The mechanisms and the scope of bilingual language production

Francesca Martina Branzi

TESI DOCTORAL UPF 2014

DIRECTOR DE LA TESI

Dr. Albert Costa

Departament de Tecnologies de la Informació i les Comunicacions

Universitat Pompeu Fabra
Barcelona

"Le Chêne un jour dit au Roseau:
"Vous avez bien sujet d'accuser la Nature;
Un Roitelet pour vous est un pesant fardeau.
Le moindre vent, qui d'aventure
Fait rider la face de l'eau,
Vous oblige à baisser la tête :
Cependant que mon front, au Caucase pareil,
Non content d'arrêter les rayons du soleil,
Brave l'effort de la tempête.
Tout vous est Aquilon, tout me semble Zéphyr.
Encor si vous naissiez à l'abri du feuillage
Dont je couvre le voisinage,
Vous n'auriez pas tant à souffrir:
Je vous défendrais de l'orage;
Mais vous naissez le plus souvent
Sur les humides bords des Royaumes du vent.
La nature envers vous me semble bien injuste.
- Votre compassion, lui répondit l'Arbuste,
Part d'un bon naturel ; mais quittez ce souci.
Les vents me sont moins qu'à vous redoutables.
Je plie, et ne romps pas. Vous avez jusqu'ici
Contre leurs coups épouvantables
Résisté sans courber le dos;
Mais attendons la fin. "Comme il disait ces mots,
Du bout de l'horizon accourt avec furie
Le plus terrible des enfants
Que le Nord eût portés jusque-là dans ses flancs.
L'Arbre tient bon; le Roseau plie.
Le vent redouble ses efforts,
Et fait si bien qu'il déracine
Celui de qui la tête au Ciel était voisine
Et dont les pieds touchaient à l'Empire des Morts."

« Le Chêne et le Roseau » de Jean de La Fontaine

Acknowledgement

The present dissertation represents the completion of a long time endeavor, during which I have been unconditionally supported by my beloved families, in Italy and in Barcelona. Hence, my foremost thanks go to Angelo, Giovanna, Emmanuel, Giulia, Camilla, Michele, Simone, Federico, Marcello, Marco and Fabrizio. I owe it all to them.

I am immensely grateful to all the people that introduced me to the world of research, since without them this dissertation would never have been possible. Enormous thanks goes to my supervisor, Albert Costa. Over these years he has represented an unrepeatable model of scientific practice, critical thinking, support and care. Special thanks go to Jubin Abutalebi and Pasquale Della Rosa that provided my first contact with research. Their collaboration over these years has been crucial for the work presented in this dissertation. I am infinitely grateful to Marco, an amazing colleague and friend, to Clara and Cristina for their insights and their support throughout my studies, and for the invaluable opportunity to learn from them.

I am grateful to all my lab mates at CBC, those of the past and of the present. Many thanks to Xavi, Elin, Jasmin, Alexandra, Sara, Kristof, Tristan and Mireia: from them I have had an amazing company and I have learned to be collaborative. I am particularly grateful also to Joanna and Elisa, for having helped a lot with the correction of my articles. I want to thank Andrea, Gisela, Nicolò, Alveno, Gabriele, Carlos and Alice for having shared with me this

journey in the bad and in the good times.

I am grateful to Nuria Sebastián Gallés, Luca Bonatti, Gustavo Deco and Salvador Soto-Faraco that in these years have provided a rich scientific environment from which I maximally profited. I am infinitely grateful to Luis Fuentes, for having welcomed me into his lab as a member of his research team. I really appreciated his support and his bright ideas that have improved my research work. Many thanks to Xavi and Sylvia in Barcelona and Pedro in Murcia for their help on technical issues, and to Natalia and Cristina Cuadrado, Neus, Santa, Aurelio, Florencia, Jaume, for their help on so many bureaucratic issues and pages of formalities necessary to realize my research.

The research reported in this dissertation was supported by a predoctoral fellowship from the Spanish Government (FPU-2009-2013).

Abstract

When bilinguals plan to speak even one word, lexicalization processes of the two languages becomes concurrently activated. Surprisingly, bilingual speech production is not dramatically affected. This observation raises the questions about the control mechanisms that ensure lexicalization in the intended language and their representational scope.

The aim of this dissertation was to increment the general knowledge on these two aspects of bilingual language control. To do so, we measured behavioral, electrophysiological, and neural responses in language switching tasks to investigate the mechanisms and the scope of bilingual language control. Moreover, we measured behavioral and neural responses in linguistic and non-linguistic switching tasks to explore the overlap between bilingual language control and domain-general executive control.

The most consistent findings of this dissertation suggest that the mechanisms of bilingual language control are different from domain-general inhibitory control and that they are applied globally on the dominant language and likely also locally on the non-dominant language.

The evidence presented in the current dissertation not only extends previous knowledge on bilingual language control, but it also provides a clearer understanding of the role of inhibitory control in switching tasks, an information relevant for any model of bilingual language control.

