching (univalent with free language selection) and voluntary switching (bivalent with free language selection) using the same set of stimuli. The reversed dominance effect only disappeared in the bottom-up switching block, and only when this block occurred first (i.e. each stimulus had not yet been named in the other language at all, therefore there was no item-specific inhibition to overcome). It remains to be seen whether any future studies employing univalent stimuli would be able to refute the prediction above.

If the reversed dominance effect results from item-specific inhibition, then what about asymmetrical switch cost? Theoretically, the latter should reflect whole-language inhibition, as the difference between a switch trial and a stay trial rests on whether there is a language change, regardless of what individual lexical items are named. It follows that any switch cost asymmetry should not be affected by stimulus valence (since whole-language inhibition should be applicable to both univalent and bivalent stimuli). Indeed, we observed no evidence of stimulus valence modulating switch cost asymmetry in the two experiments reported here⁶¹. This differs from the findings by Finkbeiner, Almeida, et al. (2006), where asymmetrical switch cost was observed for bivalent stimuli but no switch cost was

⁶¹ Note that the overall switch costs in these experiments were symmetrical. However, this does not prevent an interaction from showing up, if the pattern was different between univalent and bivalent stimuli. Therefore, the argument is still valid in this case.

observed for univalent stimuli. However, as Abutalebi and Green (2007) noted, all the univalent trials in that study were accompanied by a task switch, which might have masked the language-switch effect. When the confound of task switching is removed, it seems that asymmetrical switch cost can occur in both univalent and bivalent stimuli (Reynolds et al., 2016).

In sum, the commonly reported behavioural markers of inhibition in language switching - asymmetrical switch cost and reversed dominance effect - seem to arise from language control operating at different levels. While the former reflects the effect of whole-language inhibition, the latter reflects the effect of item-specific inhibition. In regards to what factors determine whether the switch cost asymmetry or reversed dominance would be observed in a given situation, we speculate that one major factor is the type of participants tested. Late bilinguals (who are usually more unbalanced) tend to keep their two languages separate, so they need to apply control on the whole-language level to regulate the activation of each language. On the other hand, early (or highly proficient) bilinguals may have a less rigid boundary between their two languages, and treat words from both languages as one integrated lexicon, therefore they rely more on item-specific control. Most of the existing studies show a pattern consistent with this proposal: unbalanced bilinguals tend to exhibit switch cost asymmetry in language switching (e.g. Meuter & Allport, 1999; Costa & Santesteban, 2004, Exp. 1; Philipp et al., 2007; Fink & Goldrick, 2015; Zhu et al., 2020; but see Verhoef et al., 2010), whereas highly proficient bilinguals tend to show reversed dominance effect (e.g. Costa & Santesteban, 2004, Exp. 2 & 3; Costa et al., 2006, Exp. 1). For the highly proficient bilinguals, this pattern also seems to extend to their weaker L3 (Costa & Santesteban, 2004, Exp. 4; Martin et al., 2013). This suggests that it is the language control strategy employed by bilinguals, rather than just the relative proficiency across languages, that leads to one phenomenon or the other. In some cases, bilinguals may apply control at both levels, resulting in the occurrence of both

asymmetrical switch cost and reversed dominance effect (Schwieter & Sunderman, 2008).

2.4.2 Alternatives to inhibition in bilingual language control

In designing the present study, we followed Green's (1998) model of bilingual language control, where inhibition is assumed to be the central mechanism which prevents non-target language words from reaching speech output. Whilst this is the most influential view in the current literature, there are alternative proposals on how bilinguals might achieve appropriate language selection during speech production. One model suggests that lexical selection is language-specific, i.e. only words belonging to the target language are considered by the selection mechanism, therefore there is no competition between languages (Costa & Caramazza, 1999; Costa, Miozzo, & Caramazza, 1999). This view is supported by findings from the picture-word interference paradigm, where picture naming is facilitated (rather than hindered) by a distractor word that is the translation-equivalent of the target name. Another model stipulates that language competition occurs at the semantic level. Specifically, the intended language is encoded in the preverbal message and this is sufficient to ensure higher activation levels of lexical nodes in that language (La Heij, 2005; Finkbeiner, Gollan, & Caramazza, 2006).

In addition, there exists some evidence which seems incompatible with the inhibitory account of language control. For example, Runnqvist, Strijkers, Alario, and Costa (2012) investigated the cumulative semantic interference (CSI) effect in a bilingual context. The monolingual version of this paradigm involves a picture-naming task where stimuli are chosen from a number of semantic categories. The CSI effect refers to the observation of longer naming latency for each additional picture named from the same semantic category. Such a pattern is assumed to reflect cumulative competition from the previously named objects in that category (e.g. Howard, Nickels, Coltheart, & Cole-Virtue, 2006; but see Oppenheim, Dell, &

Schwartz, 2010). Crucially, Runnqvist et al. showed that the slope of the CSI effect was unchanged even when objects belonging to the same semantic category were named in alternate languages. This speaks against Green's inhibitory control model, which would predict an absence or reduced magnitude of the CSI effect, because inhibition during language alternation should cancel out (at least part of) the previous activation of the competitors. Such findings necessarily cast some doubts on the validity of language control via inhibition, especially on the whole-language scale.

Instead of substantial modifications to the inhibitory control model, Runnqvist et al. suggest that a simpler approach would be to consider the lexical access mechanism in bilinguals as qualitatively similar to that in monolinguals. In one of their proposed solutions, language membership serves as a semantic feature, which naturally passes down more activation to words belonging to the target language, thus resolving the competition between languages at the semantic level (see also La Heij, 2005; Finkbeiner, Gollan, et al., 2006). This proposal is compatible with the observations in the present study. Let us first consider the contrast between univalent and bivalent items. If language membership is encoded in the semantic representation, then the naming of each bivalent item in two different languages would be equivalent to naming two slightly different concepts. On the other hand, the naming of each univalent item would involve repeating the exact same concept. This may contribute to the valence cost. The asymmetry in the valence cost we observed was primarily driven by slower responses in L1 compared to L2 when naming bivalent items, and this could be explained by differential priming of the semantic representation when previously naming in the other language. If we assume that the L1 name is linked with more detailed semantic features while the L2 name is only linked to a subset of these (see Finkbeiner, Forster, Nicol, & Nakamura, 2004), it then follows that the L2 name would receive more priming from the previous naming in L1 than vice versa, resulting in faster response speed in L2. In regards to how this proposal might accommodate the

common observation of asymmetrical switch cost, La Heij (2005) has provided an explanation that the asymmetry may result from processes related to incorporating the language membership information into the preverbal message, rather than from inhibition.

2.4.3 Limitations

There are a few limitations in the present study, which may be informative for future research. Firstly, a possible limitation in the experimental design lies in the way univalent and bivalent items were presented. The target response for each univalent item appeared four times as much as the target response for each bivalent item in the experiment, because univalent items maintained the same item-language mappings, including when they appeared in the training block and when they appeared on filler trials in the testing block. As a result, the target response for univalent items would have received a lot more priming compared to the bivalent items. Such differential priming may be a contributing factor to any difference observed between the univalent and bivalent stimuli. For example, the fact that naming of univalent items were robustly faster and more accurate than bivalent items could be explained by the additional priming of the target response for the univalent items. We argued that, since the valence cost was asymmetrical between L1 and L2, this signified that item-specific inhibition was at least one component in the valence cost, even if other components also existed (see Section 2.2.3 for details). Therefore, the potential repetition priming effect does not compromise such interpretation of the valence cost. However, it would be better if this confound was removed altogether from the design. One possible approach is to reduce the number of bivalent items, so that the target label for each bivalent stimulus would be named an equal number of times as the target label for each univalent stimulus. While this leads to another potential concern - the bivalent stimuli themselves would be presented a lot more frequently than univalent stimuli

- the latter is probably a less important concern than the differential priming on the target labels.

Secondly, a related point is that the small set of stimuli used in this study may not be a very good representation of a language. Since the stimuli were repeated many times in the experiment, participants' responses (especially in the later part of the experiment) might have been driven more by learned associations between each picture stimulus and the motor plan(s) to name it, than lexical access. Specifically, for the univalent stimuli, participants always retrieved the same motor plan for each appearance of the same picture; for the bivalent stimuli, participants had to constantly reconfigure the mapping between the picture and the appropriate response according to the current language requirement. Therefore, it is possible that the item-specific inhibition was applied onto the stimulus-response bindings, and such inhibitory effects may reside in event files in episodic memory (Hommel, 1998), rather than in the activation levels of lemmas. In addition, such difference between univalent and bivalent stimuli, together with the possible repetition priming effect discussed above, may be responsible for the larger magnitude of the valence cost compared to the switch cost. As explained above, these issues should not compromise the interpretation of the asymmetry in the valence cost. However, the results may be more convincing if a larger set of picture stimuli were used.

Thirdly, the lack of strong evidence for switch cost and valence cost modulation by pre-SMA perturbation (Experiment 2) could be due to a number of technical factors. Such result does not necessarily mean that the pre-SMA was not involved in whole-language or item-specific inhibition. One possible factor is that TMS might not have achieved the intended suppressive effect on pre-SMA. As most participants in this experiment had rather high motor threshold (mean 69%; range 60-76%), the calculated intensity to apply (48-61%) exceeded the maximum output available from the stimulator in the cTBS protocol (51%). Therefore, the stimulation

applied on these participants could have been too weak to be effective. Moreover, previous studies show that the suppressive effect of cTBS can be highly variable among individual participants (e.g. Heidegger et al., 2017; Murteira, Sowman, & Nickels, 2018). Another possible factor is that behavioural measures such as naming latencies and accuracies may not be sensitive enough to detect the effect from the disruption of a brain region. For example, Pestalozzi, Annoni, Müri, and Jost (2020) applied excitatory and inhibitory TMS protocols to the dorsolateral prefrontal cortex in a language-switching task; while TMS produced no visible behavioural effects, activity changes were detected in a number of brain regions in the EEG data. In our experiment, when the pre-SMA was perturbed, compensatory mechanisms might have been recruited to help mitigate the impact on participant's behavioural performance. If this was the case, it would be very interesting to look into those compensatory mechanisms by recording the participants' brain activity.

2.5 CONCLUSION

In this study, we examined a novel type of switching ("within-item switching"), alongside the commonly studied "trial-to-trial switching", in a cued language switching paradigm. This design allowed us to capture the effect of whole-language and item-specific inhibition within the same experiment task and compare them side by side. Such comparison provided a unique opportunity to explore two levels of inhibitory control in language switching and their underlying neural mechanisms. Given the growing evidence on the involvement of the executive control brain network in bilingual speech production, we investigated whether a key brain region in this network, the pre-SMA, played a causal role in either level of language inhibition. Using non-invasive brain stimulation to disrupt the functioning of this brain region, we demonstrated a performance decrement in picture naming, consistent with its role in initiating speech in general. There was also indication of a possible role of the pre-SMA in whole-language and item-

specific inhibition, although the evidence remains inconclusive and it awaits validation by future studies.

Author Contributions

Conceptualization, formal analysis, investigation, software, and writing: J.D.Z.; conceptualization, software, writing, and supervision: P.F.S. All authors read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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Appendix A. Statistical analysis results from Experiment 1

(1) Error analysis

> *GLME model*:

Generalized linear mixed model fit by maximum likelihood (Laplace Approximation) [‘glmerMod’]

Family: binomial (logit)

Formula: error ~ valence * ttype * lang + (1 | subjectID) + (1 | item)

Data: exp1_ER

Control: glmerControl(optimizer = "bobyqa")

AIC	BIC	logLik	deviance	df.resid
783.6	836.4	-381.8	763.6	1430

Scaled residuals:

Min	1Q	Median	3Q	Max
-0.5900	-0.4005	-0.1919	-0.1194	9.3559

Random effects:

Groups	Name	Variance	Std.Dev.
subjectID	(Intercept)	0.03475	0.1864
item	(Intercept)	0.03544	0.1883

Number of obs: 1440, groups: subjectID, 15; item, 8

Fixed effects:

	Estimate	Std. Error	z value	Pr(> z)
(Intercept)	-4.5141	0.7147	-6.316	0.000000000268 ***
valenceBi	2.8853	0.7379	3.910	0.000092344847 ***
ttypeSwi tch	1.2831	0.8061	1.592	0.111
langL2	0.3960	0.9171	0.432	0.666
valenceBi : ttypeSwi tch	-0.9888	0.8506	-1.162	0.245
valenceBi : langL2	-0.8217	0.9680	-0.849	0.396
ttypeSwi tch: langL2	-1.2831	1.1501	-1.116	0.265
valenceBi : ttypeSwi tch: langL2	1.1901	1.2234	0.973	0.331

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Analysis of Deviance Table (Type III Wald chi-square tests)

Response: error

	Chi sq	Df	Pr(>Chi sq)
valence	57.4183	1	3.523e-14 ***
ttype	2.3911	1	0.12203
lang	5.5610	1	0.01836 *
valence: ttype	0.4577	1	0.49870
valence: lang	0.0182	1	0.89280
ttype: lang	0.3479	1	0.55532
valence: ttype: lang	0.9463	1	0.33067

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(2) Reaction time analysis

> *LME model (raw RT):*

Linear mixed model fit by maximum likelihood . t-tests use Satterthwaite's method [lmerModelMerTest']

Formula: RT ~ valence * ttype * lang + (1 | subjectID) + (1 | item)

Data: exp1_RT

Control: lmerControl(optimizer = "bobyqa")

AIC	BIC	logLik	deviance	df.resid
17096.5	17153.4	-8537.3	17074.5	1290

Scaled residuals:

Min	1Q	Median	3Q	Max
-2.4484	-0.6075	-0.1290	0.3592	7.0417

Random effects:

Groups	Name	Variance	Std. Dev.
subjectID	(Intercept)	11283	106.22
item	(Intercept)	2317	48.13
Residual		27729	166.52

Number of obs: 1301, groups: subjectID, 15; item, 8

Fixed effects:

	Estimate	Std. Error	df	t value	Pr(> t)
(Intercept)	694.313	34.700	26.750	20.009	<2e-16 ***
valenceBi	167.596	18.981	1285.279	8.830	<2e-16 ***
ttypeSwitch	17.193	17.808	1278.921	0.965	0.3345
langL2	-25.596	18.109	1285.085	-1.413	0.1578
valenceBi:ttypeSwitch	5.280	26.558	1279.129	0.199	0.8425
valenceBi:langL2	-61.948	26.511	1284.274	-2.337	0.0196 *
ttypeSwitch:langL2	4.824	25.128	1278.894	0.192	0.8478
valenceBi:ttypeSwitch:langL2	7.444	37.108	1279.087	0.201	0.8410

Correlation of Fixed Effects:

	(Inter)	valenceBi	ttypeSwitch	langL2	valenceBi:ttypeSwitch	valenceBi:langL2	ttypeSwitch:langL2	valenceBi:ttypeSwitch:langL2
valenceBi	-0.250							
ttypeSwitch	-0.253	0.462						
langL2	-0.262	0.481	0.485					
valenceBi:ttypeSwitch	0.169	-0.682	-0.671	-0.322				
valenceBi:langL2	0.180	-0.718	-0.330	-0.682	0.487			
ttypeSwitch:langL2	0.180	-0.328	-0.709	-0.690	0.475	0.471		
valenceBi:ttypeSwitch:langL2	-0.121	0.487	0.480	0.464	-0.716	-0.688	-0.677	

Analysis of Deviance Table (Type III Wald chi-square tests)

Response: RT

	Chi sq	Df	Pr(>Chi sq)
valence	215.7919	1	< 2.2e-16 ***
ttype	6.6664	1	0.009825 **
lang	27.7909	1	1.352e-07 ***
valence:ttype	0.2403	1	0.623982
valence:lang	9.1807	1	0.002446 **
ttype:lang	0.1985	1	0.655922
valence:ttype:lang	0.0402	1	0.841017

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

> *LME model (log-transformed RT):*

Linear mixed model fit by maximum likelihood . t-tests use Satterthwaite's method [*lmerModelTest*]

Formula: $\log(\text{RT}) \sim \text{valence} * \text{ttype} * \text{lang} + (1 | \text{subjectID}) + (1 | \text{item})$

Data: *exp1_RT*

Control: *lmerControl* (optimizer = "bobyqa")

AIC	BIC	logLik	deviance	df.resid
-503.1	-446.2	262.5	-525.1	1290

Scaled residuals:

Min	1Q	Median	3Q	Max
-3.4618	-0.6601	-0.0990	0.4947	4.6041

Random effects:

Groups	Name	Variance	Std. Dev.
subjectID	(Intercept)	0.018271	0.13517
item	(Intercept)	0.003546	0.05955
Residual		0.036868	0.19201

Number of obs: 1301, groups: subjectID, 15; item, 8

Fixed effects:

	Estimate	Std. Error	df	t value	Pr(> t)
(Intercept)	6.512e+00	4.333e-02	2.581e+01	150.295	<2e-16 ***
valenceBi	2.070e-01	2.189e-02	1.285e+03	9.458	<2e-16 ***
ttypeSwitch	2.749e-02	2.053e-02	1.279e+03	1.339	0.1808
langL2	-2.767e-02	2.089e-02	1.285e+03	-1.325	0.1855
valenceBi:ttypeSwitch	-7.768e-03	3.062e-02	1.279e+03	-0.254	0.7998
valenceBi:langL2	-6.820e-02	3.057e-02	1.284e+03	-2.231	0.0259 *
ttypeSwitch:langL2	9.590e-04	2.897e-02	1.279e+03	0.033	0.9736
valenceBi:ttypeSwitch:langL2	2.274e-02	4.279e-02	1.279e+03	0.531	0.5952

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Correlation of Fixed Effects:

	(Inter)	valncB	ttypSw	langL2	vlncB: S	vlB: L2	ttS: L2
valenceBi	-0.231						
ttypeSwitch	-0.234	0.462					
langL2	-0.242	0.481	0.485				
vlncB: ttypS	0.156	-0.682	-0.671	-0.322			
vlncB: langL2	0.166	-0.718	-0.330	-0.682	0.487		
ttypSw: L2	0.166	-0.327	-0.709	-0.690	0.475	0.471	
vlncB: tS: L2	-0.111	0.487	0.480	0.464	-0.716	-0.688	-0.677

Analysis of Deviance Table (Type III Wald chi-square tests)

Response: $\log(\text{RT})$

	Chi sq	Df	Pr(>Chi sq)
valence	250.0791	1	< 2.2e-16 ***
ttype	7.8490	1	0.005085 **
lang	23.7926	1	1.073e-06 ***
valence:ttype	0.0329	1	0.856028
valence:lang	6.6031	1	0.010180 *
ttype:lang	0.2854	1	0.593208
valence:ttype:lang	0.2825	1	0.595092

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

> *Permutation test on LME model:*

Analysis of Variance Table of type I with Kenward-Roger approximation for degrees of freedom

	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)	DDf	p. value	Perm. p
valence	5943550	5943550	1	1278.4	213.1799	0.00000	1278.4	0.00000	0.001
ttype	177390	177390	1	1272.2	6.3625	0.01178	1272.2	0.01178	0.012
lang	755004	755004	1	1279.0	27.0800	0.00000	1279.0	0.00000	0.002
valence:ttype	6140	6140	1	1272.2	0.2202	0.63896	1272.2	0.63896	0.623
valence:lang	253992	253992	1	1279.1	9.1101	0.00259	1279.1	0.00259	0.008
ttype:lang	5494	5494	1	1272.1	0.1971	0.65718	1272.1	0.65718	0.656
valence:ttype:lang	1105	1105	1	1272.2	0.0397	0.84220	1272.2	0.84220	0.846

> *Follow-up tests to unpack the interaction between "valence" and "language":*

lang = L1:

	valence	emmean	SE	df	lower.CL	upper.CL
Uni		703	34.4	24.8	632	774
Bi		873	34.6	25.5	802	944

lang = L2:

	valence	emmean	SE	df	lower.CL	upper.CL
Uni		680	34.3	24.6	609	750
Bi		792	34.5	25.1	721	863

Results are averaged over the levels of: ttype

Degrees-of-freedom method: kenward-roger

Confidence level used: 0.95

contrast	lang	estimate	SE	df	t.ratio	p.value
Uni - Bi	L1	-170	14.0	1294	-12.203	<.0001
Uni - Bi	L2	-112	13.2	1291	-8.477	<.0001

Results are averaged over the levels of: ttype

Degrees-of-freedom method: kenward-roger

P value adjustment: bonferroni method for 2 tests

Appendix B. Statistical analysis results from Experiment 2

(1) Error analysis

> *GLME model*:

Generalized linear mixed model fit by maximum likelihood (Laplace Approximation) [‘glmerMod’]

Family: binomial (logit)

Formula: error ~ tms * valence * ttype * lang + (1 | subjectID) + (1 | item)

Data: exp2_ER

Control: glmerControl(optimizer = "bobyqa")

AIC	BIC	logLik	deviance	df.resid
2000.0	2108.6	-982.0	1964.0	3054

Scaled residuals:

Min	1Q	Median	3Q	Max
-1.4616	-0.3953	-0.1882	-0.0821	12.4798

Random effects:

Groups	Name	Variance	Std.Dev.
subjectID	(Intercept)	0.76039	0.872
item	(Intercept)	0.04409	0.210

Number of obs: 3072, groups: subjectID, 16; item, 8

Fixed effects:

	Estimate	Std. Error	z value	Pr(> z)
(Intercept)	-3.800e+00	4.795e-01	-7.925	2.27e-15 ***
tmsps	2.915e-05	5.896e-01	0.000	1.000
valenceBi	2.423e+00	4.563e-01	5.310	1.10e-07 ***
ttypeSwi tch	3.060e-01	5.538e-01	0.553	0.581
langL2	-1.089e+00	8.234e-01	-1.322	0.186
tmsps: valenceBi	6.446e-01	6.379e-01	1.010	0.312
tmsps: ttypeSwi tch	2.415e-01	7.671e-01	0.315	0.753
valenceBi: ttypeSwi tch	2.302e-01	6.054e-01	0.380	0.704
tmsps: langL2	-7.019e-01	1.358e+00	-0.517	0.605
valenceBi: langL2	1.127e+00	8.625e-01	1.307	0.191
ttypeSwi tch: langL2	8.278e-01	9.908e-01	0.835	0.403
tmsps: valenceBi: ttypeSwi tch	-1.202e+00	8.397e-01	-1.432	0.152
tmsps: valenceBi: langL2	-3.696e-01	1.405e+00	-0.263	0.793
tmsps: ttypeSwi tch: langL2	3.726e-02	1.585e+00	0.024	0.981
valenceBi: ttypeSwi tch: langL2	-1.238e+00	1.051e+00	-1.178	0.239
tmsps: valenceBi: ttypeSwi tch: langL2	1.350e+00	1.662e+00	0.813	0.416

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Analysis of Deviance Table (Type III Wald chi-square tests)

Response: error

	Chi sq	Df	Pr(>Chi sq)
tms	0.0153	1	0.901709
valence	233.9853	1	< 2.2e-16 ***
ttype	3.9657	1	0.046436 *
lang	10.5175	1	0.001182 **
tms: valence	0.0666	1	0.796315
tms: ttype	1.0820	1	0.298242
valence: ttype	2.3255	1	0.127266
tms: lang	2.6250	1	0.105194
valence: lang	2.0218	1	0.155055
ttype: lang	1.8891	1	0.169304
tms: valence: ttype	1.4000	1	0.236731
tms: valence: lang	0.6289	1	0.427750
tms: ttype: lang	7.0611	1	0.007877 **
valence: ttype: lang	0.7354	1	0.391145
tms: valence: ttype: lang	0.6603	1	0.416458

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

> Follow-up tests to unpack the 3-way interaction between "TMS location",
 "transition type" and "language":

tms = vt:						
ttype	lang	emmean	SE	df	asympt. LCL	asympt. UCL
Stay	L1	-2.59	0.326	Inf	-3.23	-1.95
Switch	L1	-2.17	0.307	Inf	-2.77	-1.57
Stay	L2	-3.11	0.434	Inf	-3.96	-2.26
Switch	L2	-2.48	0.325	Inf	-3.12	-1.85

tms = ps:						
ttype	lang	emmean	SE	df	asympt. LCL	asympt. UCL
Stay	L1	-2.27	0.323	Inf	-2.90	-1.63
Switch	L1	-2.20	0.299	Inf	-2.79	-1.62
Stay	L2	-3.68	0.560	Inf	-4.78	-2.58
Switch	L2	-2.70	0.355	Inf	-3.39	-2.00

Results are averaged over the levels of: valence

Results are given on the logit (not the response) scale.

Confidence level used: 0.95

tms = vt:						
ttype_pairwise	lang_pairwise	estimate	SE	df	z.ratio	p.value
Stay - Switch	L1 - L2	0.209	0.526	Inf	0.398	0.6909

tms = ps:						
ttype_pairwise	lang_pairwise	estimate	SE	df	z.ratio	p.value
Stay - Switch	L1 - L2	0.921	0.644	Inf	1.430	0.1528

Results are averaged over the levels of: valence

Note: contrasts are still on the log.o.r. scale

(2) Reaction time analysis

> *LME model (raw RT):*

Linear mixed model fit by maximum likelihood . t-tests use Satterthwaite's method [lmerModLmerTest]

Formula: RT ~ tms * valence * ttype * lang + (1 | subjectID) + (1 | item)

Data: exp2_RT

Control: lmerControl(optimizer = "bobyqa")

AIC	BIC	logLik	deviance	df.resid
33315.5	33426.7	-16638.8	33277.5	2552

Scaled residuals:

Min	1Q	Median	3Q	Max
-2.4767	-0.5420	-0.1235	0.3356	11.7271

Random effects:

Groups	Name	Variance	Std.Dev.
subjectID	(Intercept)	11378	106.7
item	(Intercept)	1989	44.6
Residual		23606	153.6

Number of obs: 2571, groups: subjectID, 16; item, 8

Fixed effects:

	Estimate	Std. Error	df	t value	Pr(> t)
(Intercept)	597.411	33.052	28.332	18.075	<2e-16 ***
tmsps	7.523	16.089	2548.011	0.468	0.6401
valenceBi	164.865	17.256	2550.882	9.554	<2e-16 ***
ttypeSwi tch	18.727	16.222	2548.011	1.154	0.2484
langL2	-9.721	16.203	2551.531	-0.600	0.5486
tmsps: valenceBi	8.385	24.772	2548.249	0.338	0.7350
tmsps: ttypeSwi tch	1.678	22.864	2548.017	0.073	0.9415
valenceBi: ttypeSwi tch	-29.910	24.810	2548.334	-1.206	0.2281
tmsps: langL2	6.442	22.647	2548.025	0.284	0.7761
valenceBi: langL2	-40.855	24.361	2549.373	-1.677	0.0937 .
ttypeSwi tch: langL2	2.821	22.724	2548.014	0.124	0.9012
tmsps: valenceBi: ttypeSwi tch	21.333	35.192	2548.380	0.606	0.5444
tmsps: valenceBi: langL2	7.767	34.498	2548.162	0.225	0.8219
tmsps: ttypeSwi tch: langL2	-8.202	32.103	2548.020	-0.255	0.7984
valenceBi: ttypeSwi tch: langL2	17.303	34.821	2548.220	0.497	0.6193
tmsps: valenceBi: ttypeSwi tch: langL2	1.117	49.088	2548.213	0.023	0.9818

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Analysis of Deviance Table (Type III Wald chisquare tests)

Response: RT

	Chi sq	Df	Pr(>Chi sq)
tms	10.2989	1	0.001331 **
valence	516.1176	1	< 2.2e-16 ***
ttype	5.8391	1	0.015674 *
lang	9.4246	1	0.002141 **
tms: valence	3.5719	1	0.058767 .
tms: ttype	0.3183	1	0.572615
valence: ttype	0.6636	1	0.415286
tms: lang	0.2391	1	0.624838
valence: lang	5.1166	1	0.023698 *
ttype: lang	0.2729	1	0.601392


```

tms: valence: ttype      0.7972  1  0.371944
tms: valence: lang       0.1149  1  0.734590
tms: ttype: lang         0.1011  1  0.750459
valence: ttype: lang     0.5298  1  0.466709
tms: valence: ttype: lang 0.0005  1  0.981838
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

```

> LME model (log-transformed RT):

Linear mixed model fit by maximum likelihood . t-tests use Satterthwaite's method ['lmerModLmerTest']

Formula: log(RT) ~ tms * valence * ttype * lang + (1 | subjectID) + (1 | item)

Data: exp2_RT

Control: lmerControl(optimizer = "bobyqa")

AIC	BIC	logLik	deviance	df.resid
-1341.3	-1230.1	689.6	-1379.3	2552

Scaled residuals:

Min	1Q	Median	3Q	Max
-2.7452	-0.6402	-0.1076	0.4877	6.0468

Random effects:

Groups	Name	Variance	Std. Dev.
subjectID	(Intercept)	0.020628	0.14363
item	(Intercept)	0.003841	0.06197
Residual		0.032939	0.18149

Number of obs: 2571, groups: subjectID, 16; item, 8

Fixed effects:

	Estimate	Std. Error	df	t value	Pr(> t)
(Intercept)	6.370e+00	4.421e-02	2.705e+01	144.096	<2e-16 ***
tmsps	5.451e-03	1.901e-02	2.548e+03	0.287	0.774
valenceBi	2.251e-01	2.039e-02	2.550e+03	11.041	<2e-16 ***
ttypeSwi tch	2.588e-02	1.916e-02	2.548e+03	1.351	0.177
langL2	-1.014e-02	1.914e-02	2.551e+03	-0.530	0.596
tmsps: valenceBi	7.237e-03	2.926e-02	2.548e+03	0.247	0.805
tmsps: ttypeSwi tch	1.237e-02	2.701e-02	2.548e+03	0.458	0.647
valenceBi : ttypeSwi tch	-3.082e-02	2.931e-02	2.548e+03	-1.052	0.293
tmsps: langL2	1.361e-02	2.675e-02	2.548e+03	0.509	0.611
valenceBi : langL2	-5.912e-02	2.878e-02	2.549e+03	-2.054	0.040 *
ttypeSwi tch: langL2	6.306e-03	2.684e-02	2.548e+03	0.235	0.814
tmsps: valenceBi : ttypeSwi tch	1.320e-02	4.157e-02	2.548e+03	0.318	0.751
tmsps: valenceBi : langL2	8.756e-03	4.075e-02	2.548e+03	0.215	0.830
tmsps: ttypeSwi tch: langL2	-1.903e-02	3.792e-02	2.548e+03	-0.502	0.616
valenceBi : ttypeSwi tch: langL2	2.135e-02	4.113e-02	2.548e+03	0.519	0.604
tmsps: valenceBi : ttypeSwi tch: langL2	-2.654e-03	5.799e-02	2.548e+03	-0.046	0.963

```

---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

```


Analysis of Deviance Table (Type III Wald chi square tests)

Response: log(RT)

	Chi sq	Df	Pr(>Chi sq)
tms	8.7796	1	0.0030462 **
valence	657.6509	1	< 2.2e-16 ***
ttype	11.6650	1	0.0006369 ***
lang	10.7716	1	0.0010307 **
tms: valence	1.4715	1	0.2251123
tms: ttype	0.2868	1	0.5922502
valence: ttype	0.9213	1	0.3371374
tms: lang	0.2645	1	0.6070647
valence: lang	9.3186	1	0.0022684 **
ttype: lang	0.1369	1	0.7114306
tms: valence: ttype	0.1669	1	0.6829159
tms: valence: lang	0.0660	1	0.7972995
tms: ttype: lang	0.4938	1	0.4822207
valence: ttype: lang	0.4766	1	0.4899545
tms: valence: ttype: lang	0.0021	1	0.9634929

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

> Permutation test on LME model:

Analysis of Variance Table of type I with Kenward-Roger approximation for degrees of freedom

	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)	DDf	p.value	Perm.p
tms	247944	247944	1	2533.2	10.4417	0.00125	2533.2	0.00125	0.061
valence	12144022	12144022	1	2540.8	511.4220	0.00000	2540.8	0.00000	0.001
ttype	141298	141298	1	2533.1	5.9505	0.01478	2533.1	0.01478	0.022
lang	217356	217356	1	2540.0	9.1535	0.00251	2540.0	0.00251	0.118
tms: valence	78429	78429	1	2533.2	3.3029	0.06928	2533.2	0.06928	0.079
tms: ttype	9369	9369	1	2533.2	0.3946	0.52997	2533.2	0.52997	0.568
valence: ttype	16069	16069	1	2533.1	0.6767	0.41080	2533.1	0.41080	0.422
tms: lang	5719	5719	1	2533.2	0.2408	0.62365	2533.2	0.62365	0.619
valence: lang	123969	123969	1	2537.3	5.2207	0.02240	2537.3	0.02240	0.025
ttype: lang	6931	6931	1	2533.1	0.2919	0.58906	2533.1	0.58906	0.573
tms: valence: ttype	19009	19009	1	2533.2	0.8005	0.37102	2533.2	0.37102	0.378
tms: valence: lang	2922	2922	1	2533.2	0.1230	0.72579	2533.2	0.72579	0.728
tms: ttype: lang	2347	2347	1	2533.1	0.0988	0.75328	2533.1	0.75328	0.756
valence: ttype: lang	12511	12511	1	2533.2	0.5269	0.46799	2533.2	0.46799	0.470
tms: valence: ttype: lang	12	12	1	2533.2	0.0005	0.98174	2533.2	0.98174	0.980

> Follow-up tests to unpack the interaction between "valence" and "language":

lang = L1:

valence	emmean	SE	df	lower.CL	upper.CL
Uni	611	32.2	24.5	544	677
Bi	770	32.4	25.2	704	837

lang = L2:

valence	emmean	SE	df	lower.CL	upper.CL
Uni	604	32.2	24.5	537	670
Bi	735	32.4	25.0	669	802

Results are averaged over the levels of: tms, ttype

Degrees-of-freedom method: kenward-roger

Confidence level used: 0.95


```
contrast lang estimate SE df t.ratio p.value
Uni - Bi L1 -159 9.08 2570 -17.558 <.0001
Uni - Bi L2 -131 8.83 2570 -14.878 <.0001
```

Results are averaged over the levels of: tms, ttype
Degrees-of-freedom method: kenward-roger
P value adjustment: bonferroni method for 2 tests

> *Follow-up tests to unpack the marginal interaction between "TMS location" and "valence":*

```
tms = vt:
valence emmean SE df lower.CL upper.CL
Uni 603 32.2 24.5 536 669
Bi 736 32.4 25.1 670 803
```

```
tms = ps:
valence emmean SE df lower.CL upper.CL
Uni 612 32.2 24.5 546 679
Bi 769 32.4 25.0 702 836
```

Results are averaged over the levels of: ttype, lang
Degrees-of-freedom method: kenward-roger
Confidence level used: 0.95

```
contrast tms estimate SE df t.ratio p.value
Uni - Bi vt -134 8.95 2570 -14.952 <.0001
Uni - Bi ps -157 8.85 2569 -17.740 <.0001
```

Results are averaged over the levels of: ttype, lang
Degrees-of-freedom method: kenward-roger
P value adjustment: bonferroni method for 2 tests

CHAPTER 3

Neuro-dynamics of executive control in bilingual language switching

This chapter has been published as:

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Abstract

Bilinguals have a remarkable ability to juggle two languages. A central question in the field is concerned with the control mechanisms that enable bilinguals to switch language with ease. Theoretical models and neuroimaging evidence suggest that a range of control processes are at play during language switching, and their underlying neural mechanisms are closely related to executive function. What remains unclear is when these control processes are engaged in language switching. In this study, we used magnetoencephalography (MEG) to examine the brain activity while unbalanced Mandarin-English bilinguals performed a digit-naming task with cued language switching. Following presentation of the language cue, an asymmetrical switch effect was observed in the left inferior frontal gyrus (IFG), where switch-related increase in evoked brain activity was larger for switching into the non-dominant language. Following presentation of the naming target, evoked brain activity in the right IFG was larger when naming was required in the non-dominant language compared to the dominant language. We conclude that control processes take place in two stages during language switching, with the left IFG resolving interference following cue presentation and the right IFG inhibiting competing labels following target presentation.

Keywords

bilingualism; language switching; executive control; magnetoencephalography (MEG); speech production

3.1 INTRODUCTION

Bilinguals have a remarkable ability to juggle two languages in daily life. When communicating with other individuals who share the same languages, they naturally adopt a bilingual mode and switch between these languages seamlessly. Yet, in a monolingual setting, they are able to keep the languages separate, and converse in the required language without intrusion from the other. A long-standing question in bilingualism research is concerned with the control mechanisms which enable bilinguals to switch language as desired during speech production. The present study explores this question by examining the neuro-dynamics of control processes in bilingual language switching.

In a seminal paper, Green (1998) proposed that bilinguals inhibit one language in order to produce speech in the other language. Green further suggested that the dominant language would receive stronger inhibition when production occurs in the non-dominant language than vice versa. This view is well supported by behavioural findings from unbalanced bilinguals. In a typical language-switching paradigm, bilingual participants name digits or pictures according to language cues, which instruct them what language to use on each trial. Reaction times (RT) are longer on trials where the language changes from the previous trial (*switch trials*) compared to trials where the language stays the same as the previous trial (*stay trials*). The RT difference between stay and switch trials is referred to as the *switch cost*. Usually a larger switch cost is observed when bilinguals switch into the dominant language, compared to when they switch into the non-dominant language. This phenomenon, commonly referred to as *switch cost asymmetry*, has been reported in many studies (e.g. Meuter & Allport, 1999; Jackson, Swainson, Cunningham, & Jackson, 2001; Costa & Santesteban, 2004, Exp. 1; Campbell, 2005; Philipp, Gade, & Koch, 2007; Schwieter & Sunderman, 2008), and it has become the signature evidence of inhibitory control enactment in bilingual speech production (but also see Bobb & Wodniecka, 2013 and Declerck & Philipp, 2015, for alternative

explanations of this phenomenon). The switch cost asymmetry between the two languages supports Green's proposal that the dominant language receives strong suppression when production occurs in the non-dominant language; it then takes more time to overcome this suppression when the bilingual subsequently switches back to the dominant language.

The electrophysiological evidence for the inhibition of non-target language is less consistent. Early studies looking at event-related potentials (ERP) in bilingual language switching typically focused on the N2 component (a negative deflection around 200 - 300 ms following stimulus onset), which is thought to represent inhibition (Jodo & Kayama, 1992; Falkenstein, Hoormann, & Hohnsbein, 1999; Bruin & Wijers, 2002; but alternative interpretations exist, see Nieuwenhuis, Yeung, Van Den Wildenberg, & Ridderinkhof, 2003 and Yeung, Botvinick, & Cohen, 2004). Jackson et al. (2001) were among the first to conduct ERP studies using a language-switching paradigm. In a digit-naming task with cued switching, these authors found a switch effect in the ERP, indexed by a larger N2 component on switch trials compared to stay trials. This N2 switch effect was only present when bilinguals switched into the non-dominant language (and not in the other direction), suggesting that stronger inhibition (applied onto the dominant language) was required for switching into the weaker language. This inhibition then needs to be overcome when bilinguals switch back to the dominant language, resulting in a larger RT switch cost for that language. While this study offers strong support for Green's proposal, subsequent ERP studies of language switching have not been able to demonstrate such clear evidence for inhibition of the non-target language. Christoffels, Firk, and Schiller (2007) showed a "switch advantage" (smaller N2 amplitude on switch trials compared to stay) when bilinguals switched into the dominant language, and no difference between stay and switch trials in the non-dominant language. They argued that no inhibition is required for language switching. Verhoef, Roelofs, and Chwilla (2010) found a switch effect in the N2 component in response to the language cue, which they interpreted to be in favour

of attentional control rather than inhibition. Blanco-Elorrieta and Pylkkänen (2016) were the first to conduct a language-switching study using magnetoencephalography (MEG), a technique that offers relatively superior ability to reconstruct source activity in specific brain regions (Cohen & Cuffin, 1983). This study found that switch trials elicited increased activity in the dorsolateral prefrontal cortex (DLPFC) compared to stay trials, and the authors considered this brain region to play a role in response inhibition or proactive control (to retrieve target word while maintaining the task goal). Taken together, these findings do not arrive at the simple conclusion that language switching relies on inhibition; rather, they suggest that a range of control processes may be at play during language switching (see Green & Abutalebi, 2013, for a proposal on eight possible control processes in bilingual speech production).

It has been suggested that the brain mechanisms underlying bilingual language control are domain-general and closely related to executive function (e.g. Bialystok & Craik, 2010; Kroll & Bialystok, 2013; Green, 1998; Green & Abutalebi, 2013; but for alternative views, see Declerck, Koch, & Philipp, 2015 and Grainger, Midgley, & Holcomb, 2010). Recent neuroimaging studies have identified a number of brain regions involved in language switching, and these regions are also part of the executive control brain network (for a meta-analysis, see Luk, Green, Abutalebi, & Grady, 2012). The anterior cingulate cortex (ACC) has been reported to be responsible for conflict monitoring in both language control and non-verbal cognitive control (Abutalebi et al., 2012; Van Heuven, Schriefers, Dijkstra, & Hagoort, 2008); an alternative view suggests that the left ACC carries out inhibitory control in language switching (Wang, Xue, Chen, Xue, & Dong, 2007). The right inferior frontal gyrus (IFG) and pre-supplementary motor area (pre-SMA) have been found to be involved in language inhibition (de Bruin, Roelofs, Dijkstra, & FitzPatrick, 2014), aligning with the well-known roles of these brain regions in response inhibition (Jahfari et al., 2011; Aron, Robbins, & Poldrack, 2004, 2014). The left IFG has been proposed to carry out interference resolution in language

switching (Green & Abutalebi, 2013), which matches its role of resisting interference in working memory (Nee et al., 2012) and in non-verbal task switching (Garbin et al., 2010). The dorsolateral prefrontal cortex (DLPFC) has also been reported to be involved in suppressing interference in language switching and mixed-language production (Hernandez, Dapretto, Mazziotta, & Bookheimer, 2001; Wang et al., 2007; Blanco-Elorrieta & Pylkkänen, 2016, 2017).

Despite the abundant evidence from neuroimaging studies showing the involvement of executive-control brain regions in language control, it remains unclear *when* these brain regions (and the control processes they are associated with) are engaged during language switching. Are bilinguals able to proactively regulate the activation levels of their two languages, as soon as they know which language to speak; or can they only exert control reactively to resolve competition between words from both languages after they know what concept to express? This is the central research question of the present study. The traditional language-switching paradigm is unable to answer this question: when the language cue and naming target are presented simultaneously (e.g. Jackson et al., 2001; Christoffels et al., 2007), the neural processes in response to the cue and those in response to the target cannot be differentiated. Therefore, a modification to the task design - which separates the cue and the target by a brief time interval - is required to answer such a question. In behavioural studies that adopt this modified design, a reduction in switch cost is sometimes observed when cue onset and target onset are separated by a longer interval compared to a shorter interval (Costa & Santesteban, 2004; Fink & Goldrick, 2015; Khateb, Shamshoum, & Prior, 2017; but see Philipp et al., 2007; Stasenko, Matt, & Gollan, 2017; Lavric, Clapp, East, Elchlepp, & Monsell, 2019). This shows that, at least in certain cases, bilinguals may be able to utilise the “preparation time” after they see the cue, to perform some components of the language switch. Subsequently, when participants see the target and perform the naming, a switch cost is still present in the RT, even when a long preparation time is given (e.g. Costa & Santesteban, 2004). This suggests that

some other components of the language switch can only be completed after the naming target is known. Overall, the behavioural findings show that there may be distinct control processes taking place both following cue onset and following target onset. This idea is consistent with the two-stage models of task switching (Rogers & Monsell, 1995; Meiran, 2000; Rubinstein, Meyer, & Evans, 2001), based on findings from both linguistic and non-linguistic switching tasks (see Kiesel et al., 2010, for a review).

Taking advantage of the high temporal resolution of electrophysiological techniques, a language-switching paradigm with separate cue and target presentation has the ability to disentangle the cue-locked and target-locked brain response, making it possible to examine the different brain regions and control processes engaged at each stage. A few recent EEG/MEG studies have adopted such a design; however, they report mixed findings. In two ERP studies, Verhoeft, Roelofs, & Chwilla (2009, 2010) found that bilinguals start the process of language switching once the language cue is shown (switch trials elicited a larger N2 component than stay trials following cue presentation), and there were no remaining switching process taking place after the target is shown (no difference between stay and switch trials following target presentation). On the other hand, Chang, Xie, Li, Wang, and Liu (2016) observed the complete opposite in their ERP study: there was no switch effect following cue onset; rather, the switch effect only occurred between 270 - 400 ms following target onset. To examine switching-related activity in specific brain regions (DLPFC and ACC), Blanco-Elorrieta and Pylkkänen (2017) conducted an MEG study, in which they found that the switch effect took place between 100 - 160 ms following target presentation. In sum, some studies have found that the language-switch effect occurs only following cue onset, while others report that the effect occurs only following target onset. A recent fMRI study of language switching (Reverberi et al., 2015) has also adopted a design with separate cue and target presentation, using a much longer delay between cue and target to allow sufficient time for the haemodynamic response. The authors report

that a few brain regions activate more on switch trials compared to stay trials during the cue window (precuneus, right superior lateral parietal lobe, and middle temporal gyrus), whereas a number of other brain regions show differential activation between L1 and L2 naming during the target window (most notably the ACC and caudate). Crucially, the brain areas engaged at the cue stage and at the target stage differed from each other. These findings support the idea that language control takes place at both stages, but different control mechanisms are involved at each stage.

One possible explanation for the seemingly contradicting results from the electrophysiological studies mentioned above is that there are a number of differences in the study designs. In the present MEG study, we considered these design choices carefully and combined the improvements made by each of these studies (more details in Section 3.2.2), with the aim of resolving the discrepancy in these previous findings. Based on the behavioural and neural evidence discussed above, we hypothesised that control processes take place in two stages during language switching. When the language cue is presented, the bilingual participants know which language is required for production. At this point, they may start disengaging from the previously-used language and engaging the newly required language (Verhoef et al., 2010). However, participants cannot prepare for the (as yet unknown) specific word they will be required to produce. When the naming target is presented, the participants now know exactly what they need to say. If the concept still activates words in both languages during lexical selection, then any reactive control required to resolve this competition should occur at this time (Chang et al., 2016). According to Abutalebi and Green (2008), switching can be unpacked into three basic processes: shifting, goal updating, and inhibition. In the task switching literature, it is generally accepted that shifting and goal updating are carried out by endogenous control processes in the first stage of switching, which can be completed before target onset (Rogers & Monsell, 1995; Meiran, 1996; Karayanidis, Coltheart, Michie, & Murphy, 2003); the second stage of switching,

which can only take place following target onset, is thought to reflect inhibition of the currently-irrelevant task or overcoming lingering inhibition of the currently required task (Arbuthnott & Frank, 2000). In line with these theories, we made the following predictions in the present study: (1) A switch effect would occur following cue presentation, reflecting the process of shifting away from the language no longer required and updating the task goal to speaking the currently required language. We predicted that this process would be carried out by one or more brain regions in the executive control network (ACC, IFG, DLPFC; see review of neuroimaging studies above). For unbalanced bilinguals, this switch effect may be asymmetric across the two languages, as it should be more difficult to switch away from the dominant language and suppress its interference. (2) Inhibition would occur following target presentation, and there would be stronger inhibition of the dominant language while production occurs in the non-dominant language than vice versa (Green, 1998). We predicted that this process would be carried out by the right IFG and pre-SMA, given the important role of these brain regions in domain-general inhibitory control (Jahfari et al., 2011; Aron et al., 2004, 2014) and recent evidence showing the involvement of these regions in language inhibition (de Bruin et al., 2014). Such inhibition may be required equally on stay and switch trials, in which case we would observe a main effect of language; alternatively, the inhibition may be required only on switch trials, in which case we would observe an asymmetric switch effect.

3.2 METHODS

3.2.1 Participants

Twenty right-handed Mandarin-English bilinguals participated in this study (age 25.9 ± 4.5 years; six males). Information on participant characteristics were gathered through a language history questionnaire, which probed their language

use patterns and self-rated proficiencies in the two languages (more details in Table 3-1). All participants were native speakers of Mandarin (age of acquisition 0.4 ± 1.0 years), and learned English in primary school or junior high school, at the age of 9.4 ± 3.5 years. We specifically recruited late bilinguals who have unbalanced proficiency in the two languages, in an effort to examine whether the dominant language and non-dominant language would be suppressed to different extents during language production, as suggested by Green (1998). As is usually the case, the dominant language for these bilinguals was their first language (L1), and the non-dominant language was their second language (L2); from here onwards, we will use the terms “*dominant/non-dominant*” and “*L1/L2*” interchangeably. At the time of participation, all the bilinguals had been living in an English environment for no more than 3 years, and in their daily life, they used Mandarin $69.2\% \pm 19.1\%$ of the time. All participants were free from neurological conditions, and had normal or corrected-to-normal vision. This study was approved by the Human Ethics Committee of Macquarie University, and informed consent was obtained from all participants.

3.2.2 Stimuli and experimental design

3.2.2.1 Target stimuli

The digits 1 to 8 were chosen as naming targets. The consideration behind this was that even quite proficient bilinguals are known to process numbers in their first language, while they might be comfortable to process other things in their second language (see claim in Meuter & Allport, 1999). Although we already targeted unbalanced bilinguals in our recruitment, our participants were relatively proficient in their L2 compared to some previous studies (e.g. Jackson et al., 2001; Christoffels et al., 2007). Therefore, digit stimuli were used to (possibly) maximise the imbalance between the two languages, which would enable us to observe proficiency-related effects. The digit ‘9’ was the naming target on filler trials.

	Mean	SD
Age (in years)	25.9	4.5
Age of acquisition - Mandarin (L1)	0.4	1.0
Age of acquisition - English (L2)	9.4	3.5
Mandarin listening ability ^a	7.0	0.0
Mandarin speaking ability ^a	7.0	0.0
Mandarin reading ability ^a	7.0	0.0
Mandarin writing ability ^a	7.0	0.2
English listening ability ^a	4.7	0.9
English speaking ability ^a	4.2	0.9
English reading ability ^a	5.1	0.9
English writing ability ^a	4.5	0.9
English listening ability relative to Mandarin ^b	2.8	0.8
English speaking ability relative to Mandarin ^b	2.4	0.7
English reading ability relative to Mandarin ^b	3.3	1.4
English writing ability relative to Mandarin ^b	2.8	0.9
Number of years living in L2 environment	1.4	0.9
Percent L1 use in daily life	69.2	19.1
Switching frequency in daily life ^c	3.8	1.0

Table 3-1. Participant characteristics.

^a Language proficiency based on self-ratings on a 7-point scale: 1 = little to no knowledge, 7 = like a native speaker.

^b Relative proficiency based on self-ratings on a 5-point scale: 1 = much worse than Mandarin, 5 = just as good as Mandarin.

^c Based on a 6-point scale: 1 = never, 6 = constantly.

3.2.2.2 Language cues

To ensure the language-switch effect was not contaminated by cue-related processes, we used natural language cues and adopted a design where two cues were mapped onto each language. The reasons for this approach are as follows. Firstly, Blanco-Elorrieta and Pylkkänen (2017) showed that artificial language cues,

such as colours, produced an increased switch effect compared to more natural cues, such as faces of interlocutors. Lavric et al. (2019) observed a similar pattern when using auditory language cues, where more opaque cues (short fragment of national anthem) resulted in a larger switch cost compared to more familiar cues (spoken word “English” or “Deutsch”). These findings suggest that when artificial or indirect cues are used, the switch cost may reflect some cue-related processes that are independent of the language-switch process (Heikoo, Declerck, Los, & Koch, 2016). To ensure that the switch effect we observe in this study more specifically reflects language switching, we used face cues, which are natural and direct language cues. In a real-world setting, the face of the interlocutor should naturally prompt the appropriate response language (Woumans et al., 2015; Molnar, Ibáñez-Molina, & Carreiras, 2015; Li, Yang, Scherf, & Li, 2013). Secondly, most previous language-switching studies involve a confound of cue-switching: if one cue is mapped to each language, whenever there is a language change, the cue also has to change. Therefore, the switch cost is likely to be a combined effect from both the cue switch and the language switch. We addressed this issue by mapping two cues to each language and making the cue change on every trial (Verhoef et al., 2010). Even though this does not remove the effect of cue-switching, that effect would be controlled for because it occurs on both language-stay and language-switch trials.

The language cues in this study consisted of four grayscale images: two Chinese faces for Mandarin and two Caucasian faces for English (Figure 3-1), taken from Rhodes, Hickford, and Jeffery (2000). Each face was an average of 24 real photographs. To ensure the face change was obvious on every trial, we used one female face and one male face for each language (the gender changed on every single trial). Before the MEG session started, participants were introduced to the faces and told that they would be playing a number game with these four people: they would see a face first, followed by a number, and their task was to tell that person (in the language he/she speaks) what number they see next.

One potential concern with using faces as language cues is whether any difference in the face images themselves might introduce artificial effects. To avoid this potential problem, we made the four face images as similar as possible in terms of low-level visual features, and equalised the luminance across the four images using the SHINE toolbox (Willenbockel et al., 2010). It has also been reported that there may be an “own-race / other-race” effect in face perception, but findings on this have been inconsistent. Some ERP studies report a larger N170 component for other-race faces (e.g. Stahl, Wiese, & Schweinberger, 2008; Caharel et al., 2011), while some report a larger N170 for same-race faces (e.g. Ito & Urland, 2005). At the same time, other studies were unable to replicate these effects and found the N170 to be insensitive to the race of the faces (e.g. Caldara, Rossion, Bovet, & Hauert, 2004). Here, we ran a pilot MEG study to check if there was any difference in the visual evoked field (VEF) elicited by the Chinese faces and Caucasian faces, in order to make sure there was no difference in the low-level sensory effect produced by the faces from different races. No significant race effect was found in the VEF (details of this pilot study can be found in Appendix A).



Figure 3-1. Two Chinese faces (left) as cues for Mandarin, and two Caucasian faces (right) as cues for English. The faces were taken from Rhodes, Hickford, and Jeffery (2000).

3.2.2.3 Trial structure

To examine language control in distinct stages of processing, we separated the cue onset and target onset by an interval of 750 ms, which has been shown to be

sufficient for optimal preparation (Rogers & Monsell, 1995; Verhoef et al., 2009). On each trial, the language cue (face of interlocutor) was displayed for 750 ms, followed immediately by the target (digit to be named), which was shown for 1500 ms. The inter-trial interval was jittered between 800 - 1000 ms, during which a fixation cross was displayed. Participants were instructed to name the digit as quickly and accurately as possible upon target onset.

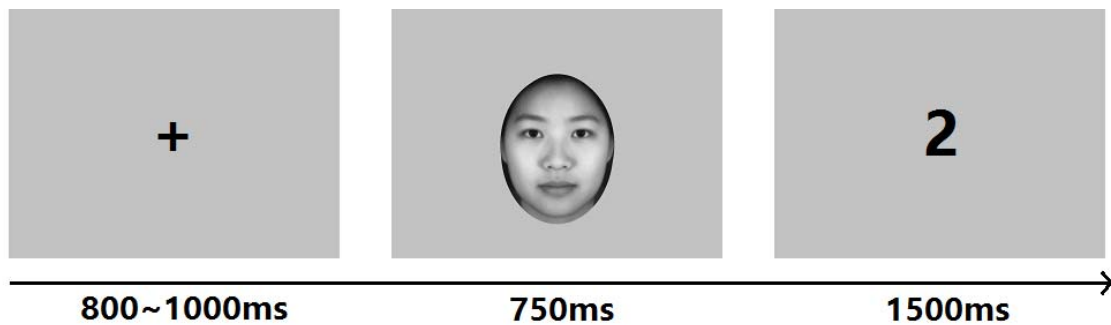


Figure 3-2. On each trial, the face cue was displayed for 750 ms, followed immediately by the target digit, which was displayed for 1500 ms. The inter-trial interval was jittered between 800 - 1000 ms.

3.2.2.4 Task procedure

Trials were presented in a pseudorandom order, satisfying two constraints: (1) there were no consecutive trials with the same target digit (2) each trial type had a maximum run length of 3 (i.e. no more than 3 consecutive stay trials or switch trials). One consideration when generating the trial sequence is that switch costs can carry over onto the next trial (Blanco-Elorrieta & Pylkkänen, 2016). To avoid any switch trials contaminating its following trial, a filler was inserted after every switch trial. The naming target on filler trials was the digit 9. As the filler trials were all stay trials themselves, they would not produce a carry-over effect onto the next critical trial.

The entire experiment consisted of 4 blocks, with 168 trials per block (including fillers). Trials were evenly distributed across the four experimental conditions: L1 stay, L1 switch, L2 stay, L2 switch. This provided 108 critical trials in each condition

overall (27 per block). Each block lasted approximately 9 minutes. Participants were given a short rest break after completing each block.

3.2.3 Data acquisition

Data collection took place at the KIT-Macquarie Brain Research Laboratory, Sydney, Australia. Behavioural and MEG data were collected simultaneously. Visual stimuli were displayed via a projector (EPSON EB-G7400U; refresh rate 60 Hz) and reflected by a mirror onto a white screen placed directly above the participant's head, at a distance of 1.06 meters. The experiment was controlled by the Presentation software (Version 18.3; Neurobehavioral Systems, Inc., Berkeley, CA, USA). MEG measurements were acquired using a 160-channel whole-head axial gradiometer system (Model PQ1160R-N2; Kanazawa Institute of Technology, Kanazawa, Japan). Participants were tested while lying supine, in a dimly-lit and magnetically-shielded room (Fujihara Co. Ltd., Tokyo, Japan).

Before participants entered the magnetically-shielded room, head shape information were recorded using the Polhemus Fastrak system and digitizing pen (Colchester, VT, USA). Approximately 4000 points were collected from each participant's head surface, and the locations of three cardinal landmarks (nasion and bilateral preauricular points) were also recorded. In addition, participants wore a tight-fitting elastic cap with five marker coils attached to it, which allowed measurement of participant's head position in relation to the MEG sensors. During each testing session, the participant's head position was measured at the beginning, middle, and end of the session. All participants' head movements from beginning to end were less than 5mm (averaged across the five marker coils).

Continuous MEG data were acquired at a sampling rate of 1000 Hz (online bandpass filter 0.03 - 200 Hz). Participants' vocal responses were captured using an MEG-compatible microphone and saved for offline analysis. The RT on each trial

was determined by the software voice key in Presentation. Behavioural errors (including incorrect responses as well as all verbal disfluencies, e.g. partial responses, stuttering, and utterance repairs) were manually coded by the experimenter. Any trials involving these behavioural errors were excluded from RT analysis and subsequent MEG data analysis.

3.2.4 Behavioural data analysis

Statistical analysis of the behavioural data was performed in R (Version 3.4.4; R Core Team, 2018) using the “lme4” package (Bates, Maechler, Bolker, & Walker, 2015). The RT and error rate data were submitted to a 2 x 2 linear mixed effects model. “Language” (L1 vs L2), “transition type” (stay vs switch), and the interaction between the two factors were entered as fixed effects; “participant” and “item” were entered as random effects. The RT values were Box-Cox transformed (Box & Cox, 1964) to satisfy the assumption of normality of residuals. All effects were categorised as significant at $p < .05$.

3.2.5 MEG data analysis

Preprocessing and analysis of MEG data were performed in Matlab (Version R2014b; MathWorks, Inc., Natick, MA, USA) using the FieldTrip toolbox (Oostenveld, Fries, Maris, & Schoffelen, 2011; <http://fieldtriptoolbox.org>). The preprocessing steps were as follows: MEG data were bandpass filtered between 0.5 - 40 Hz (using a two-way Butterworth filter), and bandstop filtered between 49.5 - 50.5 Hz to remove electrical line noise. Epochs were created from -1000 to 1000 ms around critical stimulus onset (each cue and each target was treated as a separate stimulus), based on the timing of photodetector triggers. Data were then downsampled to 200 Hz to save disk space and improve processing speed.

Any trial that resulted in a behavioural error was excluded from the MEG data analysis. Since this experiment involved a naming task with overt responses, it is important to remove possible contamination from muscular activity. The 0.5 - 40 Hz bandpass filter during preprocessing removed most of the muscle artefacts, which typically affect the gamma frequency range (> 40 Hz; Gross et al., 2013; Muthukumaraswamy, 2013). In addition, we created epochs around the speech onset (-1000 to 1000 ms) on each trial, and computed the event-related field (ERF) time-locked to speech onset. A principal component analysis (PCA) was performed on this ERF time course to identify the main components that best characterise the speech-related artefact, and these components were projected out from the original epoched MEG data (similar to the approach used by Salmelin, Schnitzler, Schmitz, & Freund, 2000). Outlier trials (e.g. those containing large amplitude artefacts) were subsequently identified using the “visual artifact rejection” method in FieldTrip, and these trials were excluded from analysis.

3.2.5.1 ERF analysis

For all MEG sensors, we calculated ERFs time-locked to both the cue onset and the target onset. Statistical analysis was conducted using a similar 2 x 2 design as for the behavioural data analysis, with “language” (L1 vs L2) and “transition type” (stay vs switch) as factors. All trials belonging to each condition (L1 stay, L1 switch, L2 stay, L2 switch) were averaged to obtain the ERFs.

Data for each time point in the ERF time courses were submitted to cluster-based permutation tests (Maris & Oostenveld, 2007). The main effect of language was tested by assessing the difference between L1 trials and L2 trials (averaged across transition types); the main effect of transition type was assessed as the difference between stay trials and switch trials (averaged across languages); and the interaction between language and transition type was assessed as the difference

between the switch cost in L1 and the switch cost in L2 (switch minus stay, in each language). Permutation tests were conducted in the time interval between cue onset and target onset (100 ms before to 750 ms after cue presentation), and the time interval between target onset and speech response onset (100 ms before to 550 ms after target presentation). Data from all sensors were included in the analysis. A cluster-based approach was used to control for multiple comparisons in both the spatial and temporal dimensions, using the following procedure. A t-test was first performed on each individual sample (one sample = one time-channel pair) to select candidates to form clusters, with an alpha of 0.05. The selected samples were then grouped into clusters on the basis of spatial and temporal proximity. Cluster-level statistics were obtained by calculating the sum of the t-values within every cluster, and the maximum of these sums was taken as the test statistic. The data were permuted 2000 times, each time the condition labels were randomly shuffled and the test statistic was recomputed. The final p-value was defined as the proportion of recomputed test statistic values (out of the 2000 shuffles) that exceeded the initial test statistic value (calculated from the real observed data). We report spatio-temporal clusters thresholded at $p < .05$ as significant effects.

3.2.5.2 ROI analysis

We reconstructed brain activities in pre-defined regions of interest (ROIs). The ROIs were selected according to previous neuroimaging studies on language switching (see Section 3.1); these included the bilateral ACC (Abutalebi et al., 2012; Wang et al., 2007; Reverberi et al., 2015), IFG (de Bruin et al., 2014; Green & Abutalebi, 2013; Reverberi et al., 2015), pre-SMA (de Bruin et al., 2014), and DLPFC (Hernandez et al., 2001; Wang et al., 2007; Blanco-Elorrieta & Pylkkänen, 2016, 2017). The ROIs were defined anatomically using the AAL atlas (Tzourio-Mazoyer et al., 2002): the ACC was defined as the “anterior cingulate gyrus”; the IFG was defined as the “pars

opercularis" and "pars triangularis" combined (note that with this definition, the left IFG would be roughly equivalent to Broca's area); the DLPFC was defined as the "middle frontal gyrus" (this included BA9, 10 and 46, consistent with the definition of DLPFC in previous language-switching studies, e.g. Blanco-Elorrieta & Pylkkänen, 2016); the pre-SMA was defined as the "supplementary motor area" (no sub-division exists in the atlas to specifically define the *pre-SMA*).

As the participants in this study did not have individual MRI scans, we used the MEMES toolbox (Seymour, 2018; <https://github.com/Macquarie-MEG-Research/MEMES>) to estimate the best-matching structural scan for each participant, by searching through an existing database. The MEMES tool works by matching the participant's head shape data collected during the MEG session to the MRI scans in the database using an Iterative Closest Point algorithm, and choosing the best-fitting MRI with the lowest objective registration error (Gohel, Lim, Kim, Kwon, & Kim, 2017). Because the Mandarin-English bilinguals we tested in this study were all Chinese, we selected a Chinese MRI database (Southwest University Longitudinal Imaging Multimodal Dataset; Liu et al., 2017) and customised it for use with MEMES. For each participant, an appropriate cortical mesh and source grid were created from the custom-matched MRI and co-registered with the MEG sensor positions. The forward model (i.e. leadfield) was computed using the cortical mesh as the volume conductor model. Source reconstruction was performed using a linear constrained minimum variance (LCMV) beamformer. A spatial filter (for each vertex in the source grid) was computed separately for cue-locked and target-locked brain response, based on the covariance matrix computed from data combined across conditions. The spatial filters for all vertices within an ROI were then combined into a single spatial filter by way of singular value decomposition, which was then used to estimate the source activities in that ROI (by multiplying the spatial filter with the respective ERF time course in each condition; also see Seymour, Rippon, Gooding-Williams, Schoffelen, & Kessler, 2019). This procedure produced a time course of brain

activity in each condition for each ROI, time-locked to the cue onset and target onset.

Statistical analysis was performed separately for each ROI. As with the ERF analysis, data for each time point in the ROI time courses were submitted to cluster-based permutation tests, using a 2 x 2 design with “language” and “transition type” as factors, to identify temporal clusters during which the ROI activity differed significantly across conditions. The cluster-based approach was used to control for multiple comparisons in the temporal dimension. The data were permuted 2000 times. We report the temporal clusters thresholded at $p < .05$ as significant effects.

3.3 RESULTS

3.3.1 Behavioural results

The error rate data were submitted to a 2 x 2 linear mixed effects model (see Section 3.2.4 for details). The model with the main effects of “language” and “transition type” had the best fit (AIC = 2070.0, BIC = 2112.6). Bilinguals made more errors on switch trials compared to stay trials (error rate difference was 3.3%; $z = 7.851$, $p < .0001$), and more errors on L1 trials compared to L2 trials (3.2%; $z = 4.035$, $p < .0001$).

All error trials were excluded from the RT analysis. The RT data were submitted to a 2 x 2 linear mixed effects model (see Section 3.2.4 for details). The full model (main effects of “language” and “transition type”, plus the interaction term) had the best fit to the data (AIC = -96410.9, BIC = -96361.6). Specifically, naming was slower on switch trials compared to stay trials ($F = 56.432$, $p < .0001$), and slower on L2 trials compared to L1 trials ($F = 17.383$, $p < .0001$). The interaction between language and transition type ($F = 5.461$, $p = .0195$) revealed that the switch cost in L1 (RT difference between L1 switch and L1 stay) was significantly larger than the

switch cost in L2. This result replicates the switch cost asymmetry found in many language-switching studies (e.g. Meuter & Allport, 1999; Jackson et al., 2001; Campbell, 2005; Philipp et al., 2007; Schwieter & Sunderman, 2008). Post-hoc analysis showed that the switch cost was significant both in Mandarin (32 ms; $t = 6.234$, $p < .0001$) and in English (16 ms; $t = 3.98$, $p < .0001$). The threshold was adjusted for the post-hoc analysis using Bonferroni correction ($0.05 / 2 = 0.025$).

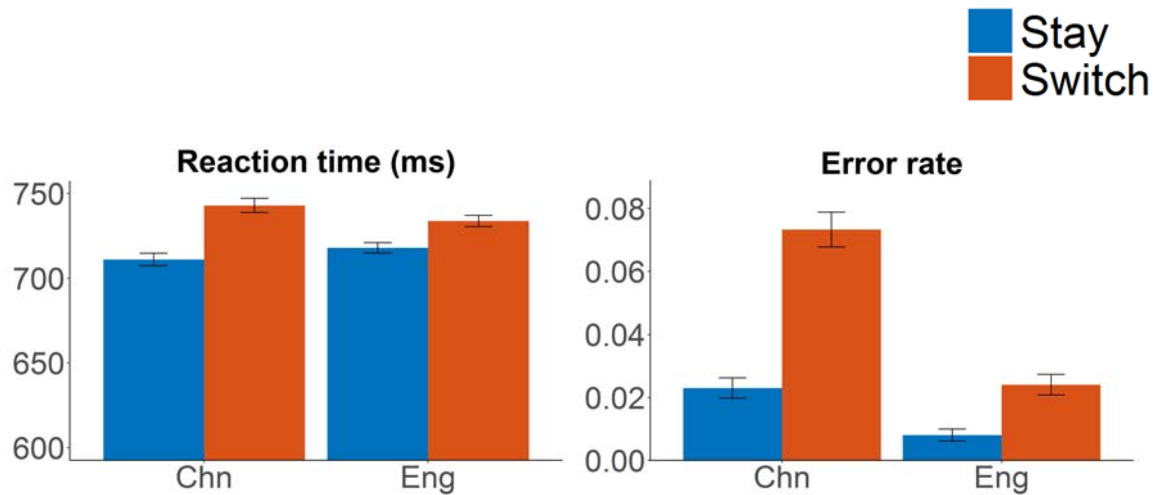


Figure 3-3. Mean reaction times and error rates as a function of language (L1 Chinese vs L2 English) and transition type (stay vs switch). “Stay” means staying in the language shown on the x-axis (i.e. previous trial and current trial are both in that language), and “Switch” means switching into the language shown on the x-axis (i.e. previous trial was in the other language). Error bars indicate one standard error above and below the mean values.