Resumen

En el momento que los bilingües planean hablar, incluso si es sólo una palabra, los procesos de lexicalización se activan simultáneamente en ambas las lenguas. Sorprendentemente, la producción del habla bilingüe no se ve afectada de forma significativa. Esta observación plantea preguntas acerca de los mecanismos de control que garantizan la lexicalización en la lengua deseada así como su alcance.

Esta tesis tiene como objetivo incrementar el conocimiento general sobre estos dos aspectos de control lingüístico en los bilingües. Para ello, en diferentes experimentos se midieron respuestas conductuales, electrofisiológicas y neuronales en tareas de cambio lingüísticas para investigar los mecanismos y el alcance del control de las lenguas. Además, se midieron las respuestas conductuales y neuronales en tareas de cambio lingüísticas y no lingüísticas para explorar el solapamiento entre el control lingüístico y el control ejecutivo de dominio general.

Los hallazgos más consistentes de esta tesis sugieren que los mecanismos de control lingüístico en los bilingües son diferentes de control inhibitorio de dominio general y que se aplican a nivel global en la lengua dominante y probablemente también a nivel local en la lengua no dominante.

La evidencia aportada en esta tesis no sólo extiende el conocimiento previo sobre el control lingüístico en los bilingües, sino que además proporciona una comprensión más clara sobre el papel del control

inhibitorio en las tareas de cambio, una información relevante para cualquier modelo de control lingüístico bilingüe.

Preface: On the origin of the “hard problem”

It is largely understood that even when they want to speak in one language alone, bilinguals experience the parallel activation of the two languages, during which a shared semantic representation simultaneously activates two possible lexical candidates[1] (e.g., Colomé, 2001; Costa et al., 2000; Hermans, Bongaerts, De Bot, & Schreuder, 1998; Poulisse, 1999; Thierry & Wu, 2007; Wu & Thierry, 2010, 2012).

The evidence for such phenomenon comes from different studies, such as experiments that showed cognate effects[2] in naming latencies for bilinguals but not for monolinguals (Costa et al., 2000), studies that revealed translation effects during phoneme monitoring tasks (Colomé, 2001) and other studies that demonstrated that when assessing to the intended language, bilinguals cannot avoid unconscious translation effects to the non-intended language (e.g., Thierry & Wu, 2007).

Importantly, the parallel activation of the two languages seems to have some consequences on bilingual language

---

[1] This situation of “pervasive synonymy” regards all levels of linguistic representation, that is, lexical, syntactic and phonological. Importantly, research in this field and the work presented in this thesis has particularly focused on the lexical level of the linguistic representation, for which each concept has two equally good word-candidates that map onto it.

[2] “Cognate effects” are referred to experimental comparisons between cognate and non-cognate words. C*ognates* are those translation words that have similar orthographic-phonological forms in the two languages of a bilingual (e.g., *gat*—Catalan, *gato*—Spanish [*cat* in English]); non-cognates are those translations that only share their meaning in the two languages (*pastanaga*— Catalan, *zanahoria*—Spanish [*carrot* in English]).

production. One of them is that language production in the non-dominant language (L2) is generally less efficient compared to that in the dominant language (L1), even in high-proficient bilinguals and in contexts in which only one language is used (e.g., Ivanova & Costa, 2008). Bilinguals are also slower in articulating complete words and sentences, and they often speak with a more or less perceptible foreign accent (Gollan, Fennema-Notestine, Montoya, & Jernigan, 2007; Gollan, Montoya, Cera, & Sandoval, 2008; Gollan & Silverberg, 2001; Ivanova & Costa, 2008; Kohnert, Hernandez, & Bates, 1998; Roberts, Garcia, Desrochers, & Hernandez, 2002).

More surprisingly, bilinguals have a speech production disadvantage in comparison to monolinguals when they speak in their dominant language (i.e., L1). These effects have been observed in word naming latencies (Gollan et al., 2008; Gollan, Montoya, Fennema-Notestine, & Morris, 2005; Ivanova & Costa, 2008; Sadat, Martin, Alario, & Costa, 2012), in the amount of lexical items produced in standardized naming tests (e.g., Boston naming test) (Gollan et al., 2007; Kohnert, Hernandez, & Bates, 1998a; Roberts et al., 2002) and in timed verbal fluency tasks (Bialystok, Craik, & Luk, 2008; Gollan, Montoya, & Werner, 2002). Moreover, bilinguals as compared to monolingual counterparts are more prompt to incur in “tip of the tongue” states (i.e., the impossibility in retrieving a known word) (e.g., Gollan & Acenas, 2004; Gollan & Silverberg, 2001; Sandoval, Gollan, Ferreira, & Salmon, 2010).

These observations have been taken to reflect an increased difficulty of lexicalization processes for bilinguals as compared to their monolingual peers, due to the simultaneous activation of two languages. However, this “problematic” situation seems to be somehow negotiable, since cross-language intrusions are very rare in bilingual language production (e.g., Gollan, Sandoval, & Salmon, 2011) and since high-proficient bilinguals, for whom the lexical selection should be most difficult, do not find difficult to speak in one language instead of the other[3].