3.3.2 ERF results

Cluster-based permutation tests were performed on the ERF time courses from all sensors, time-locked to the cue onset and the target onset. This analysis revealed a main effect of language following target onset ($p = .0200$), meaning that the brain activity after the target digit appeared was significantly different between L1 and L2 trials. The sensors that formed the cluster were distributed around the right-frontal region (Figure 3-4 B), and the cluster occurred between 360 - 515 ms after

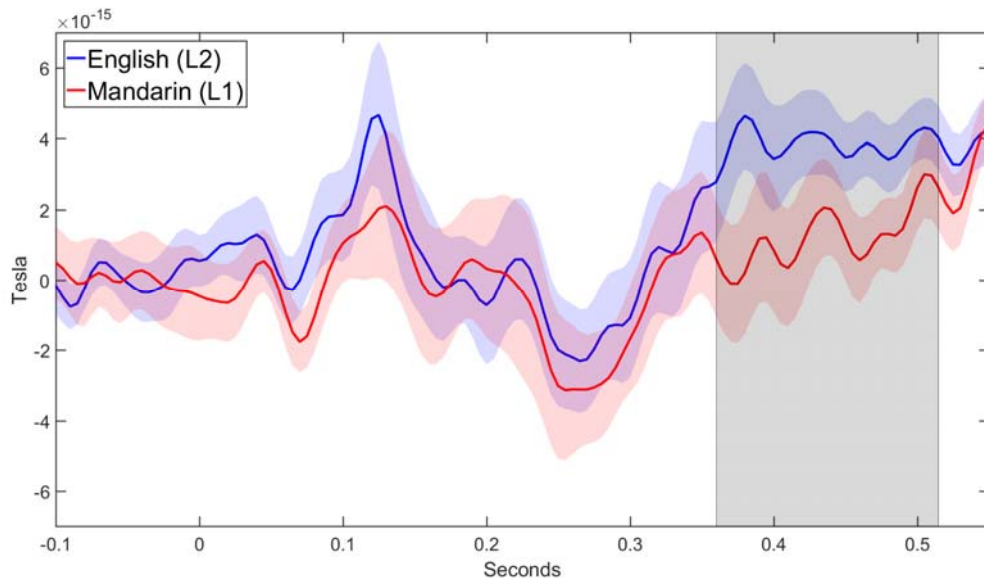
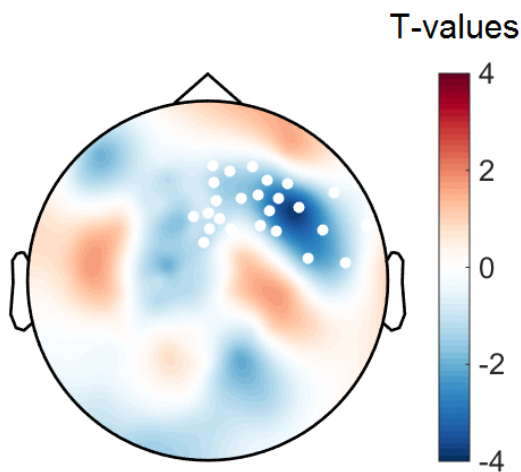
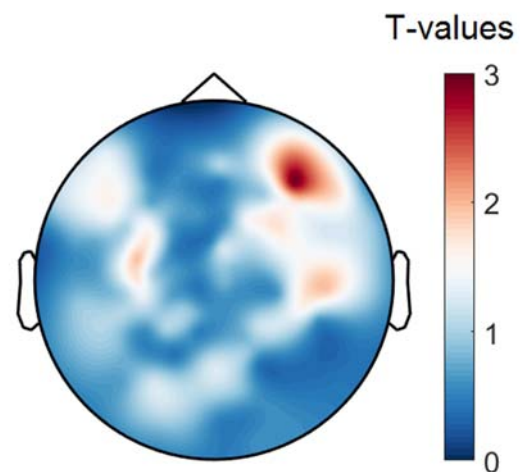
(A)**(B)****(C)**

Figure 3-4. Cluster-based permutation tests on the sensor-level ERFs revealed a main effect of language following target onset, corresponding to a right-frontal cluster between 360 - 515 ms after target presentation. **(A)** ERF time course averaged over all the sensors that formed the cluster, showing increased activity on English (L2) trials compared to Mandarin (L1) trials during this time interval. Time 0 is the onset of target digit, and the shaded region indicates the temporal extent of the cluster. **(B)** Topography averaged over the time interval of the cluster. White dots show the location of sensors which formed the cluster. **(C)** Topography transformed into planar gradients for illustration purposes.

target onset. The average ERF time course from these sensors showed increased evoked activity on L2 trials compared to L1 trials during this time interval (Figure 3-4 A). The sensor-level analysis revealed no significant clusters in the time window following cue onset and before target onset.

3.3.3 ROI results

The sensor data were mapped to source space to examine the brain activity in pre-defined ROIs: bilateral ACC, IFG, pre-SMA, and DLPFC. Source reconstruction was carried out using a LCMV beamformer (see Section 3.2.5.2). This produced a time course of brain activity in each condition for each ROI, time-locked to the cue onset and target onset. The time courses in each ROI were then submitted to statistical analysis using cluster-based permutation tests.

3.3.3.1 Cue-locked response: asymmetrical switch effect

Following cue onset, there was an interaction between language and transition type in the left IFG ($p = .0340$), revealing a significant difference between the switch effect in the two languages. This corresponded to a cluster occurring between 315 - 345 ms after cue onset. The reconstructed brain activity time course shows a larger switch effect for L2 compared to L1 (Figure 3-5); in other words, there was increased evoked activity in this brain region when switching from L1 production into L2 production, compared to switching in the other direction. Post-hoc t-tests showed that the switch effect in each language was not significant ($p > .1$). In all other ROIs, no significant clusters were identified in the time window following cue onset (see Appendix B).

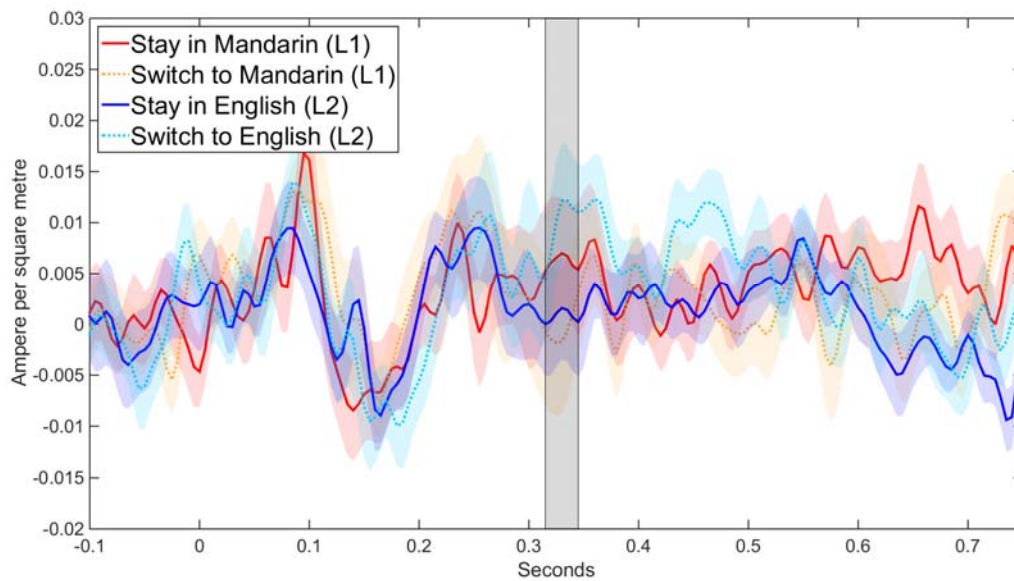


Figure 3-5. Reconstructed brain activity in left IFG in the cue-locked window. There was an interaction between language (L1/L2) and transition type (stay/switch), corresponding to a cluster between 315 – 345 ms following cue onset. This interaction was characterized by a larger switch effect for English (L2) compared to Mandarin (L1). Time 0 is the onset of language cue. Shaded region indicates the temporal extent of the cluster.

3.3.3.2 Target-locked response: language effect

Following target onset, there was a main effect of language in the right IFG ($p = .0450$), revealing a significant difference in the activity of this brain region between L1 and L2 trials. This effect corresponded to a cluster occurring between 200 - 230 ms. The right IFG showed increased activity when L2 production took place compared to L1 production (Figure 3-6). In all other ROIs, no significant clusters were identified in the time window following target onset (see Appendix B).

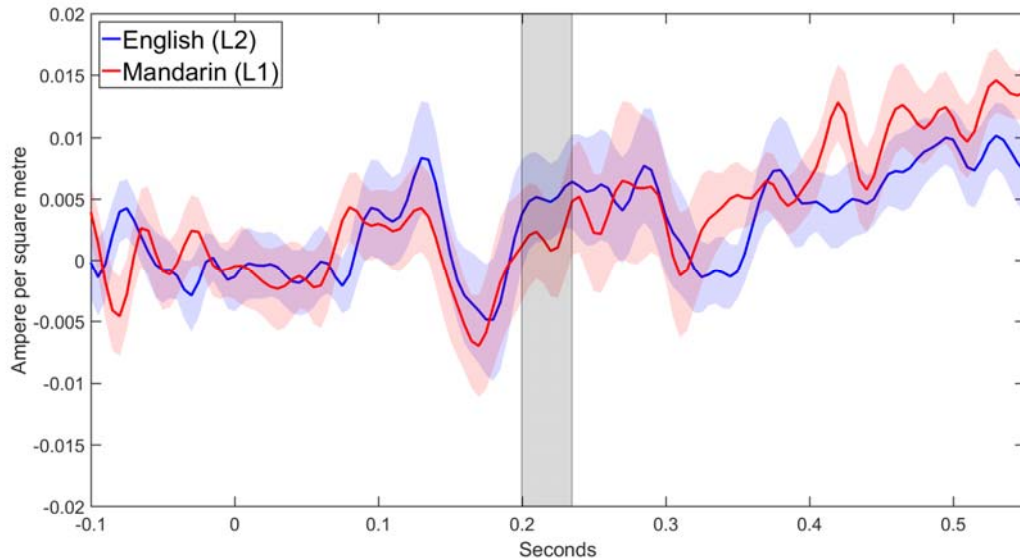


Figure 3-6. Reconstructed brain activity in right IFG in the target-locked window. There was a main effect of language, corresponding to a cluster between 200 – 230 ms following target onset. Increased activity was observed in this brain region on English (L2) trials compared to Mandarin (L1) trials. Time 0 is the onset of target digit. Shaded region indicates the temporal extent of the cluster.

3.4 DISCUSSION

This MEG study investigated the neural mechanisms of language control underlying bilinguals' ability to switch language in speech production. The main aim was to examine *when* control processes take place during language switching: as soon as the bilingual knows which language to speak, or only after they know specifically what to say. To resolve the discrepancy in previous findings (Verhoef et al., 2009, 2010; Chang et al., 2016; Blanco-Elorrieta & Pylkkänen, 2017), we brought together a number of design improvements in this study, as detailed in the Methods section.

3.4.1 When does language control take place?

Our main research question concerns the timing of the control processes in language switching: do they take place following the cue or following the target? Results suggest that control processes are engaged at both stages. In the cue window, we found an interaction between language and transition type, indicating an asymmetrical switch effect across the two languages. This interaction was characterised by increased brain activity in the left IFG when switching from L1 into L2 (compared to switching in the other direction). A similar effect was reported by Hosoda, Hanakawa, Nariai, Ohno, and Honda (2012) in an fMRI study on unbalanced Japanese-English bilinguals. In the language-switching literature, the left IFG has a proposed role of resolving interference from the non-target language, especially controlling interference posed by the dominant language (Green & Abutalebi, 2013; Rodriguez-Fornells, Rotte, Heinze, Nösselt, & Münte, 2002). The asymmetrical switch effect in the present study suggests that the left IFG has to exert more effort to suppress the dominant L1 (when this becomes the irrelevant task), but not as much effort to suppress the L2 (when switching away from that weaker language). Because such strong suppression is applied on L1, when the bilingual subsequently needs to switch back to L1, they have to overcome this suppression. This interpretation is corroborated by our behavioural results, where the RT switch cost was larger in L1 compared to L2 (i.e. when switching into the dominant language, it takes longer to overcome the prior inhibition applied on this language). The fact that the switch effect in the left IFG was not significant within each language may be a reflection of its small magnitude compared to the switch effect found in most previous studies; this is likely due to our deliberate design decisions to separate cue-related switching processes as much as possible from the actual language-switch effect, so that we could truly observe the specific effect of language switching. An alternative explanation for the asymmetrical switch effect in the left IFG, which does not involve inhibition of the non-target language, is also possible. Because L2 is the weaker language, increased cognitive control is required

to re-activate L2 after L1 production, hence the switch effect is larger when switching from L1 into L2. According to Branzi, Martin, Carreiras, and Paz-Alonso (2020), this effort to boost the target language activation occurs as a proactive control mechanism during the cue window; this is consistent with our observation. In this case, the behavioural asymmetry (larger switch cost for switching into L1) can be explained by assuming that the now-strongly-activated L2 induces a larger carry-over effect on the L1 than the other way round (Branzi, Martin, Abutalebi, & Costa, 2014; for similar interpretations in the task-switching literature, see Kiesel et al., 2010 for a review).

In the target window, we found a main effect of language, suggesting that the amount of control required for speaking L2 differs significantly from speaking L1. The ERF results revealed a right-frontal cluster showing increased activity on L2 trials compared to L1 trials; a corresponding effect occurred in the reconstructed activity for the right IFG in source space, where larger brain activity was observed on L2 trials compared to L1. This finding is consistent with a recent fMRI study reporting increased activity in the IFG during the target window for L2 naming compared to L1 naming (Reverberi et al., 2015). The right IFG has a well-known role in response inhibition (for reviews, see Aron et al., 2004 and 2014) and has also been shown to be involved in language inhibition (de Bruin et al., 2014). The stronger activation of this brain region during L2 production likely reflects the control processes to inhibit the prepotent L1 label in order to resolve lexical competition. Despite the earlier regulation of the two languages following cue onset, the presentation of the target may still activate the corresponding labels for that digit in both languages. In order to correctly produce the response in the required language, bilinguals must be able to manage this competition. One way to do this would be to inhibit the competing label in the non-target language. It is possible that bilinguals apply such inhibition throughout language production, that is, when they are speaking one language, they are constantly inhibiting the other language. However, due to the proficiency difference in the two languages, the L1

labels should have a higher level of baseline activation, such that bilinguals need to apply stronger inhibition on the competing L1 label during L2 production than vice versa. Green (1998) suggested that the amount of inhibition applied on a language is proportional to the relative dominance of that language in the bilingual individual. Our findings are consistent with this proposal. The increased activation of right IFG on L2 trials (compared to L1) shows that stronger inhibition is applied during L2 production, suppressing the dominant L1 label so that the correct response in L2 can be produced on these trials. An alternative possibility is that the increased right IFG activity on L2 trials reflects salient cue detection rather than inhibition (Green & Abutalebi, 2013; Hampshire, Chamberlain, Monti, Duncan, & Owen, 2010; Chatham et al., 2012). Because L2 is the more difficult language for these bilingual speakers, the cue to speak L2 may prompt a larger response in this brain region. However, if the effect in the right IFG is truly related to cue detection, it would make more sense if the effect occurred in the cue window (rather than occurring after target onset). Therefore, we believe the first interpretation is more likely. A few limitations should be noted here. Firstly, as the bilingual participants have different proficiency levels in their two languages, for a main effect of language (where the less proficient language requires more mental effort than the more proficient language) we cannot rule out the possibility that this is a language dominance effect. Similarly, due to intrinsic differences between languages, we also cannot completely rule out the possibility that the main effect of language is caused by the low-level properties (e.g. phonological differences) of the two languages. Secondly, previous research suggests that immersion in the L2 environment could influence L1 activation and the interaction between the two languages (Linck, Kroll, & Sunderman, 2009; Malt, Li, Ameel, Pavlenko, & Zhu, 2013). Although it is unlikely that our participants have switched language dominance (given that all of them maintained active use of their L1 in daily life and their self-rated proficiencies indicated a strong dominance in L1; see Table 3-1), their experience of living in an English-speaking country may nonetheless have

reduced the gap between their L1 and L2 compared to bilinguals who live in a purely L1 environment.

The other ROIs we tested (ACC, pre-SMA, and DLPFC) did not show an effect in either the cue or target window. This does not necessarily mean that these brain regions are not involved in language switching, given the current neural models of bilingual control (Abutalebi & Green, 2008; Green & Abutalebi, 2013) and existing findings from neuroimaging studies suggesting possible roles of these brain areas in language control (Abutalebi et al., 2012; Wang et al., 2007; Hernandez et al., 2001; de Bruin et al., 2014; Wang et al., 2007; Blanco-Elorrieta & Pylkkänen, 2016, 2017). It may be that the source activity reconstruction from MEG sensor data does not offer the same level of spatial preciseness as fMRI, or the definition for these ROIs differ slightly depending on the atlases used by each study. It should be pointed out that even among the existing fMRI studies, the exact location reported to be activated in language control vary from one study to the next; the general consensus is that language control engages brain areas that are associated with executive function. We provide the reconstructed source activity for all the non-significant ROIs in Appendix B.

3.4.2 Global vs local control

De Groot and Christoffels (2006) suggested that language control may act upon an entire language (*global control*) or upon specific lexical items (*local control*). A few studies have since attempted to explore this aspect of bilingual language control (for a review, see Baus, Branzi, & Costa, 2015). De Groot (2011) argued from a theoretical perspective that local control should be the primary type of language control in bilinguals, while global control may be dispensable. Van Assche, Duyck, and Gollan (2013) observed both global and local control in Mandarin-English bilinguals in a verbal fluency task. In recent fMRI studies, Branzi, Della Rosa, Canini,

Costa, and Abutalebi (2016) reported dissociable brain mechanisms for global and local control in language switching (also see Abutalebi & Green, 2016, for a discussion on this), while Rossi, Newman, Kroll, and Diaz (2018) went one step further to examine three possible levels of language control (lexical, semantic category, whole language) and found that different parts of a wide control network are engaged at each level.

In the present study, we observed that control processes are engaged both following the cue and following the target. We propose that these processes may operate on different levels of the language system. Following cue onset, the bilingual knows which language they need to speak, but the specific digit to be named is not yet known. Therefore, any control processes taking place at this stage are likely to operate on the whole-language level (or at least on the whole set of naming targets, i.e. digits 1 – 9). Each language would be treated as a task set, and the activation level of each task set is adjusted as a whole: the target language is made more active, while the non-target language is made less active. Such activation/inhibition applied on the language/set level may then get passed down to all the individual lexical representations in each language. When switching from L1 to L2, the left IFG works extra hard to suppress interference from the L1 task set (and possibly all the lexical representations in L1), in order to facilitate the switch to L2. Following target onset, the bilingual knows exactly what they need to name. At this stage, it now becomes possible to apply control on selected lexical items, specifically targeting the highly-activated representations in order to resolve any remaining competition. The fact that control is still required at this stage suggests that the whole-language control during the cue window alone was not sufficient to guarantee correct production. For example, if the bilingual needs to switch into L2 and name the digit '5', even though the L1 representation of '5' is suppressed during the cue window (as a result of the overall suppression applied on L1 upon seeing the L2 cue), the display of the digit '5' at target onset may nonetheless activate the L1 representation highly enough to form a competition with the

desired output (i.e. corresponding L2 representation); to avoid erroneous output, that specific L1 label needs to be suppressed again, and this can be accomplished via a response-inhibition mechanism involving the right IFG.

3.4.3 Conclusions

In real-life conversations, a bilingual speaker knows which language they need to speak before planning the utterance (this knowledge is acquired by checking who they are speaking with). This process can be considered analogous to seeing the face cues in this experiment. Based on this knowledge, they are able to apply some forms of proactive control (Wu & Thierry, 2017; Woumans et al., 2015), suppressing interference from the non-target language as a whole and biasing production towards the target language. However, even with such proactive control in place, a bilingual would still find that words from the non-target language sometimes pop into their mind, so they need to swallow them back to avoid actually saying these words. This is comparable to the reactive control we observed following target onset, which serves to inhibit competing words from the undesired language. We conclude that language control is a complex behaviour which engages multiple processes taking place at distinct stages (proactive and reactive) and acting on different levels of the language system (global and local) during bilingual speech production.

Author contributions

JDZ and PFS conceived and designed the study. JDZ collected the data. JDZ performed the analyses with support from PFS and RAS. All authors contributed to interpreting the results and writing the manuscript.

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Declaration of competing interest

None.

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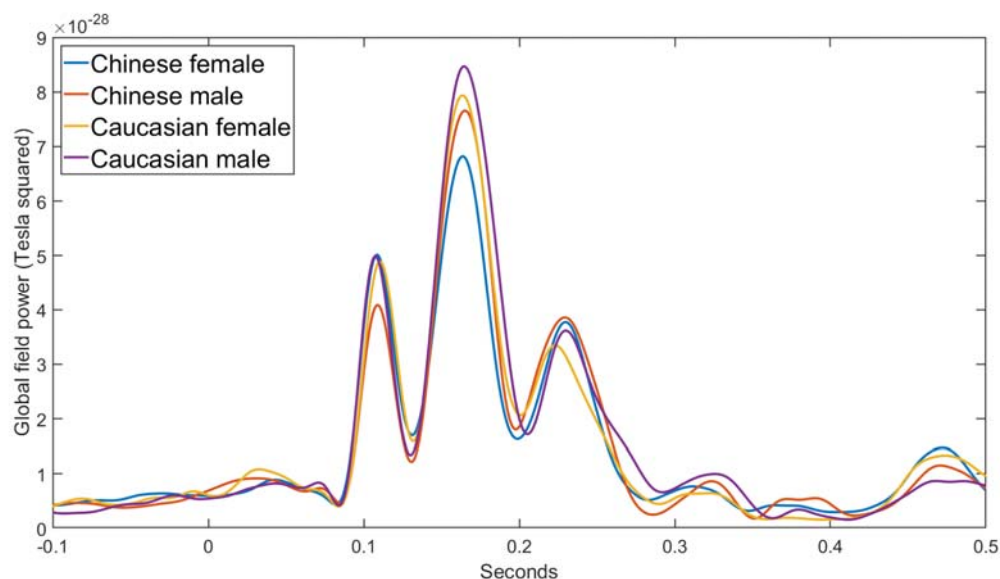
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Appendix A. Pilot study to verify the validity of face cues

Using faces as language cues introduces a potential concern that own-race and other-race faces might produce different brain responses. This would result in an artificial effect which confounds with a main effect of language. To address this concern, we ran a pilot MEG study to check if there was any difference in the visual evoked field (VEF) elicited by the two Chinese faces and two Caucasian faces. In this pilot study, participants viewed the four faces repeatedly in a random sequence. The procedure was the same as the main experiment, except that digit stimuli were not shown and there was no active task for the participant to perform.

Twelve Mandarin-English bilinguals participated in this pilot experiment. The participants were drawn from the same population as those in the main experiment. Importantly, these participants had not been exposed to the language-switching task, so their neural response to the face stimuli would reveal the effect of recognising faces belonging to different races, but not the effect of switching language upon seeing a face of a different race. The former is precisely what we are interested in controlling for, to ensure any effect we observe in the main experiment are specifically related to language switching.

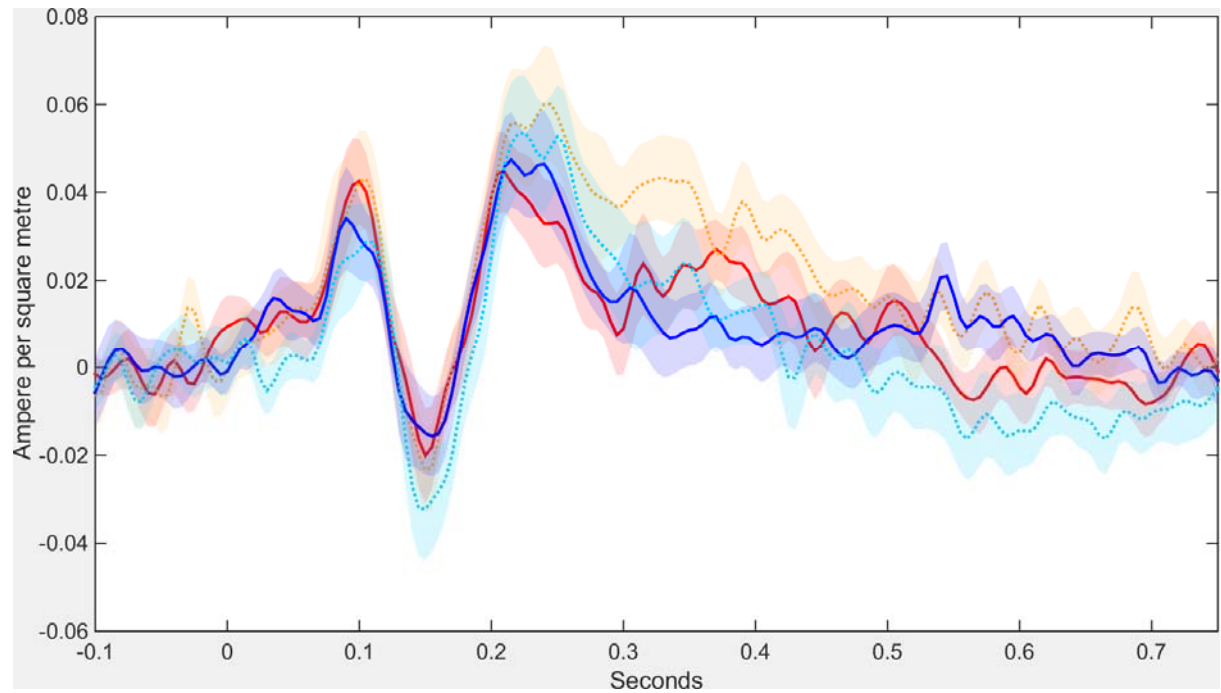
Sensor-space analysis of the VEF was performed following the same procedure as in the main experiment (see Methods). We examined whether there was any race effect that distinguished between the Chinese faces and Caucasian faces. Cluster-based permutation test revealed no significant cluster ($p > .05$). The global field power elicited by each face (averaged across subjects) are plotted below for illustration purpose.



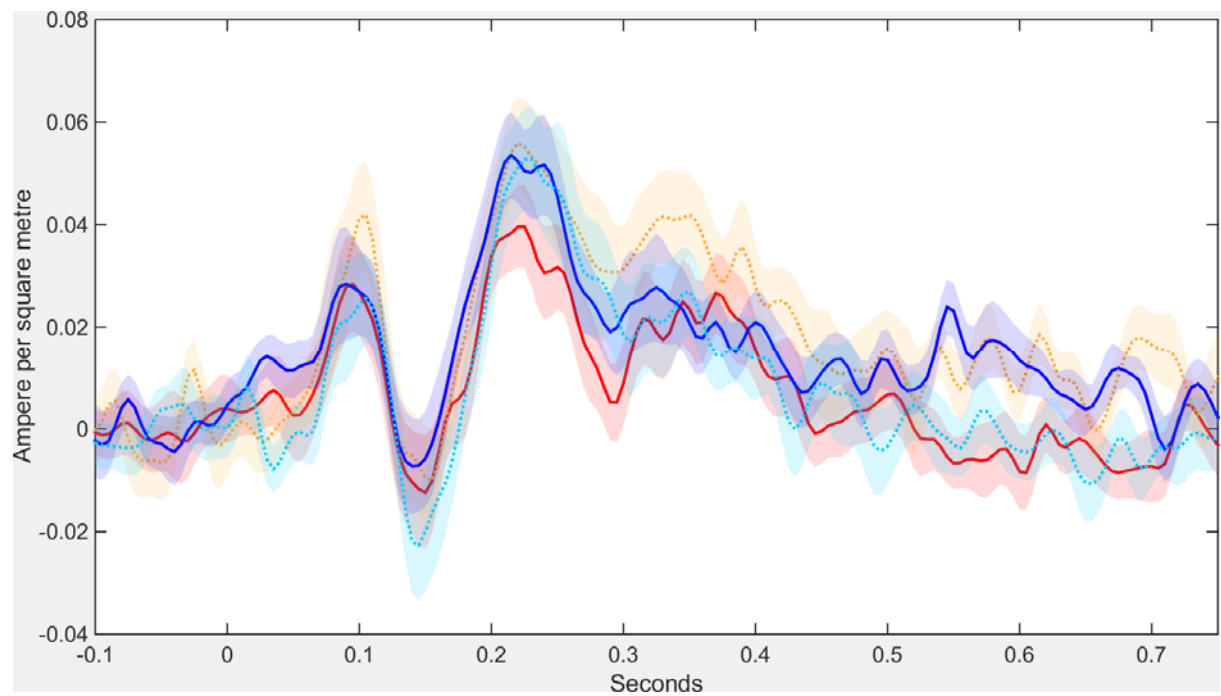
Appendix B. Reconstructed source activity in all remaining ROIs (where no significant effects were found)

(1) In the cue-locked window (time 0 is cue onset):

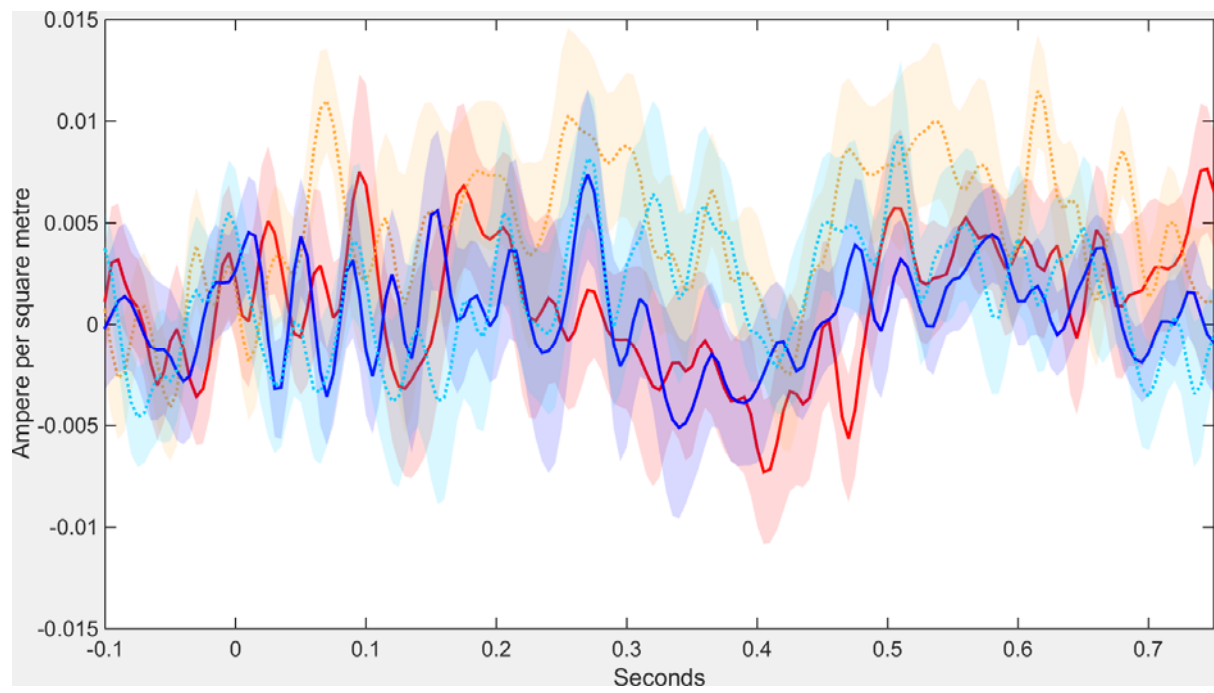
Left ACC



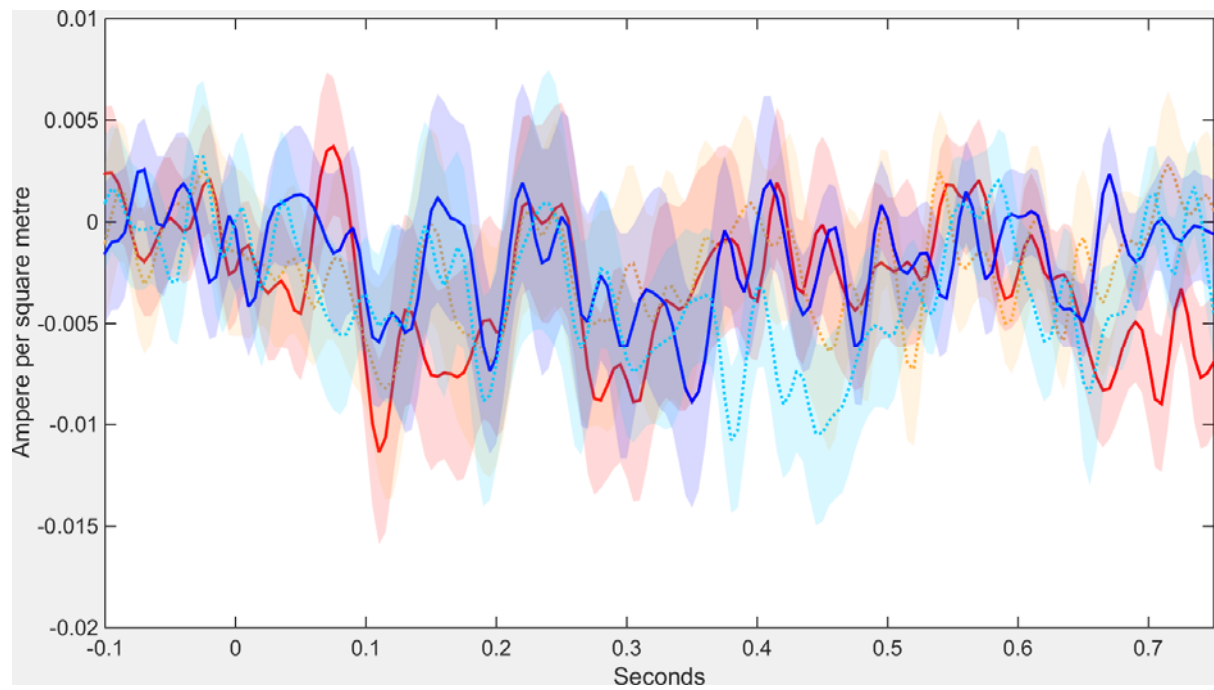
Right ACC



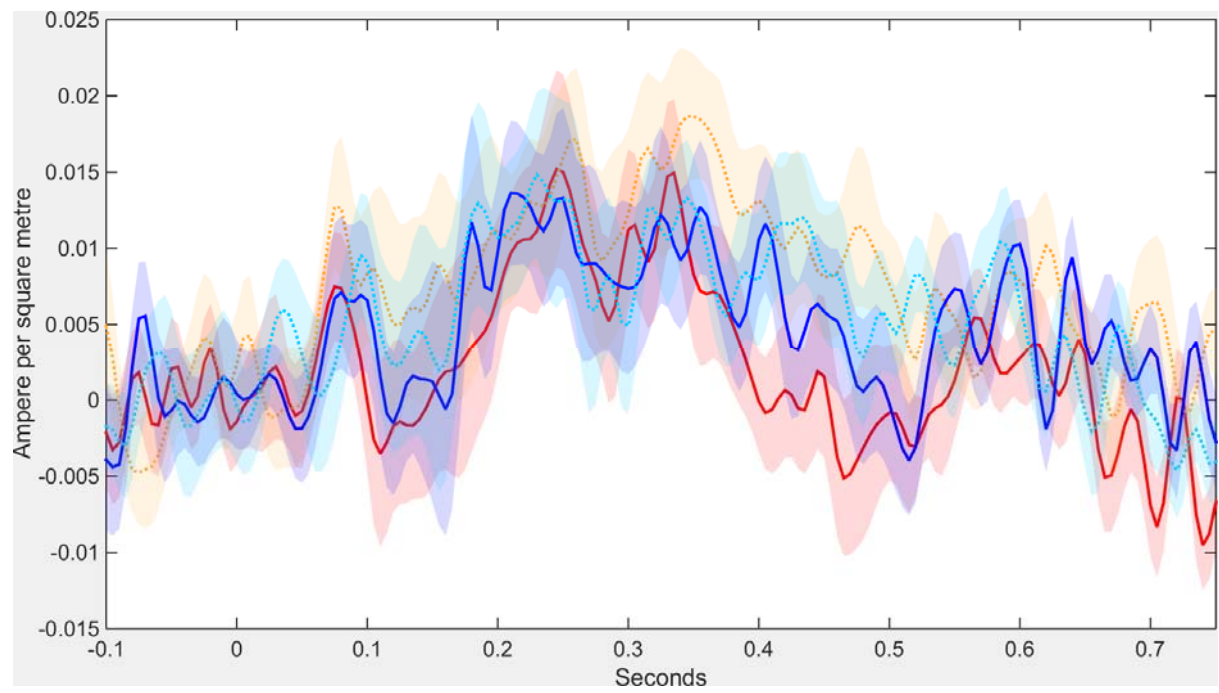
Left DLPFC



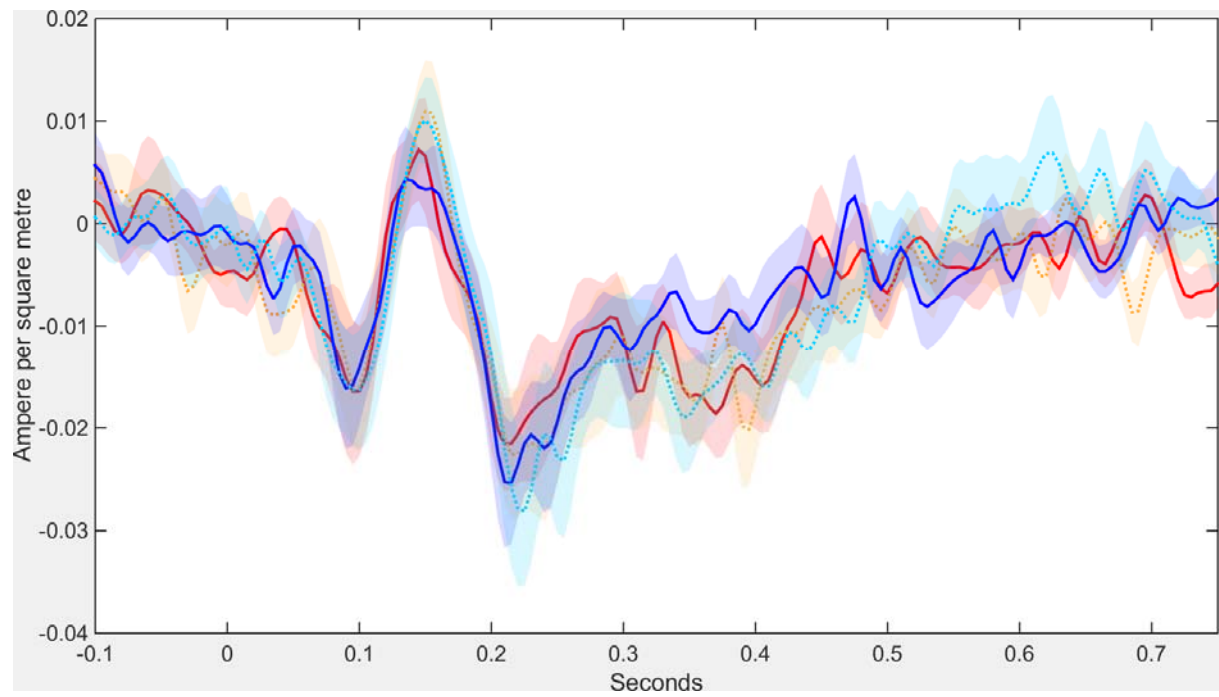
Right DLPFC



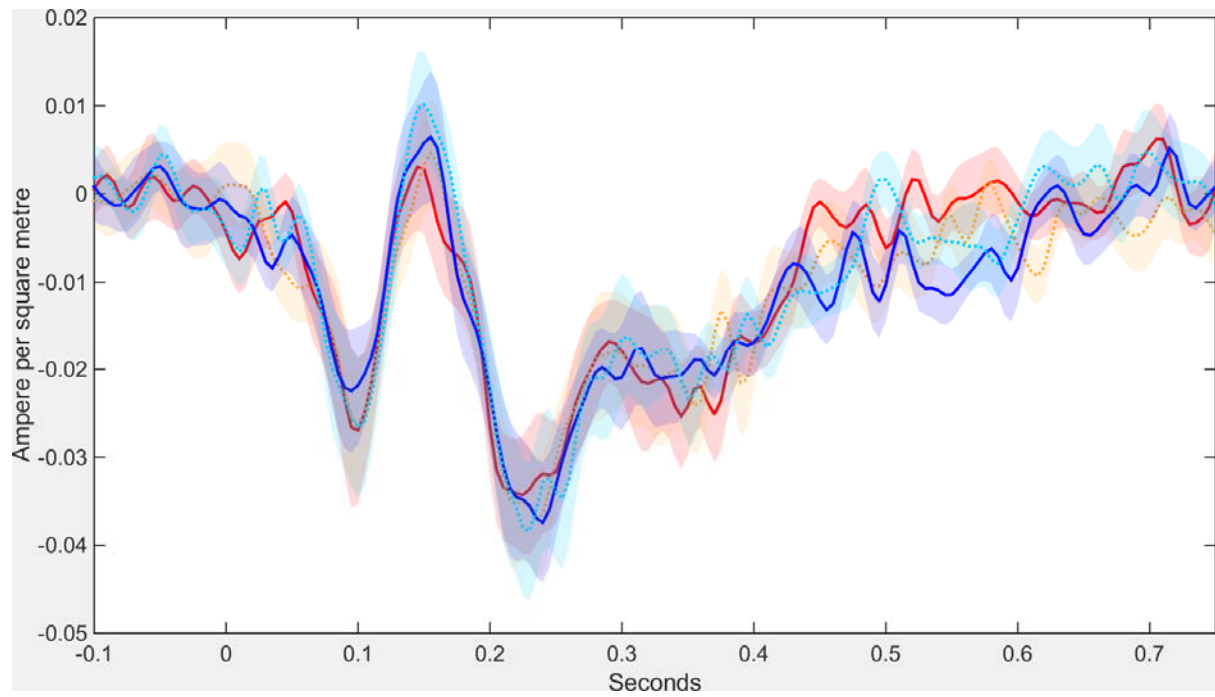
Right IFG



Left pre-SMA

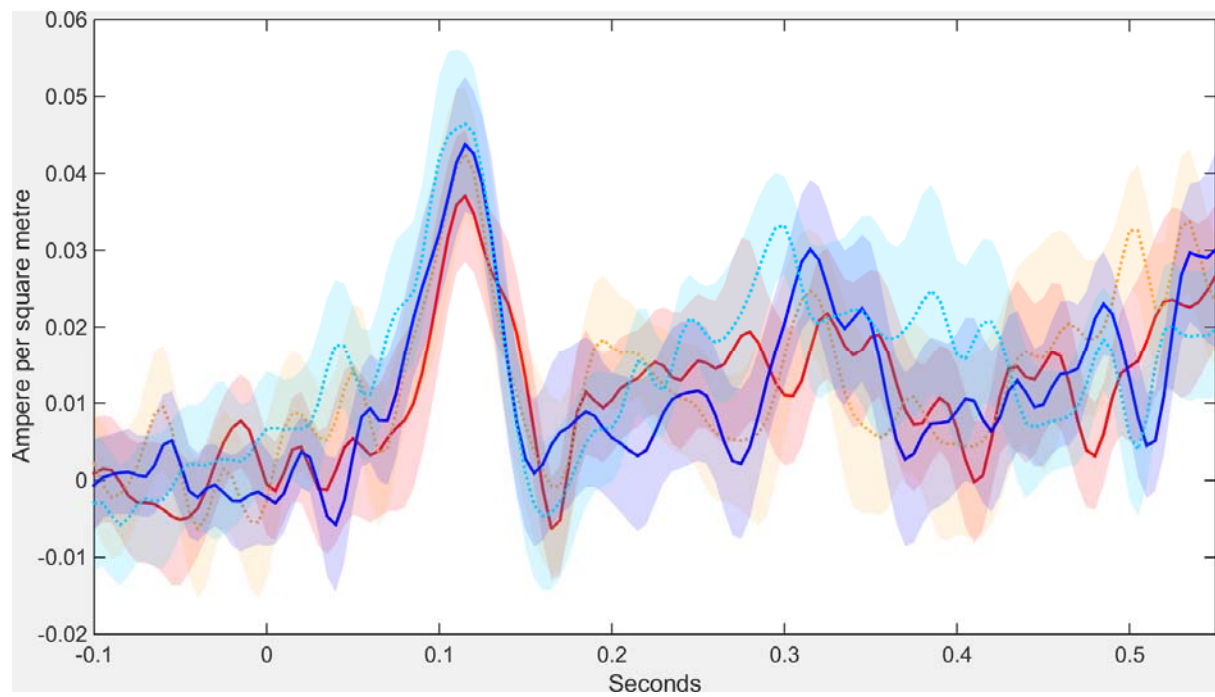


Right pre-SMA

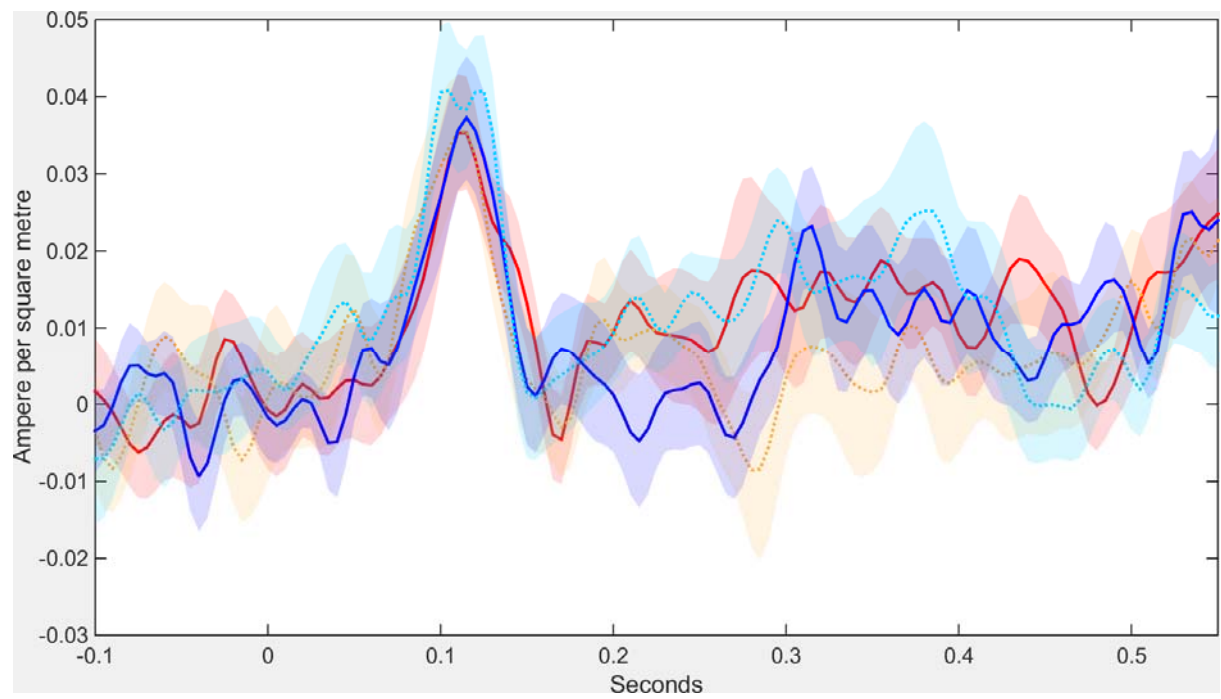


(2) In the target-locked window (time 0 is target onset):

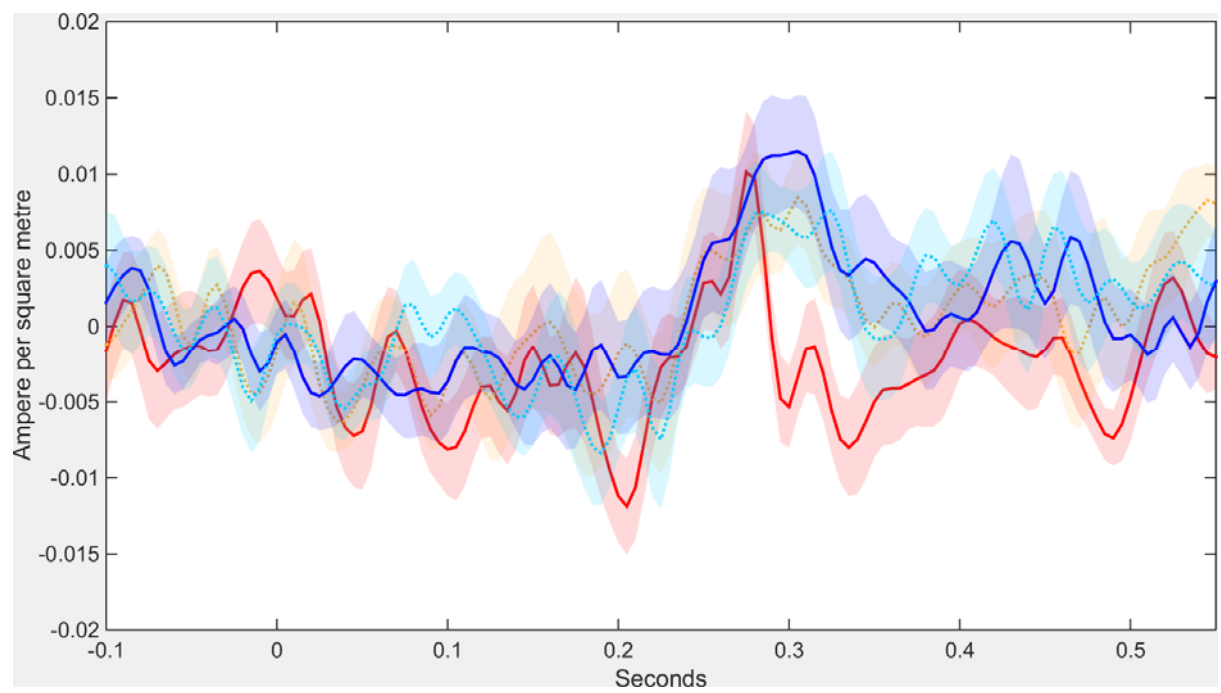
Left ACC



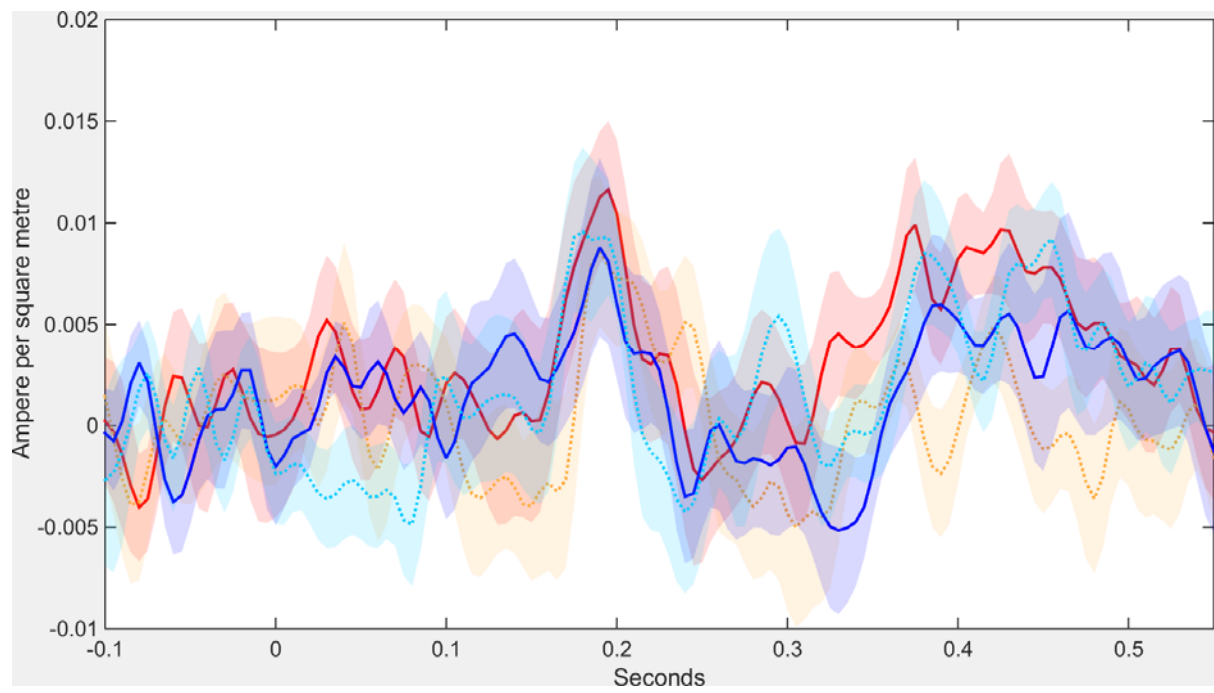
Right ACC



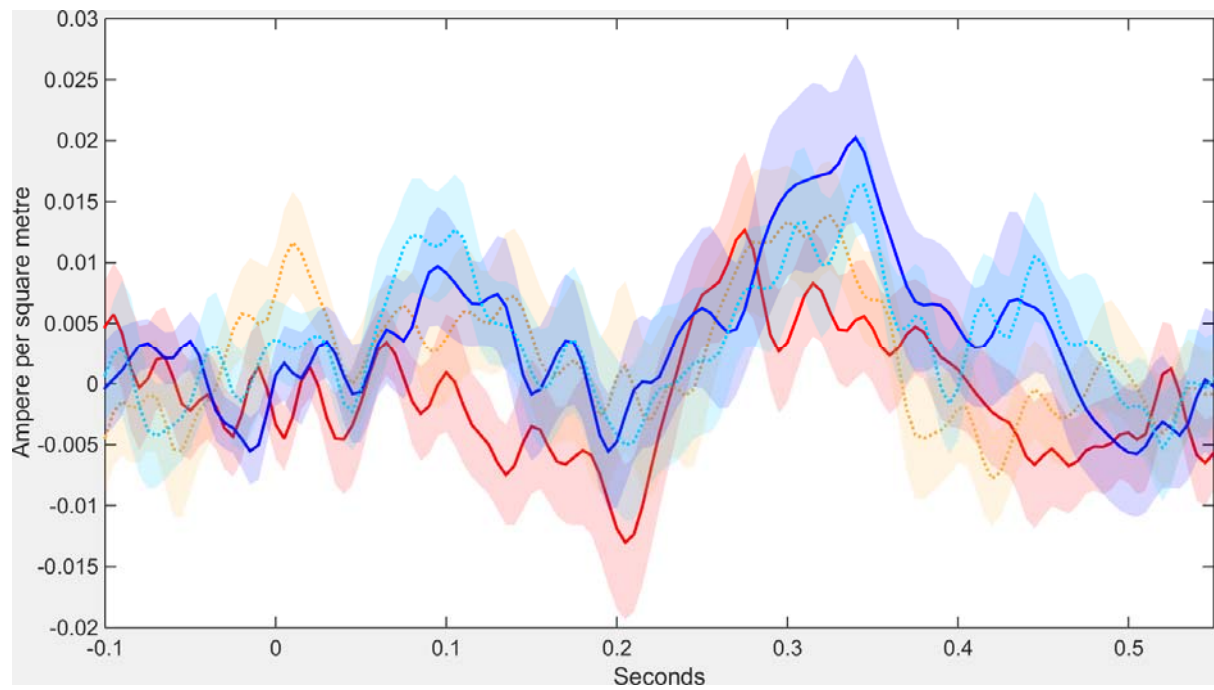
Left DLPFC



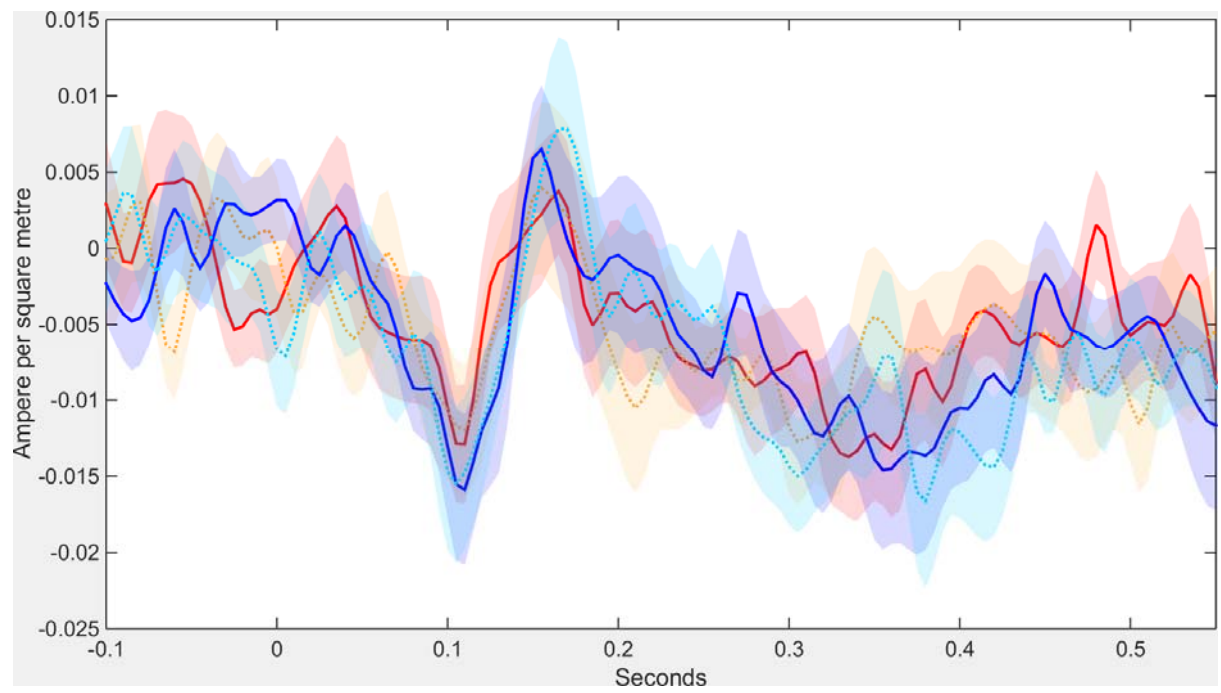
Right DLPFC



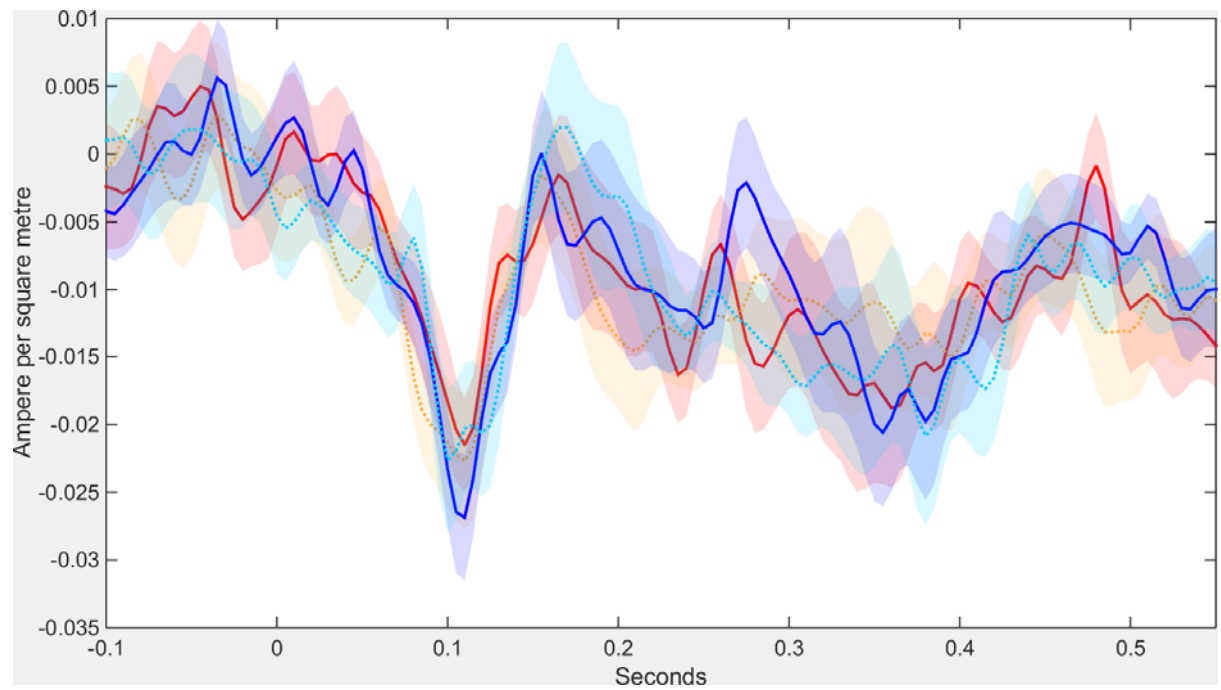
Left IFG



Left pre-SMA



Right pre-SMA



Appendix C. Data archiving

The raw data collected in this study can be accessed at the following link:

<https://cloudstor.aarnet.edu.au/plus/s/SC25Uzjpqqfle6b>

CHAPTER 4

Is natural language switching easier than forced switching (and why)?

In preparation for publication:

Zhu, J. D., Blanco-Elorrieta, E., Sun, Y., Szakay, A., & Sowman, P. F. Is natural language switching easier than forced switching (and why)?

Published as: Zhu, J. D., Blanco-Elorrieta, E., Sun, Y., Szakay, A., Sowman, P. F. (2022) Natural vs forced language switching: free selection and consistent language use eliminate significant performance costs and cognitive demands in the brain, *NeuroImage*, Vol. 247, 118797, <https://doi.org/10.1016/j.neuroimage.2021.118797>. Under a Creative Commons license.

Abstract

Bilinguals are known to switch between languages spontaneously in everyday conversations, even when there are no external requirements to do so. However, in the laboratory setting, language switching is often studied using forced switching tasks, the cognitive control demands of which are reflected in significant performance costs. The present study aimed to compare natural language switching to cued (forced) switching under the hypothesis that the former is easier than the latter. We further sought to uncover factors that might account for such a difference. The effects of language switching and mixing were compared across three production contexts: *natural* (free language selection, with strongly language-biased items), *artificially-consistent* (forced language selection, with each item always mapped to the same language), and *bivalent* (similar to traditional cued switching). The artificially-consistent context was designed as an “intermediate step”, to help tease apart two factors which differed between the natural and bivalent contexts: (1) consistency of item-language mappings (2) freedom of language selection. Behaviourally, bivalent switching incurred significantly greater switch cost and mixing cost compared to the natural context. Neural activities recorded using magnetoencephalography (MEG) suggest that language mixing in the natural context required *less* cognitive control than single-language production. Such a mixing advantage was not observed in the other two contexts, indicating that freedom of language selection was essential to obtain this advantage. Furthermore, the bivalent context was associated with increased activity in the right anterior cingulate cortex, as well as a switch-related activity increase in the right inferior frontal gyrus. These effects were not observed in the other two contexts, possibly reflecting extra demands for conflict monitoring and inhibitory control due to the inconsistent item-language mappings in bivalent switching. Taken together, the present findings suggest that natural language switching is easier than forced switching, with both consistent item-language mappings and free language selection being factors that contribute to this difference.

4.1 INTRODUCTION

In day-to-day life, bilinguals need to coordinate their languages to ensure that they speak the appropriate language at any given time. Such language control has been studied extensively using the cued language-switching paradigm (e.g. Meuter & Allport, 1999; Costa & Santesteban, 2004; Christoffels, Firk, & Schiller, 2007; Wang, Kuhl, Chen, & Dong, 2009; de Bruin, Roelofs, Dijkstra, & FitzPatrick, 2014; Jylkkä, Lehtonen, Lindholm, Kuusakoski, & Laine, 2018). In this paradigm, bilinguals typically perform a naming task, with cues on each trial instructing them which language to use. On a given trial, the language requirement may change from the preceding trial (*switch trial*) or stay the same (*stay trial*). Sometimes single-language blocks (in which the same language is used on all trials) are also included for comparison. These studies usually report significant *switch costs* (poorer performance in the comparison of switch vs stay trials) and *mixing costs* (comparison of stay trials vs single-language blocks). Consistent with these behavioural costs, neural findings generally show additional cognitive control engagement, reflecting extra effort associated with language switching and mixing. However, the cued switching paradigm only represents one type of situation that bilinguals may encounter in daily life, i.e. speaking the appropriate language to match what their conversational partner can understand. On the other hand, it is well known that bilinguals also switch languages spontaneously when there are no external requirements to do so. For example, when speaking with someone who shares both languages, they can switch seamlessly between the two languages. Is this type of free switching different from forced switching? Does it still cost extra time and cognitive resource?

To better understand free language switching in bilinguals, it is useful to create a context where participants can choose for themselves whether (and when) to switch language. One possible motivation behind spontaneous switching is that a bilingual may find some words more easily accessible in one language than

another; as such, freedom of language choice may elicit natural switches based on lexical accessibility. A few studies have so far examined this kind of language switching, both behaviourally (Gollan & Ferreira, 2009; Gollan, Kleinman, & Wierenga, 2014; Kleinman & Gollan, 2016; de Bruin, Samuel, & Duñabeitia, 2018) and with neuroimaging (Zhang et al., 2015; Blanco-Elorrieta & Pylkkänen, 2017; Reverberi et al., 2018; Liu et al., 2020). Most of these studies adopt the *fully voluntary* design, where participants are free to use whichever language they like on each trial. The fully voluntary context generally results in faster reaction times overall than cued switching; however, a significant behavioural switch cost is still observed in most cases (e.g. Gollan et al., 2014; Kleinman & Gollan, 2016; de Bruin et al., 2018; Zhang et al., 2015; but see Gollan & Ferreira, 2009, Exp. 2; Blanco-Elorrieta & Pylkkänen, 2017). Some studies also report a neural switch effect in the voluntary context (Zhang et al., 2015), while other studies do not (Blanco-Elorrieta & Pylkkänen, 2017; Reverberi et al., 2018). The voluntary mixing effect is less commonly examined, with evidence suggesting a facilitation on naming speed either for both languages (de Bruin et al., 2018) or the non-dominant language (Gollan & Ferreira, 2009; see also Gross & Kaushanskaya, 2015, for facilitation of non-dominant language in naming accuracy). There are not yet any reports on whether a neural correlate of the mixing effect exists in the voluntary context.

Gollan et al. (2014, Exp. 2) made an interesting discovery that the voluntary switch cost can be influenced by the strategies adopted by the participants. In this experiment, a small set of stimuli (eight pictures with high-frequency names) were repeatedly presented for naming. Overall, there was a significant switch cost in the voluntary context (marginally smaller than in cued switching). However, when the participants were divided into two groups, based on how consistent they were in always naming the same picture in the same language, the switch cost patterns diverged between the groups. Specifically, the group that maintained consistent language choice for most pictures achieved a significant switch cost reduction compared to cued switching (and the voluntary switch cost itself was no longer

significant); on the other hand, the group that did not maintain such consistency incurred a switch cost of similar magnitude to cued switching. The authors suggested that in the first group of bilinguals, voluntary language switches were mostly driven by bottom-up processes (i.e. based on lexical accessibility), hence they were able to switch without a cost to performance; in contrast, the second group of bilinguals applied top-down control even in the voluntary context (possibly as a consequence of the laboratory setting), and thus incurred switch cost just as they did in the cued switching context. These findings demonstrate that voluntary switching can be cost-free if the switches are driven by automatic processes (rather than intentionally switching). Kleinman and Gollan (2016) further investigated whether such a bottom-up strategy would enable all bilinguals to switch language more efficiently if they are explicitly instructed to do so. This study introduced a *bottom-up switching* context, where participants were free to choose their preferred language the first time they saw a picture, but were required to continue with the same language choice for each subsequent appearance of that picture (i.e. maintaining consistent item-language mappings). Language switching in the bottom-up block incurred no switch cost⁶², which represented a significant cost reduction in comparison to both cued switching and fully voluntary switching in the same study. Performance within the bottom-up block was further analysed by dividing participants into two groups, according to whether they completed this block before or after the cued block (i.e. “cued-first” vs “bottom-up-first” bilinguals). The bottom-up-first group exhibited significantly smaller switch cost and mixing cost compared to the cued-first group. This pattern was even more pronounced in the second half of the bottom-up block, where the mixing cost became non-significant for the bottom-up-first bilinguals (but remained significant for the cued-first bilinguals). These findings suggest that bottom-up switching is more efficient than cued switching and fully voluntary switching; however, such

⁶² With a Bayes factor favouring non-existent switch cost.

efficiency can be hindered by prior performance of cued switching. This influence from the prior cued block might be due to altering participants' strategy (i.e. they entered a top-down mode in the cued block, which persisted into the subsequent bottom-up block), or due to contamination of the consistent item-language mappings (as all items were named in both languages in the cued block).

Kleinman and Gollan (2016) argue that the bottom-up switching design ensures that bilinguals adhere to their preferred language for each item (and therefore do not need to apply any top-down control), whereas in the fully voluntary design, the participants might still be applying some sort of control (e.g. switching for the sake of switching). This view is supported by evidence from de Bruin et al. (2018), where a mixing benefit was observed overall in the voluntary context but it was larger on items that were more consistently named in the same language. Thus, consistency of item-language mappings seems to promote a bottom-up strategy in lexical selection, resulting in increased efficiency in language switching and mixing. However, the disadvantage of the bottom-up design is that there is an external requirement attached, i.e. it is the participant's responsibility to ensure that consistent item-language pairings are maintained. Therefore, participants do not enjoy complete freedom of language selection (as they would in a fully voluntary design), and the extra requirement (to keep track of which language they are using for each item and to continuously monitor that they are using the correct language at any given time) could very well add to the demand for cognitive control in this task. In other words, the advantage of the fully voluntary design is that participants are freed from imposed constraints; in contrast, the advantage of the bottom-up design is that participants adopt a strategy where lexical accessibility naturally drives language selection. In order to incorporate the strengths of both of these approaches, we implement a modified design which makes use of strongly language-biased stimuli, such that the name for each object is only accessible in one particular language (for details on how these items are selected, see Section 4.2.2.1). In this case, bilinguals are very likely to maintain consistent language

choice in naming each item, even without explicit instructions to do so. Thus, participants still have complete freedom in language selection (based on their own lexical accessibility, without any external constraints), while consistent mappings are also achieved at the same time (ensuring that they do not switch language for the sake of switching, which may invoke unnecessary control). We refer to this as the *natural* switching context. In this study, we compare bilinguals' performance in the natural switching context to that in traditional cued switching (which we shall refer to as *bivalent* context, highlighting the fact that each item elicits responses in both languages in that context).

The natural context differs from the bivalent context in two respects. Firstly, language selection on each trial is free rather than forced. Secondly, each target item always elicits responses in the same language (i.e. consistent mappings). Therefore, if we observe a switch cost or mixing cost difference between the two contexts, that could be a result of either of these factors, or a combined effect of both. In order to tease apart the roles of these two factors, we include another context in which language selection is forced (i.e. according to cues) but each item is always named in the same language. In other words, consistent item-language mappings are artificially enforced by the language cues provided. We call this the *artificially-consistent* context. This context acts as an "intermediate step" between natural and bivalent switching (see Table 4-1), so that the contribution of the two factors mentioned above can be examined in a stepwise manner. Specifically, the comparison between the artificially-consistent context and the bivalent context will reveal the effect of maintaining consistent item-language mappings, while the comparison between the natural context and the artificially-consistent context will reveal the effect of having freedom in language selection.

	<i>Forced language selection</i>	<i>Free language selection</i>
<i>Inconsistent mappings</i>	cued / bivalent	fully voluntary *
<i>Consistent mappings</i>	artificially-consistent	natural / bottom-up

* Not examined in the present study.

Table 4-1. A comparison of different language-switching contexts. These contexts are classified here based on whether language selection is free or forced, and whether consistent item-language mappings are maintained. Note that consistency of mappings is only applicable if each target item is named more than once (which is the case in most existing language-switching studies). The traditional cued switching context (called “bivalent” in the present study) involves forced language selection on each trial, with inconsistent item-language mappings (i.e. each item is named in different languages on different trials). The fully voluntary context involves free language selection, with (potentially) inconsistent mappings, depending on the strategy adopted by each individual participant. The artificially-consistent context involves forced language selection with consistent mappings. Finally, the natural context (which combines the advantages of fully voluntary and bottom-up switching) involves free language selection with consistent mappings.

To summarise, the present study aims to examine (1) whether natural language switching is more efficient than forced switching (e.g. less behavioural costs, reduced engagement of cognitive control), and (2) if so, which factor(s) are responsible for such efficiency (free language selection and/or consistent item-language mappings). To answer these questions, we compare the switch effect and mixing effect (behaviourally and neurally) across the three contexts introduced above: natural, artificially-consistent, and bivalent.

These three contexts impose increasing levels of external constraints on language selection. In real life, bilinguals may also switch language under a number of different scenarios. Firstly, when their conversational partner is highly proficient in both languages, they have complete freedom to express concepts in either

language; in this case, they may switch language to maximise efficiency (e.g. because some words are more easily accessible for them in one language over another). This is represented by the natural switching context in this study. Secondly, if they know that the conversational partner prefers to discuss certain concepts in a particular language, then they may switch language to match those preferences. For example, a bilingual child might be more familiar with school-related concepts in one language, and home-related concepts in the other language; therefore, the parent will switch language according to the topic of discussion. In this case, language switching is based on external constraints, but the same concept tends to be always discussed in the same language. This is similar to the artificially-consistent context in this study. Thirdly, sometimes it may be necessary to speak to two or more people at the same time, but use a different language with each person (e.g. interpreting for two people who do not share a common language). In this case, the bilingual must use a designated language every time they speak, and they will likely need to repeat the same concepts in both languages. This is analogous to the bivalent context in this study. Therefore, aside from the theoretical motivations explained above, the three contexts explored in the present study may also help provide some understanding of language switching and mixing in these real-life scenarios.

4.2 METHODS

4.2.1 Participants

Twenty-four right-handed Mandarin-English bilinguals participated in this MEG study (age 25.3 ± 5.6 years; nine males). Participant information was collected via a language history questionnaire, which probed language use patterns and self-

rated proficiencies⁶³ in Mandarin and English (see Table 4-2). All participants had acquired both languages at a young age and were highly proficient in both languages. None of them spoke any other languages in daily life. We aimed to recruit bilinguals who were as balanced as possible between the two languages, so as to elicit the most natural language-switching performance and compare this with forced switching. The participants came from a range of backgrounds: some grew up in a bilingual environment (e.g. in Singapore or Malaysia), some were born to Chinese parents in Australia and had spent a number of years living in China, while others were born in China and moved to an English-speaking country at an early age. Uniformity of demographic background across the sample was not achievable given our strict inclusion criteria on language use background combined with the various exclusion criteria associated with MEG (e.g. non-removable metal in body, inability to lie flat and still for the session length, claustrophobia or various medical conditions). We also excluded any participants with professional experience in translation and interpreting, as this might mean that they have quite different language use patterns (e.g. a lot more switching) compared to bilinguals who did not have such experience. All participants were free from neurological conditions and linguistic or cognitive impairments, were not taking psychoactive medication, and had normal or corrected-to-normal vision (in the latter case, they either wore contact lenses or MEG-compatible glasses were provided to them). This study was approved by the Human Ethics Committee of Macquarie University, and informed consent was obtained from all participants.

⁶³ It has been shown that self-ratings of language proficiency are strongly correlated with objectively measured proficiency levels (see Marian, Blumenfeld, & Kaushanskaya, 2007).

	Mean	SD
Age (years)	25.3	5.6
Age of acquisition - Mandarin	0.5	1.7
Age of acquisition - English	6.2	4.4
Mandarin listening ability ^a	6.9	0.3
Mandarin speaking ability ^a	6.8	0.5
Mandarin reading ability ^a	6.7	0.7
Mandarin writing ability ^a	6.2	1.5
English listening ability ^a	6.3	0.7
English speaking ability ^a	6.2	0.8
English reading ability ^a	6.3	0.7
English writing ability ^a	6.0	0.9
Immersion in Mandarin environment (years) ^b	19.9	6.1
Immersion in English environment (years) ^b	11.3	6.8
Percent use in daily life - Mandarin	39.9	22.5
Percent use in daily life - English	60.1	22.5
Switching frequency in daily life ^c	3.6	1.2

Table 4-2. Participant characteristics.

^a Language proficiency based on self-ratings on a 7-point scale: 1 = little to no knowledge, 7 = like a native speaker.

^b Periods of living in a bilingual environment (e.g. for those who grew up in Singapore) count towards both Mandarin immersion and English immersion.

^c Switching frequency based on self-ratings on a 6-point scale: 1 = never, 6 = constantly.

4.2.2 Stimuli and Experimental Design

4.2.2.1 Language switching in three different contexts

To assess the effects of language switching and mixing in the three different contexts introduced earlier (see Section 4.1), this study included three mixed-language blocks (natural, artificially-consistent, and bivalent) plus a single-language block for each language (English and Mandarin). In the *natural* block, there were eight target items. Four of them were strongly biased towards English,

i.e. difficult or impossible to name in Mandarin (e.g. *wombat*, an Australian animal); the other four were strongly biased towards Mandarin, i.e. difficult or impossible to name in English (e.g. *jiànzi*, a kicking toy popular in China). Participants were instructed to “use whichever language is easier to name the picture on each trial”. The idea behind this was to create a context for language switching to occur naturally (i.e. without external constraints), but to maintain consistent item-language mappings at the same time. The language-biased items were selected from a pool of candidate items, through a survey conducted on twenty Mandarin-English bilinguals from the same population (no overlap between participation in the survey and the MEG study). The survey asked participants to enter a name for each object in English and in Mandarin, as well as rate the percentage of time they would refer to this item using each language in everyday life. An item was selected if more than 80% of survey respondents could only name it in one language and the average rating for use of this language to refer to the item exceeded 80%.

In the *artificially-consistent* block, there were eight target items, and each item was neutral to the two languages (e.g. *funnel-lòudǒu*). That is, they were possible to name in both English and Mandarin, and the names in both languages were of similar lexical frequency (see Section 4.2.2.2 for more details). For each participant, half of these items always required a response in English and the other half always required a response in Mandarin. Item-language mappings were counterbalanced across participants (see Table 4-3). In this block, bilinguals were instructed to “use the appropriate language according to the interlocutor on each trial”. This context was designed so that language selection was forced on each trial (i.e. according to the cue) but consistent item-language mappings were maintained (artificially) throughout the experiment.

In the *bivalent* block, there were four target items, each of which had to be named half the time in English and half the time in Mandarin. Participants were instructed to “use the appropriate language according to the interlocutor on each trial”. This

context was meant to replicate the classical cued-switching paradigm, where language selection is forced on each trial and the item-language mappings are not consistent throughout the experiment. The reason for using only four items in the bivalent context (compared to eight items in the other two contexts) was that each bivalent item was associated with two different labels in the experimental task (i.e. they had to be named in both languages). Halving the number of items in the bivalent context allowed us to keep the total number of trials equal across all three contexts while ensuring the number of times each label was named was also equal across all contexts.

Following the three mixed-language blocks, each participant completed two single-language blocks, where they named all the target items from the mixed-language contexts (presented in a mixed fashion). In one block, they were instructed to name all pictures in English; in the other block, they were instructed to name all pictures in Mandarin. Each item from the natural and artificially-consistent contexts appeared in one of these blocks according to which language it was named in during the mixed-language blocks, while each item from the bivalent context appeared in both the English block and the Mandarin block. These single-language blocks served as the baseline for examining the effect of language mixing.

The order in which the three mixed-language blocks appeared were counterbalanced across participants, to ensure that any difference observed between the three naming contexts would not be due to the order in which the blocks were presented. For a similar reason, the order of the two single-language blocks was also counterbalanced across participants. Counterbalancing resulted in 12 possible block orders, which were evenly distributed across the participants. Together with the counterbalanced item-language pairings in the artificially-consistent context, there were exactly 24 combinations, which were mapped onto the 24 participants (see Table 4-3).

Participant ID	Order of mixed-language blocks	Order of single-language blocks	Item-language pairings in artificially-consistent block
A01	Nat, Art, Bi	English, Mandarin	A
A02	Nat, Bi, Art	English, Mandarin	A
A03	Art, Nat, Bi	English, Mandarin	A
A04	Art, Bi, Nat	English, Mandarin	A
A05	Bi, Nat, Art	English, Mandarin	A
A06	Bi, Art, Nat	English, Mandarin	A
A07	Nat, Art, Bi	Mandarin, English	A
A08	Nat, Bi, Art	Mandarin, English	A
A09	Art, Nat, Bi	Mandarin, English	A
A10	Art, Bi, Nat	Mandarin, English	A
A11	Bi, Nat, Art	Mandarin, English	A
A12	Bi, Art, Nat	Mandarin, English	A
B01	Nat, Art, Bi	English, Mandarin	B
B02	Nat, Bi, Art	English, Mandarin	B
B03	Art, Nat, Bi	English, Mandarin	B
B04	Art, Bi, Nat	English, Mandarin	B
B05	Bi, Nat, Art	English, Mandarin	B
B06	Bi, Art, Nat	English, Mandarin	B
B07	Nat, Art, Bi	Mandarin, English	B
B08	Nat, Bi, Art	Mandarin, English	B
B09	Art, Nat, Bi	Mandarin, English	B
B10	Art, Bi, Nat	Mandarin, English	B
B11	Bi, Nat, Art	Mandarin, English	B
B12	Bi, Art, Nat	Mandarin, English	B

Table 4-3. Counterbalancing of the order of mixed-language and single-language blocks, as well as the item-language pairings in the artificially-consistent block. Counterbalancing resulted in exactly 24 combinations, which were mapped onto the 24 participants. Nat = natural context; Art = artificially-consistent context; Bi = bivalent context.

4.2.2.2 *Target stimuli*

The naming targets in this experiment were black-and-white line drawings of everyday objects (see Appendix A). There were a total of twenty objects: eight in the natural-switching context, eight in the artificially-consistent context, and four in the bivalent context. All names in English were short words (no more than 7 letters) with one or two syllables; all names in Mandarin were two-character (and hence two-syllable) words. To minimise any possibility of introducing artificial differences into the three contexts, the items used in all contexts were carefully controlled to ensure they had similar properties. The most important of these properties was lexical frequency. Because the natural-switching context required language-biased items, which were mostly low-frequency words (since high-frequency words usually have easily-accessible labels in both languages), we needed to make sure that the items used in the other two contexts were similarly low-frequency. Otherwise, if we found, for example, that the switch effect differed between the natural context and the bivalent context, we would not be able to tell whether that was due to the different language-switching contexts, or due to differences in the lexical frequency of the stimuli. The language-biased items (for the natural context) were carefully selected via a survey to ensure they were as specific to each language as possible (see Section 4.2.2.1), and then items were selected for the artificially-consistent context and the bivalent context, with the aim of matching the lexical frequency of those language-biased items. Across the three contexts in this experiment, there were essentially five groups of picture stimuli (see Table 4-4). Since the stimuli in the artificially-consistent context and bivalent context each involved naming in both languages (when considering across all participants), we took into account their frequencies in both English and Mandarin. This resulted in a total of eight groups of lexical frequencies that needed to be matched. We selected items for the artificially-consistent context and the bivalent context according to this criterion. The lexical frequency data for English were retrieved from the Australian component of the International Corpus of English

(ICE-AUS; <https://www.ausnc.org.au/corpora/ice>), and the lexical frequency data for Mandarin were retrieved from the Chinese Corpus Online database (www.cncorpus.org). For the final chosen set of stimuli, the eight groups of lexical frequencies (see explanations above) were submitted to a one-way ANOVA, and no significant difference was found across these eight groups ($p > .1$).

Natural	4 items strongly biased towards English	4 items strongly biased towards Mandarin
Artificially-consistent	4 items consistently requiring response in English*	4 items consistently requiring response in Mandarin*
Bivalent	4 items (each requires response in English and in Mandarin, depending on the face cue on each trial)	

* Language mappings were reversed for half the participants, for counterbalancing purposes.

Table 4-4. Five groups of stimuli across the three contexts in this experiment.

In addition to lexical frequency, the five groups of picture stimuli were matched on visual features, in order to minimise any differences in the visual processing of the images themselves. Some of these pictures were taken from the Multilingual Naming Test (Gollan, Weissberger, Runnqvist, Montoya, & Cera, 2012), while others came from various Internet sources or were drawn by us in a similar style. To give all pictures the same cartoonish look, all images were converted into SVG format first, and then converted back to PNG format for display. Visual complexity of the images was measured based on file size in KB (a similar approach to that used by the International Picture Naming Project). A one-way ANOVA was performed to compare the visual complexity across the five groups of picture stimuli. No significant difference was found across these five groups ($p > .1$). All images were equalised on mean luminance using the SHINE toolbox (Willenbockel et al., 2010) in Matlab.

4.2.2.3 Language cues

In an effort to keep the duration of the MEG session reasonable, we decided to present the language cue and target picture simultaneously on each trial⁶⁴. Whilst this meant that we could not separate the cue-related and target-related control processes, the focus of the present study was how these control processes differed across the three types of context, rather than at what stage they occurred. There were two major considerations in deciding what language cues should be used. Firstly, previous studies show that language-switch costs are heavily influenced by the type of language cues used in the experiment (Blanco-Elorrieta & Pylkkänen, 2017; Lavric, Clapp, East, Elchlepp, & Monsell, 2019). When artificial cues (such as colours or shapes) are used, they create a larger switch effect compared to when natural language cues (such as faces of interlocutors) are used. This may be due to artificial cues requiring additional cue-related processing, which is independent of the language-switch process. In the current literature, faces seem to be generally regarded as a good choice of natural language cues. In real-world settings, the face of the interlocutor naturally prompts the appropriate response language (Li, Yang, Scherf, & Li, 2013; Woumans et al., 2015; Martin, Molnar, & Carreiras, 2016). Secondly, most language-switching studies conducted so far involve a confound of cue-switching. In these studies, only one cue is used to represent each language; whenever the required language changes, the cue must also change, thus mixing together the effect of cue-switching and language-switching. One way to circumvent this problem is to map two cues to each language and ensure the cue changes on every trial (Verhoef, Roelofs, & Chwilla, 2010). Even though this does not remove the effect of cue switching, that effect would now occur on both language-stay and language-switch trials, therefore it is essentially controlled for.

⁶⁴ This is different from our previous MEG study (Chapter 3), where we presented the cue first for 750 ms, followed by the target. The separate cue and target presentation allowed us to look at distinct control processes occurring at each stage.

In the artificially-consistent context and bivalent context, participants were instructed to speak the appropriate language on each trial according to the face cue, so four language-specific cues were required. Two Chinese faces acted as cues for Mandarin, and two Caucasian faces acted as cues for English (Figure 4-1 A). These faces were taken from Rhodes, Hickford, and Jeffery (2000), and we have previously validated that they did not introduce artificial effects due to low-level visual differences (see Chapter 3, Appendix A). For the natural context, participants were allowed to freely choose which language to speak on each trial, so we created four neutral face cues which did not represent one particular language. To maximise the similarity across contexts, each neutral cue was created by blending together a pair of language-specific cues (always taking one face from each language). Four such pairs could be formed, resulting in exactly four blended faces. To make these blended faces more easily distinguishable from the language-specific cues (and from each other, so that participants would still detect a clear cue change on every trial), a different pair of glasses were added to each of the four neutral faces (Figure 4-1 B). We surveyed 15 people to ensure that each neutral face did not have a strong bias towards either Chinese or Caucasian (see Appendix B). All eight face cues were greyscale images and they were equalised on mean luminance using the SHINE toolbox (Willenbockel et al., 2010) in Matlab. In the single-language blocks, the type of face cues that appeared with each target item were the same as in the mixed-language blocks (i.e. language-specific cues accompanied items from the artificially-consistent and bivalent contexts, and neutral cues accompanied items from the natural context). This consistency served to ensure that when we compare the stay trials (from the mixed-language blocks) with the single-language trials to examine the mixing effect, such comparison would be valid and not contaminated by any difference in face cues.

(A)**(B)**

Figure 4-1. **(A)** Four language-specific cues, used in the artificially-consistent context and bivalent context. In these contexts, participants were required to speak the appropriate language according to the face cue on each trial. Two Chinese faces (left) served as cues for Mandarin, and two Caucasian faces (right) served as cues for English. These faces were originally created by Rhodes, Hickford, and Jeffery (2000). **(B)** Four neutral cues, used in the natural context. In this context, participants were allowed to freely choose which language to speak on each trial. Each neutral face was created by taking a pair of language-specific faces (one from each language) and blending the two faces together. Four such pairs could be formed from the set of language-specific cues above, resulting in exactly four neutral cues.

4.2.2.4 Task procedure

The main experimental task consisted of three mixed-language blocks followed by a single-language block in each language, all in counterbalanced order (see Section

4.2.2.1). In each mixed-language block, there were 64 stay trials and 64 switch trials. Each target item appeared an equal number of times on stay trials and switch trials. Trials were presented in a pseudorandom order, satisfying the following constraints: no immediate repetition of any target item on consecutive trials; each trial type had a maximum "run length" of 3 (i.e. no more than 3 consecutive stay trials or switch trials). It has been shown that switch costs could carry over onto the immediately following trial (e.g. Blanco-Elorrieta & Pykkänen, 2016). To avoid such carry-over effects, a filler trial was inserted after every switch trial. The naming targets on filler trials were drawn from the same set of items used in the current context (maintaining any item-language pairings where applicable), and each item appeared an equal number of times as fillers. Because the filler trials were all "stay" trials themselves, they would not contaminate the next critical trial. Each mixed-language block thus consisted of a total of 192 trials (including fillers), and lasted for approximately 10 minutes. Participants were given a short rest break half-way through each block and after completing a block. In each single-language block, there were no switch trials (as all trials were in the same language), therefore no fillers were required. Trials were presented in a pseudorandom order, with no immediate repetition of any target item on consecutive trials. Items from all three contexts were mixed together, and the number of times each item appeared in the single-language block matched the number of times they appeared on stay trials in the mixed-language blocks (for calculation of the mixing effect). Thus, each single-language block consisted of 96 trials, and lasted for approximately 5 minutes. Participants were given a short rest break between the two single-language blocks.

The trial structure in the experiment was as follows. On each trial, the face cue and the target picture were displayed simultaneously for 2000 ms, followed by an inter-trial interval jittered between 1200 and 1400 ms. The screen was designed such that it looked like a person was holding a picture for the participant to name (Figure 4-2). To minimise eye movements (e.g. possible saccades between the face and the

picture), a red fixation cross was placed on the nasion of the face, and participants were told to maintain their gaze on the fixation cross at all times. This also helped ensure that participants pay attention to the face cues even during the natural-switching block (in which case the cues were uninformative). The red fixation cross remained on screen during the inter-trial interval.

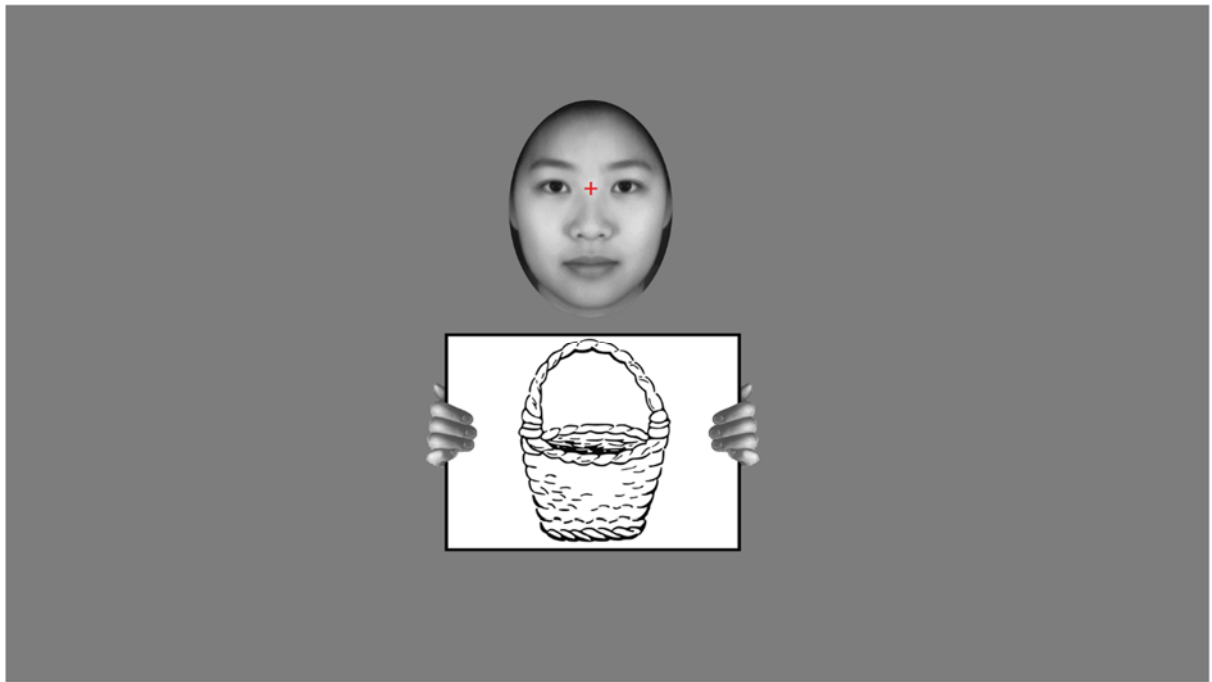


Figure 4-2. A typical trial. Here a Chinese interlocutor is holding a picture of a basket, so the participant is required to name this item in Mandarin. The red fixation cross on the nasion helps participants to maintain their gaze at one spot and minimise eye movements.

Before starting the experimental task, participants were introduced to the face cues and were told that they would be playing a game with these people: they would see one person appear at a time, holding a picture, and their task was to tell that person what was in the picture. Participants were instructed to speak Mandarin with the Chinese interlocutors, speak English with the Caucasian interlocutors, and speak whatever language they want with the bilingual interlocutors (while ensuring they responded as quickly as possible). To avoid unexpected errors (e.g. due to not recognising a picture correctly), participants were given “study cards” to help

familiarise them with all the picture stimuli and the corresponding names. For items in the natural and artificially-consistent contexts, names were only given in the language in which they were required to respond in the experiment; for items in the bivalent context, names were given in both languages. When selecting the stimuli set, we were careful to avoid items with alternative names, so as to minimise the possibility of any provided name not matching what a participant usually calls that item. Additionally, we checked with each participant during the study phase and confirmed that all the provided names matched their preference. This ensured that the “study cards” simply served the purpose of familiarisation rather than forcing participants to adopt a new name for any particular item. Two versions of “study cards” were used (with participants split into Group A and Group B) in order to achieve counterbalancing of item-language pairings in the artificially-consistent context (see Appendix A).

Each participant performed a short practice task before entering the MEG. The practice task included all three mixed-language contexts (24 trials in each context, total 72 trials), in the same order that these blocks would appear in the main experiment, and the artificially-consistent stimuli were mapped to the appropriate language as they would be in the main experiment. Participants were told to practice looking at the fixation cross only and not anywhere else; all participants reported being able to do so without difficulty by the end of the practice task.

4.2.3 Data Acquisition

Data collection took place at the KIT-Macquarie Brain Research Laboratory in Sydney, Australia. Behavioural and MEG data were collected simultaneously. Visual stimuli were displayed via a projector (EPSON EB-G7400U; refresh rate 60 Hz) and reflected by a mirror onto a white screen placed directly above the participant’s head. The experiment was controlled by the Presentation software (Version 18.3; Neurobehavioral Systems, Inc., Berkeley, CA, USA). MEG measurements were

acquired using a 160-channel whole-head axial gradiometer system (Model PQ1160R-N2; Kanazawa Institute of Technology, Kanazawa, Japan). Participants were tested while lying supine, in a dimly-lit magnetically-shielded room (MSR; Fujihara Co. Ltd., Tokyo, Japan).

The experimental task was explained to each participant on their arrival, and they spent five minutes familiarising with the picture stimuli using the study cards (see Section 4.2.2.4). Before participants entered the MSR, their head shape information was recorded using a Polhemus Fastrak system and digitizing pen (Colchester, VT, USA). Approximately 4000 points were collected from each participant's head surface, and the locations of three cardinal landmarks (nasion and bilateral preauricular points) were also recorded. In addition, participants wore a tight-fitting elastic cap with five marker coils attached to it, which allowed measurement of their head position in relation to the MEG sensors while inside the MSR. Participants were instructed to relax but minimise any head movements throughout the MEG session. Each participant's head position was measured at the beginning, middle, and end of the session. All participants' head movements from beginning to end (averaged across the five marker coils) were less than 5 mm.

Continuous MEG data were acquired at a sampling rate of 1000 Hz (online band-pass filtered between 0.1 - 200 Hz ⁶⁵). Due to increased environmental noise around the campus, we also recorded 3 channels of reference data during all MEG sessions, which served as the basis for noise correction (these sensors were far enough from the head so that they could not pick up the brain signals, but close enough to the

⁶⁵ In the previous MEG study (Chapter 3), an online band-pass filter of 0.03 – 200 Hz was used; however, that option subsequently became infeasible due to increased magnetic noise in the environment. This noise was mostly characterised by low-frequency drifts, which led to frequent occurrences of MEG sensor saturation (in which case the data were lost). After conducting some empty-room testing, it was determined that a high-pass cutoff of 0.1 Hz was necessary, and the signal amplification was also lowered from x500 to x200. Using these settings, no sensor saturation occurred in any of the MEG sessions in the present study. It should be noted that, as a result of the changed settings, the raw signal amplitudes are not directly comparable across the two studies.

sensor array so that the environmental noise they pick up would be very similar to the noise blended into the actual MEG data). Noise correction was performed offline in the MEG Laboratory software (Yokogawa Electric and Eagle Technology) using the time-shifted PCA algorithm (De Cheveigné & Simon, 2007; block width of 10 seconds, 3 shifts). During the experimental session, participants' vocal responses were captured using an MEG-compatible microphone and saved for offline analysis. The RT on each trial was determined by the software voice key in Presentation. Behavioural errors (including incorrect responses and all verbal disfluencies, e.g. partial responses, stuttering, and utterance repairs) were manually coded.

4.2.4 Behavioural Data Analysis

Statistical analysis of the behavioural data was performed in R (Version 3.6.1; R Core Team, 2019) using the "lme4" package (Bates, Maechler, Bolker, & Walker, 2015). The optimal transformation power for RT values was calculated using the Box-Cox method (Box & Cox, 1964; Osborne, 2010), to satisfy the assumption of normally-distributed residuals. RT and error rate data were submitted to 3 x 3 linear mixed-effects modelling. The fixed effects in the model included "context" (natural/artificially-consistent/bivalent), "transition type" (single/stay/switch), and the interaction between these two factors; the random effects in the model included "participant" and "item". As we tested highly-balanced bilinguals in this study, "language" was not included as a factor in the analysis. The reference level in the model was set to represent the "stay" condition in the "artificially-consistent" context (i.e. the middle level in each factor), and variables' coefficients were compared to this intercept. Because each factor in the model involved three levels, any main effects or interactions that were found to be significant were unpacked further to reveal the underlying pattern. These follow-up tests were performed using the "emmeans" package (Lenth, 2020) in R. In addition, planned pairwise

comparisons were performed within each context to assess whether a switch cost (stay vs switch) and/or a mixing cost (single vs stay) were present. All the p -values obtained were adjusted for multiple comparisons using the Holm-Bonferroni method. All effects were categorised as significant at $p < .05$.

4.2.5 MEG Data Analysis

MEG data preprocessing and analysis were performed in Matlab (Version R2017b; MathWorks, Inc., Natick, MA, USA) using the FieldTrip toolbox (Oostenveld, Fries, Maris, & Schoffelen, 2011; <http://fieldtriptoolbox.org>). The data preprocessing steps were as follows. Continuous MEG data were low-pass filtered at 40 Hz (using a onepass-zero phase Blackman filter), and then band-stop filtered between 49.5 - 50.5 Hz to remove electrical line noise. The raw data for each participant were visually inspected to detect any large and unusual artefact (not including typical artefacts such as eye blinks, which were removed later), and sections of data containing these artefacts were rejected. Bad channels identified during visual inspection were also removed. Independent component analysis (ICA) was used to automatically characterise components that represent eye blinks and saccades (if any), and these were manually checked and then removed. Epochs were created from -200 to 600 ms relative to stimulus onset (based on the timing of photodetector triggers). MEG data were then downsampled to 200 Hz to save disk space and improve processing speed. Any trials involving behavioural errors were excluded from the subsequent MEG data analysis.

4.2.5.1 ERF analysis

The study design involves three levels in the factor "context" (natural/artificial/bivalent) and three levels in the factor "transition type" (single/stay/switch), resulting in a total of 9 conditions. All trials belonging to each

condition were averaged to obtain the ERF time-locked to stimulus onset. ERF time courses from all sensors were included in the statistical analysis. Because this type of analysis involves multiple comparisons in both the spatial dimension (i.e. multiple sensors) and the temporal dimension (i.e. multiple time points), we used cluster-based permutation tests (Maris & Oostenveld, 2007), which has been shown to be effective in controlling for Type I errors while maximising power in the analysis of MEG and EEG data (Pernet, Latinus, Nichols, & Rousselet, 2015). The cluster-based method was used to identify *spatio-temporal clusters* containing significantly different evoked activity across the conditions of interest (more detailed explanation in Chapter 3, Section 3.2.5.1). The data were permuted 2000 times. We report clusters with $p < .05$ (after Bonferroni adjustment where necessary) as significant.

To assess whether the switch effect differed across the three contexts (2 x 3 interaction), we first computed a time course representing the switch effect (i.e. switch minus stay) within each context, and then compared these time courses using an F statistic. In a similar way, we assessed whether the mixing effect (i.e. stay minus single) differed across the three contexts. To examine the main effect of "context", we computed an overall time course (averaged across transition types) for each context, and compared the three contexts using an F statistic. In the "transition type" factor, we looked at the effects of "switch" and "mixing" individually, as these were two separate measures that we were interested in. To examine the effect of "switch", we compared the overall time courses for switch and stay (averaged across contexts). To examine the effect of "mixing", we compared the overall time courses for stay and single (averaged across contexts). We were not interested in the "switch minus single" contrast (or whether this differed across contexts), as this comparison did not have a clear theoretical underpinning and would not be informative towards our hypotheses. If any interactions were found to be significant, follow-up tests were conducted to reveal exactly which pair(s) of contexts differed in switch cost or mixing cost. This was done by performing three

2 x 2 interaction tests (e.g. switch effect in natural vs bivalent, natural vs artificial, and artificial vs bivalent), using data averaged over all the significant sensors and the time span of the cluster. Because of the multiple follow-up tests (3 in this case), Bonferroni adjustment was applied to the p -values obtained (i.e. multiply by 3). If a main effect of context was found to be significant, this was unpacked in a similar way using 3 follow-up tests to compare each pair of contexts. Again, data were averaged over the significant sensors and the duration of the cluster, and p -values were adjusted using Bonferroni. If a main effect of switch or mixing was found, these did not need further unpacking as there were only two levels in each of these contrasts. In addition to the overall main effects and interactions, planned pairwise comparisons were conducted within each context to assess the presence of switch effect and mixing effect, as we were interested in examining these individually, regardless of whether they differed across contexts. The p -values from these tests were adjusted using Bonferroni correction.

4.2.5.2 ROI analysis

Brain activities in pre-defined regions of interest (ROIs) were reconstructed from the MEG sensor data. These ROIs were selected based on previous neuroimaging studies of language switching (see Section 4.1), and included the following brain regions: bilateral ACC (Abutalebi et al., 2012; Wang, Xue, Chen, Xue, & Dong, 2007; Reverberi et al., 2015), IFG (de Bruin et al., 2014; Green & Abutalebi, 2013; Reverberi et al., 2015), DLPFC (Hernandez, Dapretto, Mazziotta, & Bookheimer, 2001; Wang et al., 2007; Blanco-Elorrieta & Pylkkänen, 2016, 2017), and pre-SMA (de Bruin et al., 2014). These ROIs were defined anatomically using the AAL atlas (Tzourio-Mazoyer et al., 2002): the ACC was defined as the “anterior cingulate gyrus”; the IFG was defined as the “pars opercularis” and “pars triangularis” combined⁶⁶; the

⁶⁶ With this definition, the left IFG is roughly equivalent to Broca’s area.

DLPFC was defined as the “middle frontal gyrus” (this included BA9, 10 and 46, consistent with the definition in previous language-switching studies, e.g. Blanco-Elorrieta & Pylkkänen, 2016; Zhu, Seymour, Szakay, & Sowman, 2020); the pre-SMA was defined as the “supplementary motor area” ⁶⁷.

The participants in this study did not undergo individual MRI scans. Instead, we used the MEMES toolbox (Seymour, 2018; <https://github.com/Macquarie-MEG-Research/MEMES>) to search through an existing MRI database and estimate the best-matching structural scan for each participant (based on their head shape information collected during the MEG session). This procedure is described in more details in Chapter 3, Section 3.2.5.2. For each participant, an appropriate cortical mesh and source grid were created from the estimated MRI and co-registered with the MEG sensor positions. The forward model was computed using the cortical mesh as the volume conductor model. Source reconstruction was performed using a linear constrained minimum variance (LCMV) beamformer, with free dipole orientation⁶⁸. Spatial filters were computed based on the covariance matrix derived from data combined across all conditions. For each vertex in the source grid, this produced three spatial filters (one along each axis), and each spatial filter was multiplied with the ERF time course to estimate a source activity time course along that axis. The three source activity time courses were then brought together via vector combination, resulting in a single time course which was entirely positive.

⁶⁷ No sub-division exists in the atlas to specifically define the *pre*-SMA.

⁶⁸ In the previous MEG study (Chapter 3), fixed dipole orientation was used for the LCMV beamformer. This produced source activity time courses containing both positive and negative values (where the sign represented the direction of the current flow). As a result, the statistical analyses sometimes found significant clusters due to the currents going in different directions in the conditions being compared (while the absolute magnitudes might not differ). These kinds of statistical results are tricky to interpret – when two conditions differ in the direction of current flow, what does that mean in regards to our experimental hypotheses? In the current theoretical framework, we are not able to utilise that kind of information; moreover, it occludes us from being able to statistically test whether the actual magnitudes of brain activity differ between the two conditions, which would be much more informative. Therefore, in the present study, free dipole orientation was used so that statistical tests could be conducted on the absolute magnitudes of brain activity, regardless of current flow directions.

Thus, this time course represented the length of the vector at every time sample, i.e. the absolute magnitude of brain activity at each point in time, regardless of direction. Finally, the source activities for all vertices within an ROI were averaged to obtain a combined time course for that ROI.

Statistical analysis was performed separately for each ROI. Because this type of analysis involves multiple comparisons in the temporal dimension, the cluster-based correction method (Maris & Oostenveld, 2007) was used to control for Type I errors. Cluster-based permutation tests identified *temporal clusters* during which the ROI activity differed significantly across conditions of interest. The data were permuted 2000 times. We report clusters with $p < .05$ (after Bonferroni adjustment where necessary) as significant.

As with the ERF analysis (see Section 4.2.5.1), we assessed whether the switch effect and mixing effect differed across the three contexts, as well as the overall effects of "context", "switch" and "mixing". For main effects or interactions that were found to be significant, they were unpacked via follow-up tests in the same fashion as in the ERF analysis, using data averaged over the time span of the cluster and with Bonferroni adjustment applied on p -values. Planned pairwise comparisons were also performed within each context to assess the presence of switch effect and mixing effect, again with appropriate p -values adjustment using Bonferroni correction.

4.3 RESULTS

4.3.1 Behavioural Results

A summary of the behavioural data is presented in Table 4-5 and Figure 4-3. All error trials were excluded from the RT data. Mean values and standard errors were calculated for each context and each transition type, for descriptive purposes.

Statistical analysis was performed on single-trial RT and error data, using linear mixed-effects modelling (full statistical results can be found in Appendix C).

4.3.1.1 Error analysis

The error data were submitted to a 3 x 3 generalised linear mixed-effects model using the binomial distribution (see Section 4.2.4 for details). According to the Akaike Information Criteria (AIC; Akaike, 1974), the model that included the interaction term had the best fit (model with interaction term: AIC = 2740.6; model without interaction term: AIC = 2758.0). There was a significant interaction between "context" and "transition type" ($\chi^2(4) = 24.345, p < .0001$), driven by the mixing cost (i.e. error rate difference between stay trials and single-language trials) being significantly larger in the bivalent context compared to the artificially-consistent context ($z = 3.151, p = .0114$) and compared to the natural context ($z = 2.784, p = .0322$); the mixing cost was not significantly different between the artificially-consistent and natural contexts, nor were there any significant differences in the switch cost (i.e. error rate difference between switch trials and stay trials) across the three contexts. Both of the main effects were significant. For the main effect of "context" ($\chi^2(2) = 41.506, p < .0001$), the natural context contained less errors compared to the artificially-consistent context (mean difference 1.62%; $z = 4.710, p < .0001$) and compared to the bivalent context (3.19%; $z = 5.632, p < .0001$); there was no significant difference in the error rate between the artificially-consistent and bivalent contexts. For the main effect of "transition type" ($\chi^2(2) = 25.378, p < .0001$), the single-language trials elicited less errors compared to the stay trials (1.02%; $z = 2.360, p = .0365$) and compared to the switch trials (1.84%; $z = 3.476, p = .0015$); there was no significant difference between the stay and switch trials. Planned pairwise comparisons within each context revealed a switch cost (2.26%; $z = 2.858, p = .0298$) and a mixing cost (2.89%; $z = 4.797, p < .0001$) in the bivalent context,

while neither costs were present in the other two contexts. All the p -values reported above were adjusted for multiple comparisons using the Holm-Bonferroni method.

4.3.1.2 RT analysis

All error trials were excluded prior to performing the RT analysis. The RT values were power-transformed to meet the assumption of normality of residuals. Based on the Box-Cox method (Box & Cox, 1964; Osborne, 2010), the optimal transformation power was determined to be $\lambda = -0.59$. The transformed RT data were then submitted to a 3 x 3 linear mixed-effects model (see Section 4.2.4 for details). According to the AIC scores (Akaike, 1974), the model that included the interaction term had the best fit (model with interaction term: AIC = -124702.0; model without interaction term: AIC = -124260.1). There was a significant interaction between "context" and "transition type" ($\chi^2(4) = 457.876, p < .0001$), which was driven by differences in both the mixing cost and the switch cost across contexts. The natural context had a significantly smaller mixing cost (i.e. RT difference between stay trials and single-language trials) compared to the artificially-consistent context ($z = 3.211, p = .0040$), which in turn had a significantly smaller mixing cost compared to the bivalent context ($z = 12.378, p < .0001$). The natural context also had a significantly smaller switch cost (i.e. RT difference between switch trials and stay trials) compared to the bivalent context ($z = 3.733, p = .0008$); however, there was no significant difference in switch cost when comparing the natural to the artificially-consistent context, and when comparing the artificially-consistent to the bivalent context. Both of the main effects were significant. For the main effect of "context" ($\chi^2(2) = 52.872, p < .0001$), the natural context had faster responses compared to the artificially-consistent context (mean difference 34 ms; $z = 2.175, p = .0296$), which in turn had faster responses compared to the bivalent context (120 ms; $z = 7.307, p < .0001$). For the main effect of "transition type" ($\chi^2(2) = 716.341, p < .0001$), the single-language trials elicited

faster responses compared to the stay trials (81 ms; $z = 21.392$, $p < .0001$), which in turn had faster responses compared to the switch trials (14 ms; $z = 3.539$, $p = .0004$). Planned pairwise comparisons within each context revealed a switch cost (32 ms; $z = 4.574$, $p < .0001$) and a mixing cost (176 ms; $z = 25.398$, $p < .0001$) in the bivalent context; mixing costs were also present in the natural context (27 ms; $z = 3.505$, $p = .0018$) and in the artificially-consistent context (41 ms; $z = 8.010$, $p < .0001$), while no switch costs were found in these two contexts. All the p -values reported above were adjusted for multiple comparisons using the Holm-Bonferroni method.

(A) Reaction times (ms)

	Single	Stay	Switch	<i>Mean</i>	<i>Switch cost</i>	<i>Mixing cost</i>
Nat	881	908	902	897	-6	27
Art	899	940	955	931	15	41
Bi	923	1099	1131	1051	32	176
Mean	901	982	996	960	14	81

(B) Error rates

	Single	Stay	Switch	<i>Mean</i>	<i>Switch cost</i>	<i>Mixing cost</i>
Nat	0.79%	0.72%	0.72%	0.74%	0.00%	-0.07%
Art	2.12%	2.37%	2.59%	2.36%	0.21%	0.25%
Bi	1.25%	4.14%	6.39%	3.93%	2.26%	2.89%
Mean	1.39%	2.41%	3.23%	2.34%	0.82%	1.02%

Table 4-5. Mean reaction times and error rates in each context and each trial type. Nat = natural context; Art = artificially-consistent context; Bi = bivalent context. "Switch cost" is defined as the difference between switch and stay trials; "mixing cost" is defined as the difference between stay and single-language trials.

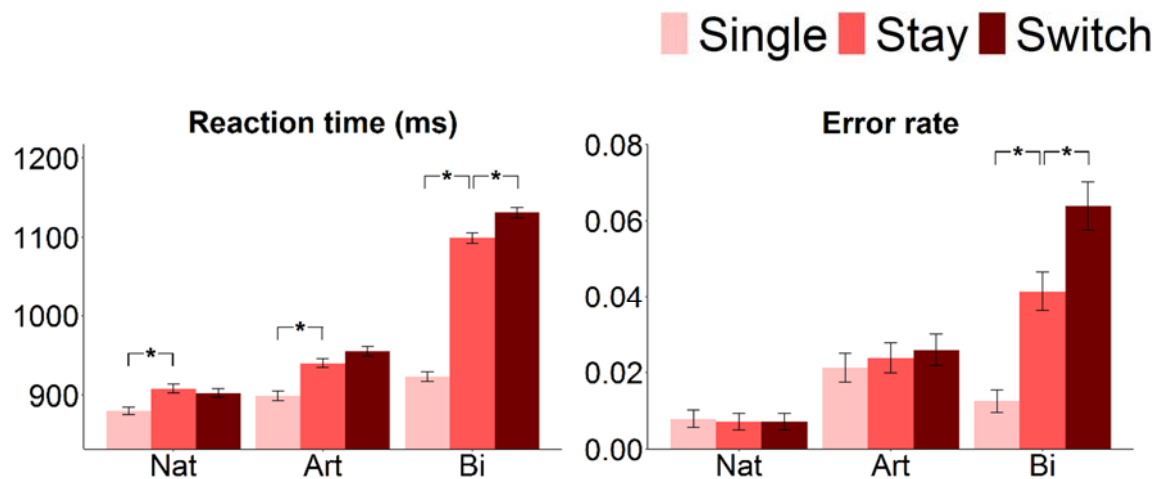


Figure 4-3. Mean reaction times and error rates as a function of context (natural/artificially-consistent/bivalent) and transition type (single/stay/switch). Asterisks indicate significance ($p < .05$ after Bonferroni correction) in the planned pairwise comparisons. Nat = natural context; Art = artificially-consistent context; Bi = bivalent context. Error bars represent one standard error above and below the mean values.

4.3.2 ERF Results

All error trials were excluded from the MEG data analysis. ERF time courses from all sensors were submitted to cluster-based permutation tests, which looked for spatio-temporal clusters that contained significantly different evoked activity across conditions of interest. An interaction was found between "context" and "mix" ($p = .0259$), demonstrating a significant difference in the mixing effect among the three contexts. This effect corresponded to a cluster in left posterior sensors occurring between 155 - 200 ms following stimulus onset. The interaction was driven by the mixing effect in the natural-switching context going in a different direction compared to the other two contexts (Figure 4-4). More specifically, stay trials evoked smaller activities than single trials (i.e. language mixing had an *advantage* rather than a cost) in the natural context. To reveal exactly which two contexts differed in mixing effect, we conducted three follow-up tests, each of which was a 2 x 2 interaction test (i.e. mixing effect in natural vs bivalent, natural vs artificial, and artificial vs bivalent). The follow-up tests were performed on data averaged over all the significant sensors and the time span of the cluster. These tests confirmed that the mixing effect in the natural context was significantly different from the bivalent context ($p = .0030$) and from the artificially-consistent context ($p = .0150$). Similar follow-up tests (averaging over sensors and time points) were performed on the mixing effect within each context, showing that the mixing advantage in the natural context ($p = .0160$) and the mixing cost in the bivalent context ($p = .0050$) were both significant, while no significant mixing effect was found in the artificially-consistent context. The p -values reported here are after Bonferroni-adjustment for multiple comparisons. No interaction was found between "context" and "switch"; in other words, the switch effect did not differ significantly across the three contexts. There were also no significant clusters found for any of the main effects ("context", "switch" and "mixing"). Planned pairwise comparisons conducted within each context did not detect any significant clusters representing a switch effect in any of the three contexts.

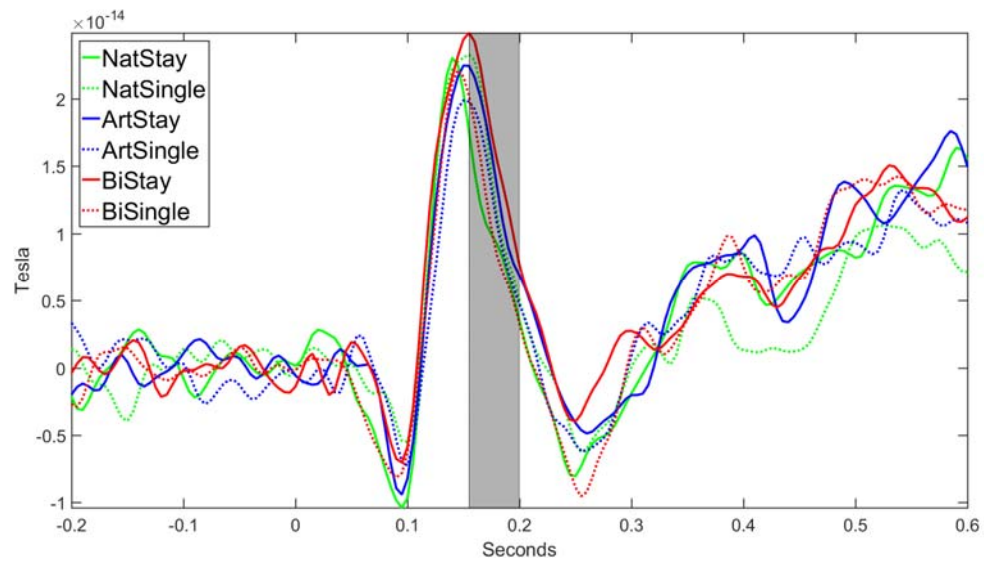
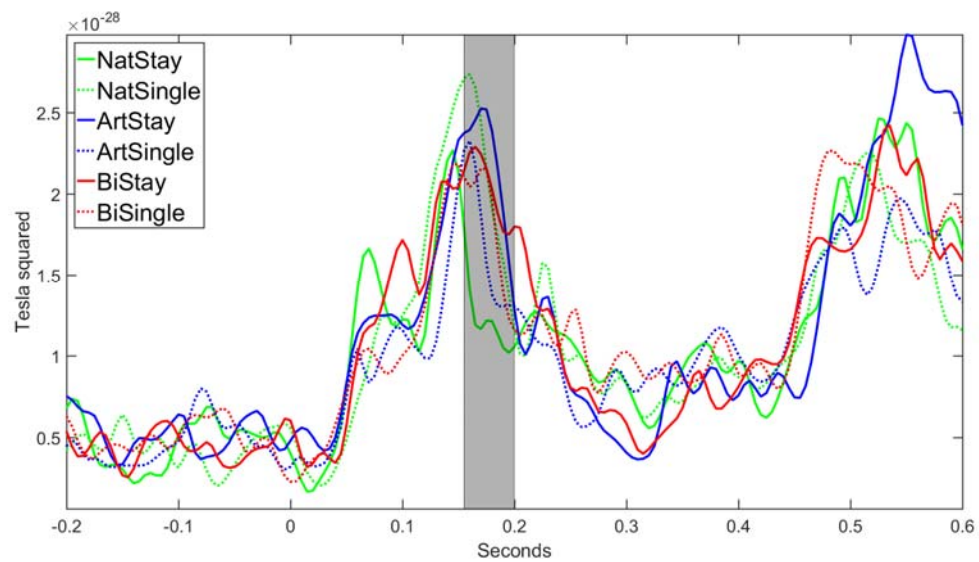
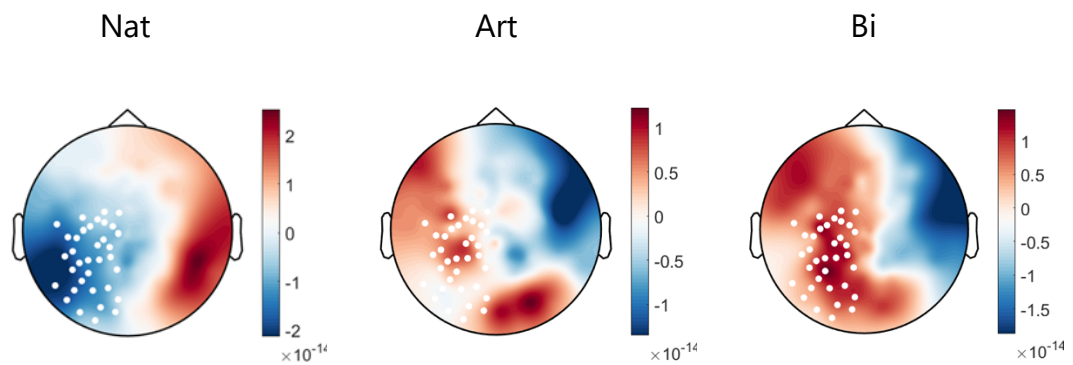
(A) Average of all sensors in the cluster**(B) GFP of all sensors in the cluster****(C) Topography of mixing effect in each context**

Figure 4-4. Cluster-based permutation tests conducted on the ERFs revealed an interaction in the mixing effect ($p = .0259$), corresponding to a left-posterior cluster which occurred between 155 - 200 ms following stimulus onset. Nat = natural context; Art = artificially-consistent context; Bi = bivalent context. **(A)** ERF time course averaged across all the sensors that formed the cluster, showing that the direction of the mixing effect in the natural-switching context (green lines) was different from the artificially-consistent context (blue lines) and bivalent context (red lines). Shaded region indicates the temporal extent of the cluster. **(B)** Global field power computed from all the sensors that formed the cluster. This provides a clearer view of the actual amplitude differences across conditions, as sensors containing activities in opposite directions do not cancel each other out when the power is computed. **(C)** Sensor topography plots showing the grand mean difference between stay trials and single trials (i.e. mixing effect) in each context, averaged over the duration of the cluster. The topography in the natural-switching context shows an opposite pattern to the topographies in the artificially-consistent context and the bivalent context. White dots represent the location of sensors in the cluster.

4.3.3 ROI Results

To examine brain activity in the pre-defined ROIs (bilateral ACC, IFG, pre-SMA, and DLPFC), we performed source reconstruction using an LCMV beamformer. For each ROI, this produced a time course of brain activity in every condition, representing the magnitude of activity at each point in time (see Section 4.2.5.2 for details). These time courses were submitted to cluster-based permutation tests to identify temporal clusters which contained a significant difference across conditions of interest. No interaction was found in either the switch effect or the mixing effect; in other words, these effects did not show a significant difference across contexts in any ROIs. The main effect of "context" was significant in the right ACC ($p = .0390$), corresponding to a cluster occurring between 125 – 150 ms following stimulus onset. This means that the activity in this brain region differed significantly among the three contexts (Figure 4-5). To reveal where that difference was, the three contexts were compared in pairs in the follow-up tests, which were performed on

data averaged over the duration of the cluster. These follow-up tests confirmed that right ACC activity was significantly larger in the bivalent context compared to the natural switching context ($p = .0030$) and compared to the artificially-consistent context ($p = 0.0060$). The p -values reported here are after Bonferroni-adjustment for multiple comparisons. The main effects of "switch" and "mixing" were not significant in any ROIs.

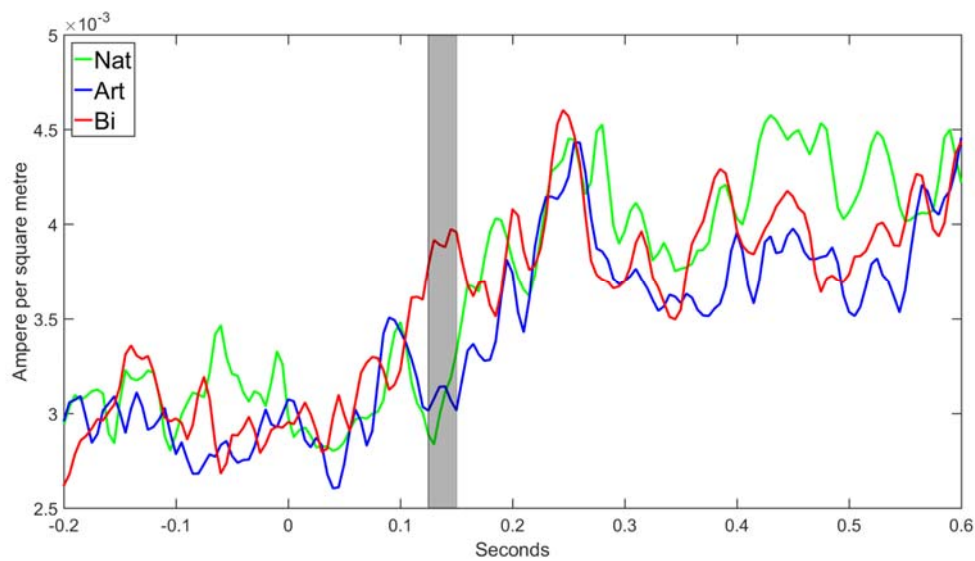


Figure 4-5. Reconstructed brain activity in the right ACC. A significant main effect of "context" was found in this brain region ($p = .0390$), characterised by increased activity in the bivalent context compared to the natural and artificially-consistent contexts. This effect corresponded to a cluster between 125 – 150 ms following stimulus onset (indicated by the shaded region). For ease of viewing, the overall activity in each context (averaged over all transition types) is shown here. Nat = natural context; Art = artificially-consistent context; Bi = bivalent context.

Planned pairwise comparisons within each context revealed one cluster which survived correction - a switch effect in the right IFG, occurring in the bivalent context only (Figure 4-6). This brain region showed increased activity on switch trials compared to stay trials ($p = .0120$, after Bonferroni), corresponding to a cluster between 210 - 260 ms following stimulus onset. Importantly, no significant clusters were detected when testing the switch effect in the natural context and in the

artificially-consistent context. No significant clusters representing a mixing effect were detected in any of the three contexts in the planned pairwise comparisons.

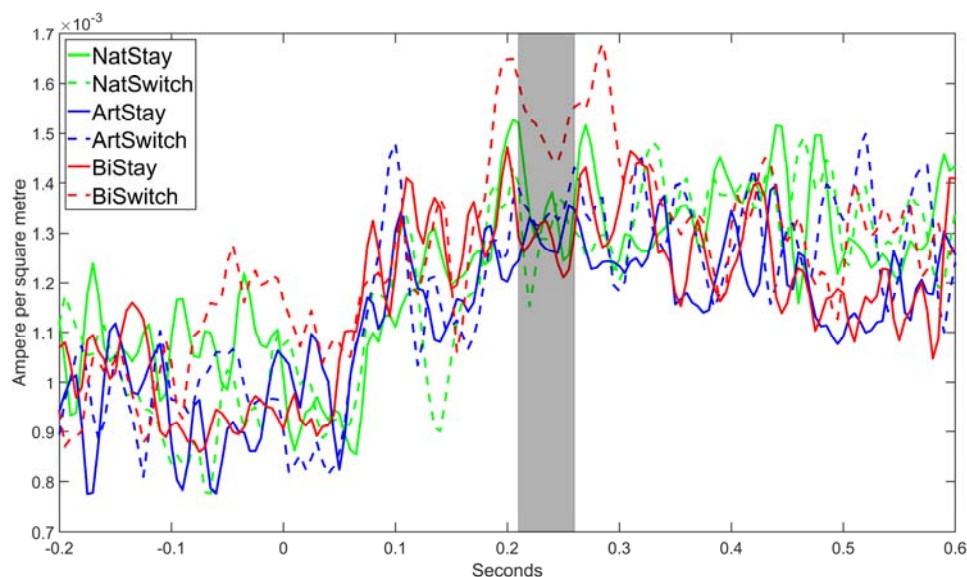


Figure 4-6. Reconstructed brain activity in the right IFG. This brain region showed increased activity on switch trials compared to stay trials in the bivalent context only ($p = .0120$; red lines), corresponding to a cluster between 210 – 260 ms following stimulus onset. No significant clusters were detected when comparing stay vs switch in the natural context (green lines) and in the artificially-consistent context (blue lines). Shaded region indicates the temporal extent of the cluster found in the bivalent context. Nat = natural context; Art = artificially-consistent context; Bi = bivalent context.

4.4 DISCUSSION

In the present MEG study, we investigated behavioural performance and neural activity when bilinguals switched language under natural and forced conditions. We aimed to find out whether natural switching was more efficient than forced switching, and if so, what factor(s) could explain this. In everyday conversations, bilinguals might switch language for a number of reasons. For example, some words may be more easily accessible in one language over another; the person they are speaking to might only understand certain words in one language and not the

other; or, sometimes it may be necessary to speak to two or more people in the same conversation, while these people do not share a common language with each other. The present study included three different production contexts, which may be considered as analogous to the scenarios above. The effects of language switching and mixing were compared across these contexts. We will now discuss the findings.

4.4.1 Is natural language switching easier than forced switching?

The first aim of this study was to examine how natural language switching differed from forced switching. To that end, we examined the switch effect and mixing effect in the natural context and the bivalent context. The purpose of the bivalent context was to replicate the traditional cued language-switching paradigm (i.e. forced switching), while the natural context was designed to elicit language switches based on lexical accessibility. In this section, we discuss the comparison between these two contexts, focussing on whether natural language selection led to improved behavioural performance and reduced engagement of cognitive control in language switching and mixing.

ERF analysis revealed a significant difference in the mixing effect between the natural and bivalent contexts. This corresponded to an effect cluster in left posterior sensors around 155 - 200 ms following stimulus onset. Specifically, in the natural context, stay trials evoked lower-amplitude activity compared to single-language trials, whereas in the bivalent context, stay trials evoked higher-amplitude activity compared to single-language trials. In other words, the natural context showed a mixing *advantage*, compared to the mixing *cost* observed in the bivalent context (both were significant in post-hoc tests with Bonferroni correction). This difference was evident in the opposite pattern shown in the ERF time course and topography for the mixing effects in these two contexts (Figure 4-4). Aligning with previous findings of mixing facilitation in the fully voluntary context (e.g. de Bruin et al., 2018;

Gollan & Ferreira, 2009), this result demonstrates that when language mixing occurs naturally, it can be less effortful than staying in the same language. While this may seem surprising at first, it becomes easy to understand if we adopt the assumption that the natural state of bilingual production is mixed-language (i.e. different languages are used to express different concepts, due to natural preference or lexical accessibility); if this is the case, the requirement to use a particular language to express all concepts actually takes extra effort. In contrast, being forced to mix language is a completely different story; when language mixing does not follow the bilingual speaker's natural preference (such as in the bivalent context), this becomes more effortful than staying in a single language. In terms of behavioural performance, we observed significantly reduced mixing cost in both reaction times and error rates in the natural context compared to the bivalent context, again demonstrating that natural language mixing was easier than forced mixing. However, here the benefit was limited to reduction or elimination of the mixing cost (in RTs and error rates, respectively), rather than an actual mixing advantage.

For the switch effect, there was no significant interaction found between the natural context and bivalent context, either in the ERF or ROI analysis. Planned pairwise comparisons (switch vs stay) were conducted within each context. These comparisons showed a switch cost in the right IFG in the bivalent context (surviving Bonferroni correction), while no switch effect was found in the natural context (Figure 4-6). Such difference between the natural and bivalent contexts was corroborated by the switch cost interaction in our behavioural results, where the natural context had a significantly smaller RT switch cost compared to the bivalent context. Pairwise comparisons within each context showed that naming on switch trials was significantly slower than on stay trials in the bivalent context, while no such difference was observed in the natural context. The increased brain activity in the right IFG on switch trials (compared to stay trials) in the bivalent context suggests that there was extra processing required on these trials, taking place

around 210 - 260 ms after stimulus onset; this may be the underlying cause of the delayed naming on these trials. In contrast, switch trials in the natural context did not elicit brain activities different from stay trials (i.e. no additional processing), hence there was no significant behavioural switch cost either. The extra processing represented by the right IFG activity may be related to inhibitory control (this will be discussed in Section 4.4.2). It should be noted that the MEG results discussed here are based on the planned pairwise comparisons within each context (with appropriate Bonferroni correction); it is unclear why an actual interaction only emerged in the behavioural data but not the MEG data.

In addition to the switch cost and mixing cost interactions, we also examined whether there was any overall difference across contexts. In the ERF analysis, no significant main effects were found. In the ROI analysis, there was a main effect of context in the right ACC, corresponding to an effect cluster between 125 - 150 ms following stimulus onset. This was characterised by increased activity in the bivalent context compared to the other two contexts (Figure 4-5). Follow-up tests to unpack the main effect confirmed that the overall difference between the natural context and bivalent context was significant during this time interval. The increased ACC activity in the bivalent context may be related to a higher demand for conflict monitoring (see more detailed discussion in Section 4.4.2). A consistent pattern was observed in the behavioural results, with the natural context showing overall significantly faster response speed and lower error rate than the bivalent context. Such increased efficiency has previously been reported for the fully voluntary context as well (e.g. Zhang et al., 2015; Blanco-Elorrieta & Pylkkänen, 2017; de Bruin et al., 2018).

Taken together, these behavioural and MEG findings reveal that language production in the natural context was more efficient than in the bivalent context. This was not only demonstrated by an overall difference between these contexts (i.e. faster and more accurate behavioural performance in the natural context, along

with a reduction in cognitive control), but was also reflected in the reduced costs of language switching and language mixing in the natural context (in terms of behavioural performance as well as cognitive demand, including reversing the mixing cost into a mixing benefit). It is important to note that the natural and bivalent contexts not only differed on whether language selection was free or forced on each trial, but they also differed on whether consistent item-language mappings were maintained. Perhaps the reduced effort in the natural context was achieved due to consistent mappings, rather than free language selection? Or it could be a combined effect of both? One way to answer these questions would be to look at the bilinguals' performance and brain activity in the artificially-consistent context, where consistent mappings were maintained but language selection was not free. We discuss those results in the next section.

4.4.2 What factor(s) make natural switching easier?

The second aim of this study was to tease apart exactly which factor(s) were responsible for the difference between natural and forced language switching. This was the purpose of the artificially-consistent context, which was designed to act as a bridge between the natural context and bivalent context. On the one hand, the artificially-consistent context was similar to the bivalent context (and different from the natural context) in that language selection on each trial was forced rather than free; on the other hand, it was similar to the natural context (and different from the bivalent context) in that all item-language mappings were consistent, rather than the same item being named in different languages on different trials. In this section, we address the following questions: (a) Do consistent item-language mappings play a role in making natural language switching easier and less effortful than forced switching? This question can be answered by comparing the artificially-consistent context to the bivalent context, to see whether consistent mappings resulted in any performance improvement and cognitive demand reduction. (b) If

so, does freedom of language selection offer any additional benefits on top of that? This question can be answered by comparing the natural context to the artificially-consistent context. We will now go through the effects in the same order as we did in Section 4.4.1.

Recall that there was an interaction in the ERF results, characterised by a mixing advantage in the natural context and a mixing cost in the bivalent context. Follow-up tests showed that the mixing effect in the artificially-consistent context was significantly different from the natural context, but not from the bivalent context. This pattern reveals that the mixing advantage in the natural context was due to freedom of language selection (i.e. the difference between natural and artificially-consistent context) rather than consistent item-language mappings (i.e. the difference between artificially-consistent and bivalent context). The RT mixing cost in the artificially-consistent context was significantly larger than in the natural context and significantly smaller than in the bivalent context; the mixing cost in naming accuracy in the artificially-consistent context was significantly smaller than in the bivalent context, but it was not significantly different from the natural context. Hence, consistent mappings reduced the mixing cost in both response speed and accuracy, and free language selection further lowered the cost to response speed. Bringing these findings together, it seems that both consistent mappings and freedom of language selection contribute to making language mixing less costly, but language mixing only becomes advantageous (i.e. even easier than staying in a single language) when language selection is free.

Moving onto the switch effect in the right IFG, this occurred in the bivalent context only. In the natural and artificially-consistent contexts, no significant difference was detected between stay and switch trials. This pattern implies that the switch effect was caused by inconsistent item-language mappings rather than forced language selection. In the bivalent context, each item elicited responses from different languages on different trials; therefore, the relevant labels in both languages were

likely to be highly activated and compete for selection. The right IFG might be involved in inhibiting the non-target-language candidate, to ensure that speech production occurs in the desired language (see de Bruin et al., 2014). Such inhibition would not be required in the natural and artificially-consistent contexts, as each item was only ever named in one particular language within these contexts. An alternative possibility is that, when item-language mappings were consistent (even though artificially enforced), participants were able to learn these mappings rather quickly. In this case, seeing each target object might have allowed them to retrieve the language associated with that item, hence the language switch itself did not have a direct impact. In terms of behavioural performance, the artificially-consistent context was not significantly different from either the natural or bivalent context (in RT or accuracy); however, as discussed earlier, the RT switch cost in the natural context was significantly smaller than in the bivalent context. This suggests an additive effect of the two factors, i.e. reduction of switch cost was achieved by a combined effect from consistent item-language mappings and free language selection.

For the main effect of context in the right ACC, follow-up tests showed that the artificially-consistent context was significantly different from the bivalent context, but similar to the natural context⁶⁹. This means that the key factor responsible for this effect was the consistency of item-language mappings. Such a pattern may reflect an overall strategy change for naming with inconsistent (vs consistent) language choices. As mentioned above, the naming of each item in both languages in the bivalent context likely leads to fiercer competition between candidate names in the two languages; therefore, bilinguals need to exert more cognitive control in this context, to monitor for conflicts and ensure that naming occurs in the correct

⁶⁹ Note that the artificially-consistent and bivalent contexts shared the same set of (language-specific) face cues, while a different set of (neutral) face cues were used in the natural context. The fact that brain activities in this early time window (125 - 150 ms) were similar between the natural and artificially-consistent contexts but different for the bivalent context offers confirmation that this context effect was not related to low-level visual features of the face cues.

language. This account aligns with the proposed role of the ACC in conflict monitoring (Luk, Green, Abutalebi, & Grady, 2012; Green & Abutalebi, 2013). Because participants always knew which context they were in, they could start engaging this mechanism from an early time (corresponding to the right ACC effect around 125 - 150 ms). In situations where conflicts were particularly high (e.g. on switch trials), an inhibitory mechanism could then kick in to suppress the competing labels (corresponding to the switch effect in right IFG around 210 - 260 ms). In the behavioural data, the overall response speed in the artificially-consistent context was significantly slower than in the natural context and significantly faster than in the bivalent context; the overall error rate in the artificially-consistent context was significantly higher than in the natural context but not significantly different from the bivalent context. These patterns suggest that consistent item-language mappings and free language selection both contributed to faster naming speed, and in addition, bilinguals were able to improve their overall naming accuracy when language selection was free.

It should be pointed out that a potential limitation exists in the present experimental design. Because we aimed to achieve both freedom of language selection and consistency of item-language mappings in the natural context, the target stimuli used for this context had to be specially selected. Each of these stimuli was strongly biased towards one of the languages (i.e. difficult or impossible to name in the other language). This made them somewhat different from the target stimuli in the other two contexts (each of which was possible to name in both languages). Thus, the natural context may have been distinct on an additional factor, namely, the absence of competition during lexical access. Such lack of lexical competition (due to the unavailability of a candidate label in the non-target language) may have played a role in making language switching and mixing easier in the natural context, aside from the two factors discussed above.

4.4.3 Conclusions

This study explored three different types of language-production contexts for bilingual speakers, and examined how the effects of language switching and mixing differed across these contexts. The natural context simulates a scenario where the interlocutor is highly proficient in both languages, therefore the speaker is free to use either language and switch as desired (i.e. according to lexical accessibility); the artificially-consistent context represents a situation where the interlocutor is more familiar with certain concepts in a particular language, so the speaker may need to switch language depending on the topic; the bivalent context is analogous to speaking to two people in the same conversation, where each of them only understands one of the languages (e.g. interpreting), so the speaker must repeat similar concepts in both languages. Findings reveal that language switching and mixing in the natural context was significantly easier than in the bivalent context (reflected by faster responses, fewer errors, and less cognitive resource recruited). The artificially-consistent context fell somewhere in between, suggesting that consistent item-language mappings and free language selection both contributed to making natural language switching easier.

Author contributions

JDZ, EB-E, and PFS conceived the study, and all authors gave input on the design. JDZ collected the data. JDZ performed the analyses with advice from YS and PFS. All authors contributed to interpreting the results and writing the manuscript.

Declaration of competing interest

None.

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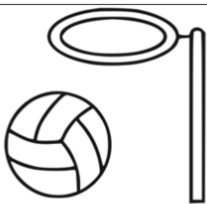
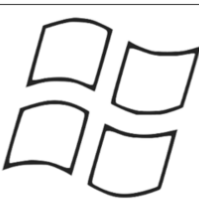
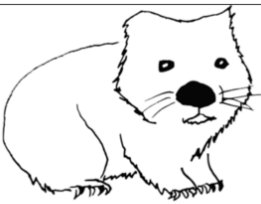





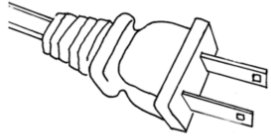


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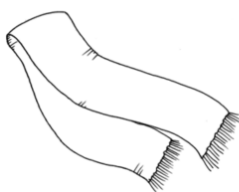



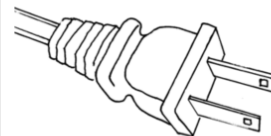


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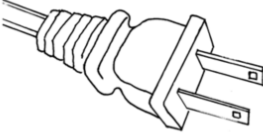
Appendix A. Study cards


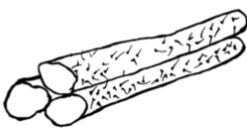

Study cards for Group A:

			
DNA	Netball	Windows	Wombat
			
Funnel	Glove	Kite	Walnut
			
Cloud	Plug	Basket	Snail

			
毽子	粽子	木鱼	山药
			
水桶	围巾	小丑	叉子
			
云朵	插头	篮子	蜗牛

Study cards for Group B:

			
DNA	Netball	Windows	Wombat
			
Bucket	Scarf	Clown	Fork
			
Cloud	Plug	Basket	Snail

			
粽子	粽子	木鱼	山药
			
漏斗	手套	风筝	核桃
			
云朵	插头	篮子	蜗牛

Two versions of “study cards” were used to achieve counterbalancing of item-language pairings in the artificially-consistent context (see Section 4.2.2.4). Top row of each card: natural context; middle row: artificially-consistent context; bottom row: bivalent context.

Appendix B. Survey results for neutral faces

Each neutral face was created by blending together a Chinese face and a Caucasian face (see details in Section 4.2.2.3). Survey respondents were asked to give a rating on how much each face was biased towards Chinese or Caucasian: 0 = Chinese; 100 = Caucasian.

	Face 1	Face 2	Face 3	Face 4
Subj01	45	50	60	40
Subj02	40	45	42	45
Subj03	65	60	70	55
Subj04	45	55	50	40
Subj05	33	48	54	36
Subj06	40	50	50	45
Subj07	52	44	50	38
Subj08	40	40	60	60
Subj09	55	55	65	45
Subj10	50	45	50	45
Subj11	45	60	30	25
Subj12	40	55	55	55
Subj13	50	40	40	50
Subj14	52	58	42	45
Subj15	50	50	60	50
Mean	46.8	50.3	51.9	44.9

Appendix C. Statistical results for behavioural data

(1) Reaction times

> *LME model:*

Linear mixed model fit by maximum likelihood. t-tests use Satterthwaite's method

[lmerModLmerTest]

Formula: RT ~ context * ttype + (1 | subjectID) + (1 | item)

Data: exp2_RT

AIC	BIC	logLik	deviance	df.resid
-124702.0	-124612.3	62363.0	-124726.0	13021

Scaled residuals:

Min	1Q	Median	3Q	Max
-3.6865	-0.5938	0.0478	0.6309	5.7576

Random effects:

Groups	Name	Variance	Std.Dev.
subjectID	(Intercept)	1.252e-06	0.0011189
item	(Intercept)	1.239e-07	0.0003519
Residual		4.030e-06	0.0020075

Number of obs: 13033, groups: subjectID, 24; item, 20

Fixed effects:

	Estimate	Std. Error	df	t value	Pr(> t)
(Intercept)	1.848e-02	2.653e-04	3.837e+01	69.664	< 2e-16 ***
contextBi	-1.583e-03	2.282e-04	2.157e+01	-6.936	6.45e-07 ***
contextNat	4.381e-04	1.910e-04	2.379e+01	2.294	0.03091 *
ttypeSingle	5.955e-04	7.435e-05	1.299e+04	8.010	1.25e-15 ***
ttypeSwitch	-1.568e-04	7.436e-05	1.299e+04	-2.109	0.03497 *
contextBi:ttypeSingle	1.306e-03	1.055e-04	1.299e+04	12.378	< 2e-16 ***
contextNat:ttypeSingle	-3.366e-04	1.048e-04	1.299e+04	-3.211	0.00133 **
contextBi:ttypeSwitch	-1.932e-04	1.067e-04	1.299e+04	-1.810	0.07025 .
contextNat:ttypeSwitch	2.041e-04	1.049e-04	1.299e+04	1.946	0.05165 .

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Note: the table above shows simple effects for "context" and "transition type". The main effects can be seen in the Analysis of Deviance table below.

Correlation of Fixed Effects:

	(Intr)	cntxtB	cntxtN	ttypSn	ttypSw	cntxtB:ttypSn	cntxtNt:ttypSn	cntxtB:ttypSw
contextBi		-0.301						
contextNat		-0.360	0.419					
ttypeSingle		-0.140	0.163	0.194				
ttypeSwitch		-0.140	0.163	0.194	0.499			
cntxtB:ttypSn		0.099	-0.234	-0.137	-0.705	-0.352		
cntxtNt:ttypSn		0.099	-0.115	-0.275	-0.709	-0.354	0.500	
cntxtB:ttypSw		0.098	-0.232	-0.135	-0.348	-0.697	0.501	0.247
cntxtNt:ttypSw		0.099	-0.115	-0.274	-0.354	-0.709	0.249	0.500 0.494

Analysis of Deviance Table (Type II Wald chisquare tests)

Response: RT

	Chisq	Df	Pr(>Chisq)
context	52.872	2	3.304e-12 ***
ttype	716.341	2	< 2.2e-16 ***
context:ttype	457.876	4	< 2.2e-16 ***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

> *Follow-up tests to unpack the main effect of "transition type":*

contrast	estimate	SE	df	z.ratio	p.value
Stay - Single	-0.000919	4.29e-05	Inf	-21.392	<.0001
Stay - Switch	0.000153	4.33e-05	Inf	3.539	0.0004
Single - Switch	0.001072	4.31e-05	Inf	24.873	<.0001

Results are averaged over the levels of: context

Degrees-of-freedom method: asymptotic

P value adjustment: holm method for 3 tests

> *Follow-up tests to unpack the main effect of "context":*

contrast	estimate	SE	df	z.ratio	p.value
Nat - Bi	0.001212	0.000220	Inf	5.514	<.0001
Nat - Art	-0.000394	0.000181	Inf	-2.175	0.0296
Bi - Art	-0.001606	0.000220	Inf	-7.307	<.0001

Results are averaged over the levels of: ttype

Degrees-of-freedom method: asymptotic

P value adjustment: holm method for 3 tests

> *Follow-up tests to unpack the interaction between "context" and "transition type":*

ttype_pairwise	context_pairwise	estimate	SE	df	z.ratio	p.value
Stay - Single	Art - Bi	0.001306	0.000105	Inf	12.378	<.0001
Stay - Switch	Art - Bi	-0.000193	0.000107	Inf	-1.810	0.1032
Single - Switch	Art - Bi	-0.001499	0.000106	Inf	-14.139	<.0001
Stay - Single	Art - Nat	-0.000337	0.000105	Inf	-3.211	0.0040
Stay - Switch	Art - Nat	0.000204	0.000105	Inf	1.946	0.1032
Single - Switch	Art - Nat	0.000541	0.000105	Inf	5.155	<.0001
Stay - Single	Bi - Nat	-0.001642	0.000105	Inf	-15.613	<.0001
Stay - Switch	Bi - Nat	0.000397	0.000106	Inf	3.733	0.0008
Single - Switch	Bi - Nat	0.002040	0.000106	Inf	19.299	<.0001

Degrees-of-freedom method: asymptotic

P value adjustment: holm method for 9 tests

> *Planned pairwise comparisons within each context:*

contrast	context	estimate	SE	df	z.ratio	p.value
Stay - Single	Art	-5.96e-04	7.43e-05	Inf	-8.010	<.0001

<-- mixing cost


```

Stay - Switch  Art    1.57e-04 7.44e-05 Inf  2.109 0.0699 <-- switch cost
Single - Switch Art    7.52e-04 7.44e-05 Inf 10.109 <.0001
Stay - Single  Bi     -1.90e-03 7.49e-05 Inf -25.398 <.0001 <-- mixing cost
Stay - Switch  Bi     3.50e-04 7.65e-05 Inf  4.574 <.0001 <-- switch cost
Single - Switch Bi     2.25e-03 7.55e-05 Inf 29.808 <.0001
Stay - Single  Nat     -2.59e-04 7.39e-05 Inf -3.505 0.0018 <-- mixing cost
Stay - Switch  Nat     -4.73e-05 7.40e-05 Inf -0.640 0.5224 <-- switch cost
Single - Switch Nat     2.12e-04 7.39e-05 Inf  2.863 0.0126

```

Degrees-of-freedom method: asymptotic

P value adjustment: holm method for 9 tests

(2) Error data

> *GLME model*:

Generalized linear mixed model fit by maximum likelihood (Laplace Approximation) ['glmerMod']

Family: binomial (logit)

Formula: error ~ context * ttype + (1 | subjectID) + (1 | item)

Data: exp2_ER

Control: glmerControl(optimizer = "bobyqa")

```

      AIC      BIC  logLik deviance df.resid
2740.6  2823.3 -1359.3  2718.6   13600

```

Scaled residuals:

```

      Min      1Q  Median      3Q      Max
-0.6048 -0.1654 -0.1128 -0.0788 17.6461

```

Random effects:

```

Groups   Name      Variance Std.Dev.
subjectID (Intercept) 0.5296  0.7277
item     (Intercept) 0.1014  0.3184

```

Number of obs: 13611, groups: subjectID, 24; item, 20

Fixed effects:

	Estimate	Std. Error	z value	Pr(> z)
(Intercept)	-4.0082	0.2557	-15.677	< 2e-16 ***
contextBi	0.6221	0.2890	2.152	0.03136 *
contextNat	-1.2428	0.3779	-3.288	0.00101 **
ttypeSingle	-0.1313	0.2431	-0.540	0.58923
ttypeSwitch	0.1061	0.2317	0.458	0.64696
contextBi:ttypeSingle	-1.1268	0.3575	-3.152	0.00162 **
contextNat:ttypeSingle	0.2332	0.4778	0.488	0.62556
contextBi:ttypeSwitch	0.3732	0.2859	1.305	0.19173
contextNat:ttypeSwitch	-0.1058	0.4798	-0.220	0.82553

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Note: the table above shows simple effects for "context" and "transition type". The main effects can be seen in the Analysis of Deviance table below.

Correlation of Fixed Effects:

	(Intr)	cntxtB	cntxtN	ttypSn	ttypSw	cntxtB:ttypSn	cntxtNt:ttypSn	cntxtB:ttypSw
contextBi		-0.562						
contextNat		-0.417	0.371					
ttypeSingle		-0.447	0.396	0.302				
ttypeSwitch		-0.472	0.416	0.317	0.494			
cntxtB:ttypSn		0.306	-0.431	-0.205	-0.680	-0.336		
cntxtNt:ttypSn		0.226	-0.201	-0.642	-0.508	-0.250	0.345	
cntxtB:ttypSw		0.380	-0.540	-0.257	-0.400	-0.810	0.436	0.203
cntxtNt:ttypSw		0.227	-0.200	-0.639	-0.238	-0.482	0.162	0.505
								0.390

Analysis of Deviance Table (Type II Wald chisquare tests)

Response: error

	Chisq	Df	Pr(>Chisq)
context	41.506	2	9.705e-10 ***
ttype	25.378	2	3.085e-06 ***
context:ttype	24.345	4	6.812e-05 ***

Signif. codes: 0 '****' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

> *Follow-up tests to unpack the main effect of "transition type":*

contrast	estimate	SE	df	z.ratio	p.value
Stay - Single	0.429	0.182	Inf	2.360	0.0365
Stay - Switch	-0.195	0.170	Inf	-1.151	0.2495
Single - Switch	-0.624	0.180	Inf	-3.476	0.0015

Results are averaged over the levels of: context

Results are given on the log odds ratio (not the response) scale.

P value adjustment: holm method for 3 tests

> *Follow-up tests to unpack the main effect of "context":*

contrast	estimate	SE	df	z.ratio	p.value
Nat - Bi	-1.571	0.279	Inf	-5.632	<.0001
Nat - Art	-1.200	0.255	Inf	-4.710	<.0001
Bi - Art	0.371	0.239	Inf	1.550	0.1213

Results are averaged over the levels of: ttype

Results are given on the log odds ratio (not the response) scale.

P value adjustment: holm method for 3 tests

> *Follow-up tests to unpack the interaction between "context" and "transition type":*

ttype_pairwise	context_pairwise	estimate	SE	df	z.ratio	p.value
Stay - Single	Art - Bi	-1.127	0.358	Inf	-3.151	0.0114
Stay - Switch	Art - Bi	0.373	0.286	Inf	1.305	0.9597
Single - Switch	Art - Bi	1.500	0.347	Inf	4.322	0.0001
Stay - Single	Art - Nat	0.233	0.478	Inf	0.487	1.0000
Stay - Switch	Art - Nat	-0.106	0.480	Inf	-0.220	1.0000
Single - Switch	Art - Nat	-0.339	0.476	Inf	-0.711	1.0000

Stay - Single	Bi - Nat	1.360	0.488	Inf	2.784	0.0322
Stay - Switch	Bi - Nat	-0.479	0.453	Inf	-1.057	1.0000
Single - Switch	Bi - Nat	-1.839	0.483	Inf	-3.807	0.0011

Note: contrasts are still on the log.o.r. scale

P value adjustment: holm method for 9 tests

> *Planned pairwise comparisons within each context:*

contrast	context	estimate	SE	df	z.ratio	p.value	
Stay - Single	Art	0.131281	0.243	Inf	0.540	1.0000	<-- mixing cost
Stay - Switch	Art	-0.106108	0.232	Inf	-0.458	1.0000	<-- switch cost
Single - Switch	Art	-0.237389	0.239	Inf	-0.993	1.0000	
Stay - Single	Bi	1.258064	0.262	Inf	4.797	<.0001	<-- mixing cost
Stay - Switch	Bi	-0.479316	0.168	Inf	-2.858	0.0298	<-- switch cost
Single - Switch	Bi	-1.737380	0.252	Inf	-6.899	<.0001	
Stay - Single	Nat	-0.101881	0.412	Inf	-0.247	1.0000	<-- mixing cost
Stay - Switch	Nat	-0.000349	0.421	Inf	-0.001	1.0000	<-- switch cost
Single - Switch	Nat	0.101532	0.412	Inf	0.246	1.0000	

Results are given on the log odds ratio (not the response) scale.

P value adjustment: holm method for 9 tests

CHAPTER 5

General Discussion

5.1 SUMMARY OF FINDINGS

The overall aim of this thesis was to advance our knowledge on the neural mechanisms of bilingual language control. In particular, I was interested in how bilinguals coordinate their two languages during speech production, as this represents a case where bilinguals have a choice of which language to use, rather than passively selecting language based on the input stimuli (e.g. in reading or speech perception). To that end, I conducted three experimental studies examining the manners in which executive control brain mechanisms were involved when bilinguals switched languages. These studies focussed on the following aspects of language control: the scope, timing, and demands for control under different circumstances.

5.1.1 The scope of language control

The scope of language control (whole-language vs item-specific) was examined in Chapter 2. This investigation was motivated by the proposal that there exists global and local language control in bilingual speech production (e.g. De Groot & Christoffels, 2006). Chapter 2 started with a behavioural experiment which utilised a combination of univalent and bivalent stimuli in a traditional language-switching paradigm. In this design, contrasting switch and stay trials (i.e. trial-to-trial switching) provided an index of whole-language inhibition, while contrasting bivalent and univalent stimuli (i.e. within-item switching) provided an index of item-specific inhibition. The subsequent TMS experiment then investigated whether whole-language and/or item-specific inhibition are carried out by domain-general brain mechanisms, by probing the causal involvement of the pre-SMA (a key brain region in the domain-general inhibitory control network). Using continuous theta burst stimulation to transiently disrupt the functioning of the pre-SMA, an overall slowing of naming responses was observed, with no strong evidence of differential

impacts between the naming of bivalent and univalent stimuli, or between switch and stay trials. Such observations suggest that the pre-SMA plays an essential role in general speech execution, but its specific involvement in each level of language control remains inconclusive.

This outcome does not seem to support a causal role of the pre-SMA in either whole-language or item-specific control (but for possible limitations of the study, see Chapter 2, Section 2.4.3). It may be useful to take one step back and look at how the broader executive control network is engaged in these two levels of language control. While only one brain area could be targeted at a time with TMS, activities in multiple brain regions could be examined simultaneously using MEG. The MEG study in Chapter 3 briefly touched on this topic again from a different angle, by decomposing the language-switching process into two stages. Specifically, whole-language control was assumed to occur when only the language cue was presented (at this stage, participants did not yet know what item needed to be named, so they could only apply control on each language as a whole), and item-specific control was assumed to take place after the naming target was shown (to resolve lexical competition as necessary). The findings in Chapter 3 revealed an asymmetrical switch effect in the left IFG during the first stage (i.e. whole-language control), and a language effect in the right IFG during the second stage (i.e. item-specific control). These results are discussed in more detail in the next section.

5.1.2 The timing of language control

The timing of language control was investigated in an MEG study in Chapter 3. Using a task design with separate cue and target presentation, neural activities in response to the language cue (i.e. preparation stage) and to the naming target (i.e. production stage) were examined. This study was motivated by behavioural findings on the effect of preparation time in language switching, which display a general trend of switch cost reduction when longer preparation time is given (e.g.

Costa & Santesteban, 2004, Exp. 5; Declerck, Philipp, & Koch, 2013; Fink & Goldrick, 2015, Exp. 1; Ma, Li, & Guo, 2016; Mosca & Clahsen, 2016; Khateb, Shamshoum, & Prior, 2017; but see Philipp, Gade, & Koch, 2007). Such findings suggest that bilinguals can prepare for an upcoming language switch in advance. However, the specific control processes that occur during preparation and during production remain unclear. Neural studies investigating such processes utilised varied designs and reported mixed findings (for a detailed review, see Chapter 1, Section 1.6). The study in Chapter 3 makes another attempt at examining the control processes occurring at these two stages in language switching, with the aim of bringing together optimal design elements from previous studies (e.g. using natural language cues, eliminating the confound of cue switching, avoiding carry-over effect in the trial sequence). The MEG data revealed different patterns of neural effects following cue and target onset, suggesting that there are distinct control processes taking place at these two stages. Following cue onset, an asymmetrical switch effect was observed in the left IFG between 315 and 345 ms, showing a larger switch-related activity increase when switching into the non-dominant language (compared to switching in the other direction). This asymmetrical effect may reflect stronger interference suppression (applied on the dominant language) in order to switch to the non-dominant language. Following target onset, increased activity was observed in the right IFG between 200 and 230 ms, for naming in the non-dominant language compared to the dominant language. This effect may reflect stronger inhibition of competing lexical items in the dominant language during non-dominant language production (than vice versa). Together, these findings suggest that bilinguals can prepare in advance for a language switch by biasing selection towards the target language (especially the non-dominant language), while some control is still required at the production stage to inhibit individual non-target lexical items that nonetheless become highly activated.

5.1.3 The demands for language control

The demands for language control in different interactional contexts were investigated in Chapter 4. Forced language switching, such as that examined in Chapters 2 and 3, is usually associated with significant performance costs and engagement of cognitive control. However, bilinguals are also known to switch languages spontaneously in daily life, even when there are no external instructions to do so. Is natural language switching easier than forced switching, and what factors might account for this difference? The MEG study in Chapter 4 compared three language-switching contexts, with increasing levels of external constraint on language selection. The natural context aimed to elicit the most free form of language switching, based on lexical accessibility and without any external constraints; the artificially-consistent context required language selection according to cues, but each item was consistently mapped to the same language; the bivalent context simulated the traditional cued switching design, with each item being named in different languages on different trials. The switch effect and mixing effect (in terms of behavioural performance and engagement of cognitive control) were compared across these three contexts. Language switching and mixing in the bivalent context incurred greater performance costs compared to the natural context (with the latter exhibiting no significant switch cost). The MEG data showed a mixing advantage in the natural context between 155 and 200 ms following stimulus onset, suggesting that mixing two languages together (freely) was even easier than staying in a single language. This was not the case in the other two contexts, indicating that the mixing advantage only occurs when language selection is free rather than forced. Additionally, the bivalent context elicited increased activity in the right ACC between 125 and 150 ms following stimulus onset (on both stay and switch trials), and increased activity in the right IFG between 210 and 260 ms (on switch trials only). These effects were not observed in the other two contexts, indicating that such patterns were likely due to each item being named in both languages in the bivalent context; the increased neural

activities may reflect extra demands for conflict monitoring and inhibitory control to resolve lexical competition in this situation. Taken together, the findings of Chapter 4 reveal that the reduced costs in natural switching (compared to forced switching) are due to both freedom of language selection and having consistent language choice for each item.

Since the bivalent context in Chapter 4 was similar to traditional cued switching, it may be useful to compare the results in the bivalent context with those from Chapter 3 (i.e. cued switching with bivalent stimuli). It should be noted though that a number of differences exist between the two studies, such as the participant population (unbalanced vs highly proficient bilinguals), the trial design (separate vs simultaneous presentation of cue and target), and the type of stimuli employed (digits vs pictures⁷⁰). The switch effect in the right IFG in the bivalent context roughly overlapped in time with the target-locked language effect in the right IFG observed in Chapter 3. This points towards an important role of the right IFG in mixed-language production under forced conditions. The different patterns of engagement (on switch trials vs for non-dominant language production in general) may reflect a control strategy difference between unbalanced and highly proficient bilinguals.

5.2 CONTRIBUTIONS TO THE LITERATURE

5.2.1 Item-specific control in bilingual production

The prevailing theory of bilingual language control positions inhibition as a central mechanism which ensures appropriate language selection in speech production (Green, 1998). This idea is supported by a variety of experimental evidence, such as the asymmetrical switch cost (e.g. Meuter & Allport, 1999; Jackson, Swainson, Cunnington, & Jackson, 2001; Campbell, 2005; Schwieter & Sunderman, 2008; Fink

⁷⁰ See Declerck, Koch, and Philipp (2012) for a comparison of switch costs in digit vs picture naming.

& Goldrick, 2015), reversed dominance effect (e.g. Christoffels, Firk, & Schiller, 2007; Gollan & Ferreira, 2009; Verhoef, Roelofs, & Chwilla, 2009; Martin et al., 2013; Peeters & Dijkstra, 2018), and n-2 language repetition cost (e.g. Philipp & Koch, 2009; Declerck & Philipp, 2018). However, there are also arguments against the existence of such inhibitory mechanisms of language control. For example, Runnqvist, Strijkers, Alario, and Costa (2012) showed that the semantic interference effect in picture naming is cumulative, irrespective of whether the response language changes or not. This is against the prediction of the inhibitory account, according to which semantic interference should be cancelled out (or reduced) following a language switch. Such evidence thus speaks against the presence of inhibition, at least on the whole-language level. Importantly, if the assumption of whole-language inhibition is incorrect, that does not rule out the possibility of inhibition taking effect on a different (e.g. item-specific) level.

In the present thesis, I attempted to look into this less-investigated level of language control and examine it alongside whole-language control. The experiments in Chapter 2 introduced a modification to the standard language-switching paradigm by using a mixture of univalent and bivalent stimuli; this enabled the two levels of language control to be examined side by side in a single task. The performance difference between univalent and bivalent stimuli was established as an index for item-specific inhibition. The study in Chapter 4 allowed another inspection of item-specific control, in the comparison between the bivalent context and the artificially-consistent context. This comparison differed from Chapter 2 in that it occurred across blocks. Performance costs and increased brain activity in executive-control regions in the bivalent context were considered to reflect item-specific control. These studies provide experimental designs which may be used in future investigations of whole-language and item-specific control in bilingual production. A potential limitation in the task design from Chapter 2 was addressed in Chapter 4 - I discuss this issue and the design improvement in Section 5.3.2.

5.2.2 Switch cost asymmetry vs reversed dominance

A long-standing question in the language-switching literature concerns why switch cost asymmetry is observed in some studies while reversed dominance is observed in others. Both of these patterns are usually considered as evidence for the involvement of inhibition in language switching; however, they seem to occur in a somewhat complementary manner⁷¹ (see Chapter 1, Sections 1.3.1 and 1.3.3). What could be the factors that give rise to one or the other pattern in a particular situation?

The contrast between univalent and bivalent stimuli in Chapter 2 provided some possible insights into this. Based on the observation of a reversed dominance effect in the bivalent (but not univalent) stimuli, I proposed a tentative answer to the question above: the two patterns may originate from language control operating on different levels. Specifically, switch cost asymmetry stems from the effect of whole-language control, whereas reversed dominance stems from the effect of item-specific control (more details in Chapter 2, Section 2.4.1). As for why different levels of control are observed across different studies, I speculated that this depended on the participants' language control strategy, which could be influenced by their language background⁷². For example, late bilinguals might be more used to keeping their two languages separate and adjusting the activation level of each language as a whole (i.e. whole-language control), therefore they exhibit switch cost asymmetry in language switching (e.g. Meuter & Allport, 1999; Jackson et al., 2001; Costa & Santesteban, 2004, Exp. 1; Philipp et al., 2007, Exp. 1;

⁷¹ Note that these two patterns are not strictly mutually exclusive. There are also studies which show both effects (e.g. Schwieter & Sunderman, 2008) or neither (e.g. Calabria, Branzi, Marne, Hernández, & Costa, 2015; Prior & Gollan, 2011).

⁷² Each study tends to recruit participants with a relatively uniform profile, so it is likely that the participants within a study adopt similar language control strategy. However, explicit comparison of bilinguals with different profiles have also been carried out (e.g. Costa & Santesteban, 2004; Martin et al., 2013), and indeed the findings reveal different control strategies across groups (e.g. early vs late bilinguals). Thus, variations in participants' language backgrounds could be a source of control strategy difference across studies, leading to different levels of language control being observed.

Martin et al., 2013; Fink & Goldrick, 2015, Exp. 2). On the other hand, early or highly proficient bilinguals may have a less rigid boundary between their two languages, treating words from both languages as belonging to one integrated lexicon; therefore, they rely more on item-specific control, which results in a pattern of reversed dominance (e.g. Costa & Santesteban, 2004, Exp. 2 & 3; Costa, Santesteban, & Ivanova, 2006, Exp. 1; Martin et al., 2013)⁷³. This provides a possible explanation of why switch cost asymmetry is observed in some cases and reversed dominance in others, based on which level of language control is being observed in each particular situation. My proposal of different underlying causes for these two patterns can be tested in future studies.

5.2.3 What makes natural language switching easier?

Recently, there has been growing interests in how (and why) bilinguals switch language spontaneously in everyday conversations, given that language switching is usually found to be costly (i.e. requires extra time and cognitive resource) in research studies. Prompted by concerns about the ecological validity of existing laboratory paradigms, this emerging line of research investigates how language control in natural switching may differ from that in forced switching (see Blanco-Elorrieta & Pylkkänen, 2018, for a review). Studies have so far compared cued switching (forced language selection with inconsistent item-language mappings), voluntary switching (free language selection with potentially inconsistent mappings), and more recently, bottom-up switching (free language selection with consistent mappings). The general trend shows that, when language selection

⁷³ Note that a reversed dominance effect has occasionally been observed in unbalanced bilinguals (Christoffels et al., 2007; Verhoef, Roelofs, & Chwilla, 2010; Zheng, Roelofs, Erkan, & Lemhöfer, 2020). In addition, Declerck, Kleinman, and Gollan (2020) report that they obtained a larger reversed dominance effect for more (vs less) balanced bilinguals in a standard analysis, but the opposite was true when they took into account the degree of language dominance in single-language blocks. These findings may thus constitute counter-evidence against my speculation. However, they do not undermine my main proposal that the phenomena of switch cost asymmetry and reversed dominance originate from language control operating on two different levels.

occurs in a more natural manner (e.g. driven by lexical accessibility), this usually brings about faster responses overall, sometimes along with reduced performance costs in switching and mixing (for more details, see Chapter 1, Section 1.7). However, there was a missing piece of the puzzle - what happens in forced language selection with consistent mappings? (see Chapter 4, Table 4-1).

The MEG study in Chapter 4 examined this by introducing the “artificially-consistent” context, where participants named pictures according to language cues but the language requirement remained constant for each appearance of the same picture. Results showed that the (behavioural and neural) costs of language switching and mixing in this context generally fell somewhere between completely natural switching and fully cued switching. This reveals that consistent item-language mappings and freedom of language selection are both factors that contribute to making natural switching easier than forced switching. Importantly, the artificially-consistent context (compared to the bivalent context) brought about a significant reduction in mixing cost and the disappearance of the neural switch effect in the right IFG, showing that these benefits can be achieved merely by having consistent item-language mappings. This suggests that some of the efficiency previously reported in bottom-up switching (Kleinman & Gollan, 2016) may be attributable to this factor, rather than being necessarily related to free language selection. Furthermore, no significant behavioural switch cost occurred in the artificially-consistent context; this demonstrates that “cost-free” switches are possible even in forced language switching, when consistent item-language mappings are maintained⁷⁴.

⁷⁴ Note that a (reduced) mixing cost was still present.

5.3 METHODOLOGICAL CONSIDERATIONS

A significant amount of time during this PhD project was spent on thinking about and trying different design options for the experimental studies. Even though the language-switching paradigm is relatively well established, many finer variations exist across studies - this could be a source of the discrepant findings in the current literature (see Chapter 1 for a detailed review). Therefore, I strived to make optimal design decisions in my experiments (e.g. using natural cues to elicit language switches, avoiding confounds as much as possible, etc).

In this section, I will reflect on the important lessons I have learned through this process, and detail the methodological issues to consider when designing (neural) studies of language switching. I will also discuss the design improvements that were made as I progressed from one study to the next.

5.3.1 Choice of language cues

Perhaps one of the most important considerations in designing a language-switching study is what type of language cues to use. Studies have shown that the choice of language cues can make a lot of difference to the behavioural and neural switch effects observed. Explicit comparisons of different types of cues reveal that artificial/opaque cues tend to result in larger switch costs than natural/transparent cues (Blanco-Elorrieta & Pylkkänen, 2017; Lavric, Clapp, East, Elchlepp, & Monsell, 2019). For example, Blanco-Elorrieta and Pylkkänen (2017) compared colour cues (artificial) with faces of interlocutors (natural) in a parallel design. Behaviourally, they observed a significant switch cost with the colour cues, but not with the face cues; MEG data showed a switch effect in both cases, but this effect was longer-lasting when colour cues were used. In a similar vein, Lavric et al. (2019) compared two types of auditory cues: name of the required language spoken in that language (transparent) vs short sped-up fragment of national anthem (opaque). Smaller

behavioural switch costs were observed with the transparent cues (compared to the opaque cues), along with a reversal of the preparation benefit on switch cost⁷⁵. A corresponding pattern was found in their ERP data, where the switch effect occurred earlier in the case of transparent cues (i.e. earlier onset of control processes led to smaller behavioural cost). In addition, the transparent cues also brought about faster and more accurate responses overall. Taken together, these findings show that bilinguals are more efficient at language switching (and mixed-language production in general) when they are given more natural language cues. This is likely because artificial cues require additional cue-related processing (especially on switch trials), the costs of which are blended into the observed "language switch" cost. On the other hand, natural cues create a more ecologically valid environment for language switching, minimising the amount of artificial processing required. Therefore, natural cues should allow a more specific examination of the language-switch effect itself. In all three experimental studies presented in this thesis, I adopted language cues that were as natural as possible.

In Chapter 2 (behavioural and TMS experiments), I used a sentence prompt as the language cue, which appeared simultaneously with the target picture on each trial. The cue was in the form of a question: "*What is this?*" indicated that an answer was required in English, while the Chinese equivalent "*这是什么?*" indicated that an answer was required in Mandarin. The purpose of using these questions was to simulate a natural interaction, where responses are elicited in the same language that the question is asked in. This approach likely introduced saccades as participants read through the sentence and moved between the sentence cue and the target picture. While this may not have had much impact on their performance in the behavioural tasks⁷⁶ (Chapter 2), eye movements could introduce undesirable artefact into MEG data. To overcome this issue, faces cues were adopted in Chapter

⁷⁵ When opaque cues were used, the switch cost was reduced with long preparation time; in contrast, when transparent cues were used, the switch cost increased with long preparation time.

⁷⁶ Or if it did, it should have impacted all conditions in a similar way.

3. These cues were again meant to simulate a natural environment, i.e. seeing the face of an interlocutor naturally prompts the appropriate response language (Li, Yang, Scherf, & Li, 2013; Woumans, Martin, et al., 2015; Martin, Molnar, & Carreiras, 2016). Two Chinese faces were used for Mandarin and two Caucasian faces for English (see Chapter 3, Figure 3-1). Participants were introduced to these interlocutors at the beginning of the experiment, and the task was placed in a context of “playing a game with these new friends”. One potential caveat of using faces as language cues is that there could be race-related effects in face perception. To ensure that the experimental findings would not be contaminated by such effects, a validation study was carried out first to check whether these faces elicited different neural responses (see Chapter 3, Appendix A). Another option that was considered involved using the printed word “say” as a cue for English and “说” for Mandarin. However, this idea was abandoned because the distinct scripts for the two languages might introduce a confound, due to possible differences in the low-level visual features (thus leading to an artificial switch effect based on cue change).

The same four face cues were used in Chapter 4, along with four newly-created neutral faces for the natural-switching condition (see Chapter 4, Figure 4-1). However, this was a difficult decision given the need to present the cue and target simultaneously in this study (to keep the MEG session within a reasonable length). If both the language cue and the target picture were visual, this would make the stimuli very complicated and also likely introduce saccades, as there would be two things competing for attention on each trial. Moreover, different participants might adopt different strategies (e.g. some might look at the cue first, while others look at the target picture first). Auditory cues were considered as an option, because different input modalities might allow the participants to more easily pay attention to both the (auditory) cue and the (visual) target at the same time. An obvious choice was voice prompts (e.g. “say” for English, “shuo” for Mandarin). However, any cues that were linguistic in nature would inevitably introduce a confound of language switch in *perception*, i.e. whenever the participants were required to

switch language in production, the cue they hear on that trial would also have to be in a different language than the previous trial, therefore language-switching effects in perception and production would be blended together. Other possible options included playing a tone with Chinese instruments vs western instruments, or playing short segments of national songs; however, these cues were likely too opaque (see Lavric et al., 2019). Other types of visual cues, which might be less attention-demanding than faces, were also considered (e.g. national flags, iconic animals/flowers, or using landmarks as the background). Each of these options had their own drawbacks, either due to difficulty in finding two cues that could be naturally associated with each language (see below), or lack of appropriate options for neutral cues. The eventual compromise was to use face cues, but display them in such a way that the face and the target picture could be easily integrated into one stimulus. Specifically, the face appeared above the target picture on each trial, with hands holding the picture (see Chapter 4, Figure 4-2), and the task instruction was to “name the picture each person is holding”. To mitigate the possible issue of saccades and different participant strategies (i.e. which part of the stimuli they attend to first), a fixation cross was placed on the nasion of the face, and participants were required to focus their gaze on the fixation cross at all times.

Another important point relating to language cues is the possible confound of cue switching. In a design where each language is represented by one specific cue, whenever the language requirement changes, the cue itself also has to change on that trial (compared to the preceding trial). Thus, any “language switching” effect observed in this case may actually be a combined result of cue switching and language switching (see Heikoop, Declerck, Los, & Koch, 2016). Most previous studies in the language-switching literature suffer from such a confound, including the study in Chapter 2. This issue can be circumvented by using two cues per language and ensuring that a cue change occurs on every trial; although this does not remove the effect of cue switching, that effect is controlled for because it now occurs on both language-stay and language-switch trials. More studies are now

adopting this kind of design, in order to clearly separate the true language-switching effect from the confound of cue switching (Verhoef et al., 2010; Reverberi et al., 2015; de Bruin, Samuel, & Duñabeitia, 2018; Lavric et al., 2019). In Chapters 3 and 4 of this thesis, two face cues were mapped to each language. To ensure that the cue change was obvious (even on stay trials), one female face and one male face were used for each language, with the gender changing on every trial.

5.3.2 Confounding factor to the effect of valence

One major focus of the present thesis is on item-specific control in bilingual production (see Section 5.2.1). This was investigated through the comparison between univalent and bivalent stimuli (Chapters 2 and 4). Because each univalent stimulus was consistently named in a particular language (i.e. not requiring item-specific inhibition) while each bivalent stimulus was named in different languages on different trials (i.e. requiring item-specific inhibition), the difference between them provided an index for item-specific control. As discussed towards the end of Chapter 2 (Section 2.4.3), the experimental design in that study included a possible confound, due to differential priming of the univalent and bivalent stimuli. Univalent items were named in the same language throughout the experiment (including in the training block and as filler trials in the testing block), therefore the target responses for these items appeared much more frequently than the target responses for bivalent items did. Such additional repetition priming could be a contributing factor to any valence-related effects observed in that study (e.g. faster and more accurate naming of univalent items compared to bivalent items). Even though this did not compromise the interpretation of the asymmetrical valence cost, it likely inflated the magnitude of the valence cost (i.e. not purely reflecting item-specific control).

This design limitation was addressed in Chapter 4, by equalising the number of times each target response appeared in the entire task. The training block was no

longer used, and bivalency was achieved purely by having these items appear in both languages on critical trials (similarly, these bivalent items also appeared equally in both languages on filler trials). The crucial design element was that the number of bivalent items were halved, such that the target response for each bivalent item in each language appeared an equal number of times as the target response for each univalent item (both on critical trials and filler trials). In other words, all the target labels in the entire experiment were named the same number of times (see Chapter 4, Section 4.2.2.1). This resolved the concern about repetition priming being one of the driving factors behind any difference between univalent and bivalent stimuli. Although this design was still not perfect, as each bivalent stimulus was now presented twice as many times as each univalent stimulus, that was a less important concern than the differential amount of priming on the target responses. A possible future improvement would be to use two different pictures for each bivalent item, so that the number of times each picture is shown would also be equalised across univalent and bivalent items.

5.3.3 Trial sequence

In all three experimental studies (Chapters 2 to 4), the trials were presented in a pseudorandom order, so that participants could not predict the target stimulus and language requirement of an upcoming trial. Aside from the basic constraints (e.g. no repeated stimuli on consecutive trials, balanced appearance of each stimulus on stay and switch trials), one important criterion in generating the trial sequence was that no critical trial was contaminated by a preceding switch trial. It has been shown that switch costs could carry over to the immediately following trial, resulting in worse performance on that trial (e.g. Blanco-Elorrieta & Pykkänen, 2016). Therefore, it is important to avoid such contamination.

In Chapter 2, this was achieved using a “triad” design, where each critical trial was preceded by two filler trials (e.g. English-English-Mandarin). The pair of filler trials

always required responses in the same language, thus ensuring that the critical trial was never preceded by a switch trial (see also Finkbeiner, Almeida, Janssen, & Caramazza, 2006). While this solution worked well for the behavioural and TMS experiments (Chapter 2), it was no longer practical when it came to the MEG studies (Chapters 3 and 4). Since neural techniques require a larger number of trials in each condition in order to average out the noise, this kind of trial sequence would make the testing session too long; as a consequence, participants would be likely to get tired or start moving around. To address this issue, an improved design was adopted, where a filler trial was inserted only after every switch trial. Each filler was a stay trial (i.e. it followed the same language requirement as the previous switch trial), so it would not contaminate the next critical trial. This design reduced the ratio between filler and critical trials from 2 : 1 to 0.5 : 1, while still ensuring that no critical trial ever followed a switch trial. Therefore, the total number of trials were reduced by half, making it possible to keep the MEG testing sessions to a reasonable length.

5.4 RELATIONS TO OTHER TOPICS

5.4.1 Language switching vs task switching

Language control is often seen as a form of action control. In particular, some researchers consider language switching to be just another instance of task switching (Abutalebi & Green, 2008). Indeed, some of the most commonly used paradigms in studying language control (e.g. the language-switching paradigm, the n-2 repetition paradigm) came from task switching, and the influential inhibitory account of bilingual control (Green, 1998) was built upon theories of generic action control. In line with such views, studies have observed similarities in participants' behavioural performance across language switching and non-linguistic task switching. For example, Prior and Gollan (2011) found that Spanish-

English bilinguals, who incurred smaller switch costs than Mandarin-English bilinguals in language switching, also did so in task switching; additional analyses showed that this advantage could be related to more frequent everyday language switching in the former. In regards to the presence of switch cost asymmetry, Liu, Rossi, Zhou, and Chen (2014) found that a group of participants who showed asymmetrical switch costs in task switching also showed asymmetrical costs in language switching, whereas another group exhibited symmetrical switch costs in both domains. Furthermore, there seems to be cross-domain transfer of training effects, i.e. training in a non-linguistic switching task improves participants' performance in language switching (Liu, Liang, Dunlap, Fan, & Chen, 2016), and vice versa (Timmer, Calabria, & Costa, 2019). On the other hand, opposing evidence has also been reported. A few studies found no correlation in participants' performance across language switching and task switching, either in the magnitude of the switch cost (e.g. Calabria, Hernández, Branzi, & Costa, 2012; Marne, Hernández, & Costa, 2015) or the n-2 repetition cost (Branzi, Calabria, Boscarino, & Costa, 2016). These studies also report qualitative differences across the two domains, such as symmetrical language-switch costs and asymmetrical task-switch costs within the same group of participants (Calabria et al., 2012), and age-related changes in switch cost being observed for task switching only (Marne et al., 2015). Such findings run counter to the evidence above, and suggest that language switching may not simply be a sub-type of task switching.

One possible explanation for these mixed patterns of similarities and differences between language switching and task switching, is that the control mechanisms may overlap partially across the two domains, thus resulting in limited skill transfer (e.g. Prior & Gollan, 2013; Weissberger, Wierenga, Bondi, & Gollan, 2012; Kang, Ma, Li, Kroll, & Guo, 2020). In support of this idea, neural evidence shows shared brain activation between language and task switching, particularly in the prefrontal cortex (Blanco-Elorrieta & Pylkkänen, 2016; Branzi, Della Rosa, Canini, Costa, & Abutalebi, 2016), while there are also differences across the two domains in certain

brain regions (De Baene, Duyck, Brass, & Carreiras, 2015; Weissberger, Gollan, Bondi, Clark, & Wierenga, 2015). So, what makes language switching different from task switching? In my view, there are a number of intrinsic differences between the two.

The first point relates to the motivation behind language/task switching. Bilinguals are known to code-switch in everyday conversations without any external instructions to do so, as long as they think the other person will understand them. Intuitively, one major reason to switch language (voluntarily) is that it is often easier to express certain ideas in one language and others ideas in another language. This means that the language preference may change dynamically within a conversation, and switching language can facilitate communication. In contrast, there is hardly any internal motivation to voluntarily switch between tasks, as it should always be easier to stay in the same task. In most cases, people have a uniform preference for one task over another, regardless of what stimuli are involved (e.g. card sorting by colour is easier than sorting by shape, reading a colour word is easier than naming the colour it is printed in, etc). One could argue that, in some particular situations, the task preference might change depending on the stimuli (e.g. $2 + 3$ might be easier than $2 - 3$, while $7 + 6$ could be more difficult than $7 - 6$). However, even when task switching occurs according to such dynamically changing preferences, it would still entail a shift from one task set to another (e.g. from addition to subtraction). This is likely to involve some kind of top-down control⁷⁷ (Arrington & Logan, 2004, 2005; Demanet, Verbruggen, Liefoghe, & Vandierendonck, 2010), which is expected to incur a cost - it is just a matter of whether this cost is worth it, depending on whether the gain from changing to the easier task outweighs the cost of switching task. On the other hand, when proficient bilinguals switch freely between languages (i.e. without external constraints), they are not really performing any "switching" at all. For them, the task

⁷⁷ Alongside possible involvement of bottom-up factors (e.g. Mayr & Bell, 2006; Yeung, 2010).

is simply to “express these thoughts”, rather than “speak in a mixture of these two languages” or “switch between these two languages”. In other words, in a context where both languages are acceptable, switching language does not require any task shifting or goal updating; the task is one and the same: speech production (in any language). In fact, the “free switching” context is what gives bilinguals the maximum freedom, whereas staying in a single language is actually more restrictive. Consistent with this idea, voluntary mixed-language production sometimes leads to *faster* response times than single-language production (de Bruin et al., 2018), especially for the non-dominant language (Gollan & Ferreira, 2009). While quite a few studies still observed voluntary language-switch costs (e.g. Zhang et al., 2015; de Bruin et al., 2018), it has been shown that this is likely related to the participants’ strategy, and such costs can be eliminated when bilinguals truly adopt a bottom-up strategy, allowing accessibility-driven lexical selection (Gollan, Kleinman, & Wierenga, 2014, additional analyses for Exp. 2; Kleinman & Gollan, 2016).

A related point is that the tasks adopted in language switching tend to be more natural than those in task switching. Language switching is typically examined using picture- or digit-naming tasks. In these tasks, the responses come from habitual associations that have been established through normal life (e.g. producing the word “door” upon seeing a picture of a door). On the other hand, in task switching studies, the stimulus-response associations are usually arbitrary and learned on the spot (e.g. press the left key for red stimuli, right key for blue stimuli). This may be a reason why voluntary language switching can be more efficient than voluntary task switching. Gollan et al., (2014, Exp. 2) showed that voluntary language switching incurred no cost in those participants who adopted a bottom-up (as opposed to top-down) strategy of language selection. In this case, speech responses were driven by automatic picture-response associations, i.e. whichever name that was activated to a greater extent by each picture (irrespective of language) was selected for output. Hence, language “switches” were not intentionally performed, but

simply a by-product of having used different languages on successive trials. The (non-existent) switch cost in these “bottom-up participants” was significantly smaller compared to that observed in “top-down participants”. This stands in clear contrast to voluntary task switching investigated in the same experiment, where similarly classified “bottom-up participants” incurred a switch cost of comparable magnitude to that in “top-down participants”. Such findings suggest that cost-free switching may only be possible when responses are highly automatic, e.g. based on *a priori* associations between concepts and their corresponding words. These automatic responses exist in language switching but not in task switching, thus representing one important difference between them.

The points discussed above seem to suggest that language switching mostly differs from task switching when performed voluntarily. However, even forced language switching can be different from task switching. One example to illustrate this is how the effect of preparation time varies depending on the type of cues used, as observed by Lavric et al. (2019). In this study, when the language cues were relatively opaque (short segments of national anthems), long preparation time led to a reduction of switch cost, a pattern similar to that commonly observed in task switching; however, when the cues were natural (spoken words “English” and “Deutsch”), this pattern was reversed, i.e. the switch cost was smaller with short preparation time. Lavric et al. argue that this kind of natural cues may have no equivalents in task switching, in that they can rapidly and automatically activate the corresponding language set, leading to more efficient switching. Therefore, it seems that perhaps only forced language switching with artificial cues would be similar to task switching.

There are also other task-specific factors that may differentiate language switching from task switching. Firstly, in task switching, the two tasks are usually associated with different attributes of the stimuli (e.g. colour and shape); on a given trial, participants must selectively attend to one of these attributes and ignore the other,

thus producing a response based on the attribute that is relevant for the current task. In other words, switching from one task to another usually involves switching attention from one dimension of the stimulus to another⁷⁸ (see Meiran, 2008, for a discussion). However, in the case of language switching, the two languages are associated with the *same* aspect of the stimuli, i.e. meaning. No matter which language is currently required, participants always attend to this same attribute. In other words, the meaning itself affords two possible responses. Secondly, task switching paradigms commonly re-use the same responses in both tasks (e.g. press the left button for red stimuli in one task and for blue stimuli in the other task). In this case, each response is associated with two different stimuli (i.e. response bivalency)⁷⁹. While this is not impossible in language switching (e.g. having multiple pictures associated with the same name), such designs are rarely seen.

These discussions lead to some avenues for future research. As mentioned above, language switching is perhaps most similar to task switching when it occurs under forced conditions with artificial cues. In other words, removing the natural elements from language switching turns it into a rather artificial task, which becomes comparable with (other types of) task switching. However, such conditions bear little resemblance to bilinguals' language use in real life. Therefore, a more ecologically valid approach to assess the similarities and differences between language switching and task switching might be to compare them under voluntary contexts. For forced switching, neural studies have observed largely shared brain networks across the two domains, with some differences in the activation of particular brain regions (De Baene et al., 2015; Weissberger et al., 2015; Blanco-Elorrieta & Pylkkänen, 2016; Branzi, Della Rosa, et al., 2016). A similar investigation

⁷⁸ Note that this does not necessarily have to be the case. For example, one task can be "press the left button when you see a triangle, and press the right button when you see a square", while the other task requires the reverse; in this case, participants always attend to the shape of the stimuli. However, it is very common for task-switching paradigms to be based on different attributes of the stimuli.

⁷⁹ Again, this is not necessarily the case, but it is very common in task-switching studies.

has yet to be conducted on the (possible) neural overlap between voluntary language switching and task switching. So far, one study has examined the behavioural patterns in a direct contrast of voluntary switching in the two domains, and found that the switch cost could be eliminated in a sub-group of participants, for language switching but not for task switching (Gollan et al., 2014). Separate investigations of the neural effects of voluntary language switching and task switching show that the latter is usually associated with a significant neural switch effect (e.g. Vandamme, Szmalec, Liefooghe, & Vandierendonck, 2010; Orr & Banich, 2014), while the former is not (Blanco-Elorrieta & Pylkkänen, 2017; Reverberi et al., 2018; Liu et al., 2020, in the sham condition)⁸⁰. Future studies can directly compare the neural effects of voluntary switching across the two domains. As discussed above, voluntary task switching likely requires an intentional process of task selection and shifting, while voluntary language switching may not involve any “switching” at all. Therefore, I predict that, unlike in forced switching, there should be minimal neural overlap between voluntary language switching and voluntary task switching.

5.4.2 Language control and the bilingual cognitive advantage

An alternative approach to examine the relationship between bilingual control and general cognitive control is to look at how bilinguals behave differently from monolinguals on tasks that tap into executive function. If coordinating two languages does indeed rely on domain-general control mechanisms, then bilinguals are expected to have enhanced their executive functioning through the

⁸⁰ One exception is Zhang et al. (2015), who observed a neural effect of voluntary language switching. However, this study was a bit of a special case as cued trials and voluntary trials were mixed together in the same block, thus participants might have had to maintain a top-down strategy throughout. Moreover, the stimuli set in this study consisted of the digits 1-9, for which a bilingual would probably have a uniform language preference over all the stimuli; therefore, the “voluntary switching” in this case would be unlikely to be driven by lexical accessibility (i.e. bottom-up processes), but rather might involve intentionally making a decision on what language to use on each trial, i.e. similar to what happens in voluntary task switching.

extensive practice of language control in everyday life (Kroll & Bialystok, 2013; Bialystok, 2017). Current evidence on this topic is highly controversial (for a recent review, see Van den Noort et al., 2019). On the one hand, a large number of studies report that bilinguals outperform monolinguals on tasks requiring executive control⁸¹ and they recruit less cognitive resources to perform these tasks (e.g. Bialystok, Craik, Klein, & Viswanathan, 2004; Bialystok, Craik, & Luk, 2008; Costa, Hernández, & Sebastián-Gallés, 2008; Garbin et al., 2010; Tao, Marzecová, Taft, Asanowicz, & Wodniecka, 2011; Marzecová et al., 2013; Woumans, Ceuleers, Van der Linden, Szmalec, & Duyck, 2015; Kousaie & Phillips, 2017; Desideri & Bonifacci, 2018). On the other hand, there are several studies which do not find superior performance in bilinguals over monolinguals on such executive-control tasks (e.g. Paap & Greenberg, 2013; de Bruin, Bak, & Della Sala, 2015; Paap et al., 2017; Papageorgiou, Bright, Periche Tomas, & Filippi, 2019), and some researchers claim that the reported cases of bilingual advantage largely arise from failures to control for confounding factors as well as publication bias favouring positive results (Paap, Johnson, & Sawi, 2015; de Bruin, Treccani, & Della Sala, 2015; Lehtonen et al., 2018). Apart from behavioural performance and functional brain activities, another type of evidence which may be informative is the neuroanatomical differences between bilinguals and monolinguals, because structural changes in the brain may reflect the long-term consequence of juggling two languages in daily life. The findings are highly variable in regards to whether such differences exist between bilinguals and monolinguals, as well as the exact brain regions involved (see García-Pentón, Fernandez Garcia, Costello, Duñabeitia, & Carreiras, 2016, for a review). A third line of evidence concerns the contribution of bilingualism to cognitive reserve (via the regular practice of executive control). These findings are again mixed, with some studies reporting that bilingualism delays the onset of dementia symptoms (e.g.

⁸¹ Such as the flanker task, Stroop task, Simon task, n-back task, attentional network test, Wisconsin card sorting test, non-linguistic switching tasks, etc. Exactly what executive-control processes are involved in each of these tasks is a matter of debate. For one influential view, see the “unity and diversity” framework (Miyake et al., 2000; Miyake & Friedman, 2012; Friedman & Miyake, 2017).

Craik, Bialystok, & Freedman, 2010; Schweizer, Ware, Fischer, Craik, & Bialystok, 2012; Alladi et al., 2013) while other studies do not observe such benefit (e.g. Sanders, Hall, Katz, & Lipton, 2012; Lawton, Gasquoine, & Weimer, 2015).

One reason for these highly inconsistent findings across studies may be that the emergence of a cognitive advantage (or not) depends on the specific language background and patterns of language use by each individual. Bilingualism is not a unitary label, but a complex phenomenon with much diversity across individuals - this should be taken into account when assessing the cognitive consequences of bilingualism (Luk & Bialystok, 2013). Indeed, several studies have observed different outcomes for bilinguals with different language profiles. For example, Tao et al. (2011) found that early bilinguals had a greater advantage in conflict resolution ability compared to late bilinguals. Similarly, Woumans, Ceuleers, et al. (2015) found that balanced bilinguals outperformed unbalanced bilinguals in the attentional network test, and only the former showed a direct correlation between fluent switching and the Simon effect. In regards to structural changes in the brain, Pliatsikas, DeLuca, Moschopoulou, and Saddy (2017) observed significant subcortical reshaping in bilinguals with extensive immersion in their L2 environment, but not in those with limited immersion (with comparable proficiency and age of acquisition). These findings all suggest that the consequences of bilingualism can be heavily influenced by factors relating to the characteristics of the bilingual individuals and their language use experience.

Given the basic premise of the "bilingual advantage" hypothesis - the advantage results from extensively utilising cognitive control in daily life - it seems reasonable that such benefit should be more pronounced in those bilinguals who apply *intentional* control to switch between languages. Based on discussions in the previous section (5.4.1), natural language switching in everyday life (e.g. when the conversational partner can understand both languages) may be largely driven by bottom-up processes rather than intentional control, hence not necessarily

exercising executive function. In fact, language switching might only rely on generic cognitive control when it is performed under highly constrained conditions. In other words, perhaps only specific types of language switching requiring a high level of top-down control will give rise to a cognitive advantage via practice over time (see Blanco-Elorrieta & Pylkkänen, 2018, for a similar argument). For example, the MEG study in Chapter 4 of this thesis showed that, forced switching recruited additional cognitive control (compared to free switching), especially when each concept was repeatedly named in both languages back and forth (i.e. the bivalent context). This can be translated to a real-life scenario of talking about the same subject matter in two different languages, where the language choice is based on external cues (i.e. the interlocutors). One example of such a circumstance is interpreting for two people who do not share a common language; in this case, each utterance needs to be repeated immediately in the other language⁸². This is arguably one of the tasks requiring the most extreme form of language control. Hence, if there are any cognitive benefits to be gained from practicing language control, these benefits should be most obvious in professional interpreters, whose daily work involves such intensive language switching according to external cues. Given that the search for a cognitive advantage in the general bilingual population (whose language use patterns are often diverse and may be difficult to categorise) has so far returned two sets of rather solid but seemingly contradicting evidence, it may be beneficial to take a step back and see if more uniform findings can be obtained first in this sub-group with known patterns of language use.

Compared to the wealth of data available on the comparison between normal bilinguals and monolinguals, studies examining the cognitive control abilities in interpreters (and comparing them to either normal bilinguals or monolinguals) are

⁸² The type of bivalent switching that occurs during interpreting is slightly different from that in a usual language-switching paradigm, as the former involves two modalities (i.e. listening to an utterance in one language and reproducing it in the other language). However, since the same person usually interprets for both parties of a conversation (i.e. converting the messages in both directions), the interpreter very likely needs to *produce* the same concepts in both languages too.

relatively scarce. From the currently available findings, interpreters exhibit an advantage on tasks involving shifting and updating but not on those involving inhibition (e.g. Dong & Liu, 2016; Yudes, Macizo, & Bajo, 2011), and the shifting ability in particular seems to be dependent on the amount of interpreting training and experience (see Nour, Struys, Woumans, Hollebeke, & Stengers, 2020, for a review). In addition, neuroimaging evidence shows that undergoing training in simultaneous interpreting results in structural changes in the brain over time⁸³, such as cortical thickening in regions related to executive and attentional control (Hervais-Adelman, Moser-Mercer, Murray, & Golestani, 2017), and increased structural connectivity in the cognitive control brain networks (Van de Putte et al., 2018). Simultaneous interpreting is a particularly demanding type of interpreting task which requires exquisite control. In a direct comparison between professional interpreters who regularly undertake this type of work and those who do not, Becker, Schubert, Strobach, Gallinat, and Kühn (2016) found that the former performed better in a dual-task scenario and a switching task, and the two groups of interpreters also differed in brain structure and functional connectivity. This may be one of the most extreme examples demonstrating the fine-grained modulation of cognitive advantage based on specific patterns of language control experience. Future studies can continue to examine professional simultaneous interpreters in a full range of executive control tasks (such as those that have been used in the comparison between bilinguals and monolinguals, see above). Additionally, most studies so far have utilised a cross-sectional design, comparing the performance across two groups of participants. A longitudinal (within-subject) design would be more desirable, e.g. testing the same group of simultaneous interpreters before and after one year of interpreting work. This type of design should help eliminate concerns about demographic factors introducing confounds between groups,

⁸³ Compared to control groups who had similar profiles but did not undergo such training.

which has been one of the main criticisms against the studies reporting a bilingual cognitive advantage (Paap et al., 2015).

5.5 CONCLUSIONS

The present thesis aimed to investigate the neural mechanisms of language control in bilingual speech production. This research was motivated by the remarkable ability of bilinguals to switch language seamlessly in natural conversations, as well as being able to stay in the same language when required. I chose to study production in particular, because this is a case where bilinguals can have control over what language to use, rather than being driven by the input stimuli.

In this thesis, I investigated three particular aspects of bilingual language control: scope, timing, and demands for control under different circumstances (Chapters 2 to 4). The findings demonstrate that (1) language control operates on both the whole-language and the item-specific level, likely supported by different neural mechanisms; (2) there are distinct control processes taking place during the preparation and the execution of a language switch; (3) the demand for language control is reduced in natural switching compared to forced switching, and it can be even less effortful to mix languages together (freely) than to stay in a single language. These findings expand our current understanding of how language control is carried out in the bilingual brain.

In establishing the control processes involved in bilingual production, my view has shifted from one that specifically focuses on inhibition-related mechanisms (Chapter 2) to one that incorporates a broader range of executive control mechanisms. From a theoretical point of view, Green and Abutalebi (2013) posited eight possible processes in bilingual control, each of which may be involved to different extents depending on the demands of the specific interactional context. Thus, the later studies in this thesis examined a broader network of brain regions

implicated in executive control, looking at the possible roles of these brain regions in two stages of language switching (Chapter 3) and how their engagement may be different when bilinguals switch language naturally rather than being forced to switch (Chapter 4).

Although the findings in this thesis were obtained from the language switching paradigm in particular, they should be applicable not just to this task, but to bilingual language control in general. Language switching was employed as a window into such control, because it represents a situation where bilinguals need to constantly regulate their two languages. I developed a novel variant of this paradigm in Chapter 2, which allowed item-specific control to be examined alongside whole-language control. This additionally brought about an interesting observation leading to a tentative explanation of the different origins of the switch cost asymmetry and reversed dominance effect. To fill a gap in the existing literature on free language switching, a new type of switching context was introduced in Chapter 4 (i.e. artificially-consistent context). This design made it possible to tease apart the contributions of two different factors in making natural switching easier than forced switching.

All together, the findings from this thesis extend our knowledge of bilingual language control, by providing a more in-depth understanding of the particular manner in which the bilingual brain coordinates two languages during speech production. The design variations (to the language-switching paradigm) developed during this thesis can be used in future investigations of item-specific control and natural language switching.

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ETHICS APPROVALS

**Human Research Ethics Committee****REQUEST FOR AMENDMENT FORM**

Please complete this form for all amendments/modifications including extensions to approved ethics projects.

For quick and efficient review of your amendment, please provide sufficient information in this document to allow the amendment to be reviewed as a standalone document (i.e. it does not require the Ethics Secretariat or HREC reviewing the original application).

Please attach tracked and clean copies of all amended documents to the amendment request. Documents could include participant information and consent forms (PICF), advertising material, surveys, interview questions, verbal scripts, support letters from external organizations.

Submitting this form:

HREC approved applications: Please send this form to ethics.secretariat@mq.edu.au.

Faculty/School-approved applications:

Please send this form to the ethics subcommittee administrator of the relevant Faculty/School

Faculty of Human Sciences: fhs.ethics@mq.edu.au

Faculty of Science and Engineering: sci.ethics@mq.edu.au

Faculty of Arts: artsro@mq.edu.au

Faculty of Business and Economics: fbe-ethics@mq.edu.au

MGSM: ethics@mgsu.edu.au

PACE: pace.ethics@mq.edu.au

Faculty of Medicine and Health Sciences: ethics.secretariat@mq.edu.au.

Handwritten forms will not be accepted.

1. **Human Research Ethics Committee Reference No:** 5201400585

2. **Chief Investigator/Supervisor:** Paul Sowman

Faculty: Human Sciences

Department: Cognitive Science

Email: paul.sowman@mq.edu.au

Date of amendment: 29/02/2016

- 3. Names of Co-Investigators/Associate Supervisors/Research Assistants:** Anina Rich, Matthew Finkbeiner, Mark Williams, Margaret Ryan, Alexandra Woolgar, Anna Hearne, Genevieve McArthur, Anne Castles, Saskia Kohnen, Soheil Afshar, Denise Moerel, Andrew Etchell, Leidy Castro-Meneses, Shahd Al Janabi, Manjunath Narra, Lina Teichmann, Rocco Chiou, Jade Jackson, Jordan Wehrman, Nathan Caruana, Yvette Kezilas, Ana Murteira, **Di Zhu and Daniéll Steinberg.**

(Note: If the project is to be undertaken by an Honours/postgraduate/HDR student, the supervisor will be considered the Chief Investigator. The student may be named as a co-investigator.)

- 4. Project Title:** Stimulating and recording the brain in studies of cognitive control

- 5. Description of the amendment/s:**

Please clearly explain the changes that have occurred or are intended. Please describe what is currently approved and how the amendment(s) alter this.

We wish to add two new students.

We wish to amend the SONA advertisement to include bilinguals, and the flyers to include controls or bilinguals.

We wish to advertise the remuneration on the Control PICF, the SONA advertisements and the flyers as \$40/\$50 per testing session.

Mr. Jordan Wehrman is now a cognitive science student so his affiliation has been changed.

Dr. Anna Hearne has left Australia so has been removed as a co-investigator

- 6. Rationale for the amendment(s):**

Clearly describe the reason for the changes listed in section 5

Ms. Di Zhu is completing her Masters of Research and will use non-invasive brain stimulation methods to research the role of the interior frontal gyrus and the pre-supplementary motor area in cognitive control of speech and movement in bilinguals. Di Zhu is supervised by Drs. Sowman and Finkbeiner.

Ms. Daniéll Steinberg completing her Masters of Research and Masters of Clinical Neuropsychology. Ms. Steinberg will use non-invasive brain stimulation methods to research the role of the visual cortex in cognitive control. Daniéll Steinberg is supervised by Dr. Finkbeiner

We wish to advertise that participants will be paid \$40 or \$50 for their participation. Some participants may need a structural MRI to identify the relevant brain areas for TMS application. These participants will be required to travel to Macquarie University Hospital from Macquarie University, and hence will be compensated the larger sum for their travel and time; the participants who undergo TMS only will be paid \$40 for their time and travel.

- 7. Changes to study documents:**

Re: Request for amendment 5201300054 - Addition of researcher

APPROVED

By Fran Thorp at 10:11 am, Mar 22, 2017

Elisabeth Magdas

Mon 20/03/2017 9:11 AM

FT To do

To: Ethics Secretariat <ethics.secretariat@mq.edu.au>;

Cc: DI ZHU <di.zhu3@students.mq.edu.au>; Nick Benikos <nick.benikos@mq.edu.au>;

Categories: HUM

3 attachments (2 MB)

5201300054_request_amendment_form_DiZhu_NicholasBenikos.doc;

Appendix1_5201300054_ConsentForm_Version4.6_clean_Mar2017.docx;

Appendix1_5201300054_ConsentForm_Version4.6_tracked_Mar2017.docx;

Hi Rebeka,

Ah that makes sense! Please find attached the updated amendment request to reflect the addition of both new researchers.

With thanks,

Elisabeth

From: Rebeka Tennent on behalf of Ethics Secretariat

Sent: Friday, 17 March 2017 1:52:14 PM

To: Elisabeth Magdas

Subject: RE: Request for amendment 5201300054 - Addition of researcher

Hi Elisabeth,

We had an issue with our email the week that your original email was sent, and as such, it went astray and has not been actioned!

Could I ask you to resubmit the amendment request, including the second researcher?

Many thanks,

Rebeka.

From: Elisabeth Magdas

Sent: Friday, 17 March 2017 9:33 AM

To: Ethics Secretariat <ethics.secretariat@mq.edu.au>

Subject: Re: Request for amendment 5201300054 - Addition of researcher

Good morning Ethics secretariat,

Just wondering if there has been any updates for the amendment request below? I have since had another request to add on a second researcher.

With thanks,
Elisabeth

From: Elisabeth Magdas
Sent: Wednesday, 1 March 2017 12:34:59 PM
To: Ethics Secretariat
Subject: Request for amendment 5201300054 - Addition of researcher

Good afternoon Ethics Secretariat,

Please find attached an amendment form for the ethics ref 5201300054 to add one researcher: Ms Di (Judy) Zhu.

Also attached are the tracked and clean copies of the updated PICF which reflect this addition.

Please let me know if any further information is required.

Thank you for your time.

Kind regards,
Elisabeth