Therefore, the “hard problem” (see Finkbeiner, Gollan, & Caramazza, 2006) in bilingual speech production arises because a given semantic representation equally activates two translation equivalent lexical nodes and because, at the same time, the decision of speaking in one language cannot switch off the other language.

In turn, these considerations have prompted the questions of how lexical selection in the intended language is achieved in bilinguals and how the interference from the undesired language is avoided.

The general aim of this thesis was to advance the knowledge on how language production and control is achieved in bilingual speakers. In turn, this goal might be subdivided in two different sub aims:

---

[3] Lexical selection should be harder for high-proficient bilinguals than for low-proficient bilinguals since in the former group the two lexical candidates for a given concept should be activated by the semantic systems with the same strenght (e.g., Kroll & Stewart, 1994) .

- To test which are the specific mechanisms involved in bilingual language control, according to the proposed models in the literature.

- To test to which extent these control mechanisms are applied, that is, the representational scope of bilingual language control.

In order to advance in our knowledge on these issues, in the present dissertation we followed different approaches and we employed different methodological measurements to test these questions. Before going into the details of the experimental part, we will introduce the current evidence on these issues in order to understand the contribution of the present dissertation in respect to the literature.

Table of contents

List of figures

List of Tables

1. GENERAL INTRODUCTION: the bilingual language control system

The issue of how bilinguals control their two languages (referred as “bilingual language control”) and in particular of how bilingual speakers manage to focus lexicalization process (i.e., word selection) on the intended language, can be subdivided into two separate questions.

The first question aims to unravel the nature of the control *mechanisms* involved in bilingual language control. Interestingly, different mechanisms have been proposed in the literature regarding how bilingual language control might be achieved. However, as we will see below, despite the effort of the last 20 years to advancing our knowledge on this issue, the evidence to explain the mechanisms of bilingual language control is still not well understood.

The second question concerns the *scope* of bilingual language control, that is, how these control mechanisms are applied at the representational level. The crucial question is whether bilingual language control mechanisms are applied to specific items (such as translation equivalents, semantic competitors and recently used words) or to the whole language.

As we will see, with the book chapter presented in Section 2.3 we bring forth a critical review of these issues to provide a theoretical framework in which the relevance of the experimental work of this dissertation can be appreciated.

Throughout the first chapter of this thesis we will describe the state of the art of the literature on bilingual language production by running trough the most relevant studies that explored the mechanisms and the representational scope of bilingual language control.

1.1 On the mechanisms of bilingual language control

Various views on bilingual language control functioning have been provided in more than 20 years of research on bilingualism.

Despite of some differences, nevertheless they can be divided into two groups. Crucially, these groups do not differ in the extent to which the non-response language is activated. Rather, they differ regarding the extent to which competition at the lexical level is proposed between the two languages.

In what follows, we will try to characterize the most important views on bilingual language control and the most relevant evidence supporting these models.

1.1.1 Language-specific selection models of bilingual language production

Some researchers have proposed models in which lexical selection in bilinguals would be qualitatively similar to that of monolinguals (Costa & Caramazza, 1999; Costa, Miozzo, & Caramazza, 1999; Finkbeiner, Gollan, et al., 2006; La Heij, 2005). In that, lexical access would be a competitive process but just within languages[4]. In other words, during lexical access competition would arise only between semantic competitors, but not between translation equivalents. One of these accounts, the "concept selection account", poses that the activation levels of translation equivalent will never approximate each other, since the intended language is already specified at the conceptual level. That is, the semantic system activates the lexical nodes of the intended language to a substantially higher level than lexical nodes in the non-intended language (La Heij, 2005). This account, however, is hardly reconcilable with a series of evidence that showed that language production is not fully serial (e.g., Dell, 1986; Levelt, Roelofs, & Meyer, 1999; Morsella & Miozzo, 2002; Caramazza, 1997; Navarrete & Costa, 2005) and other findings that revealed that the two languages of a bilingual are co-activated to similar extent, even when bilinguals want to speak only in one language (e.g., Colomé, 2001; Costa et al., 2000).

Another influential account poses that although an active conceptual representation and those related to it are activated

---

[4] Another model of bilingual language production proposes that lexical selection is not a competitive process; either in monolingual or in bilingual language production (see "differential activation account" in Finkbeiner, Gollan, & Caramazza, 2006). In detail, lexical selection would be achieved by means of a "selection by threshold" mechanism. According to this framework, only the activation level of a given word is relevant to determine whether and how fast this word will be selected. Importantly, the ease to which a given word is selected is independent from the relative activation of competitors (Finkbeiner & Caramazza, 2006; Janssen et al., 2008; Mahon et al., 2007; Miozzo & Caramazza, 2003; Navarrete, Mahon, & Caramazza, 2010).

simultaneously in the two languages, once the decision of speaking in one language is taken, a lexicon-external device enables bilinguals to select the lexical representations of the intended language, without taking into account those of the non-intended language (Costa & Caramazza, 1999; Costa et al., 1999) (see Figure 1). This account, as that proposed by La Heij (2005), assumes that “selection” is language specific. However, the “selection” has its effects at lexical level instead of at the conceptual level (La Heij, 2005).

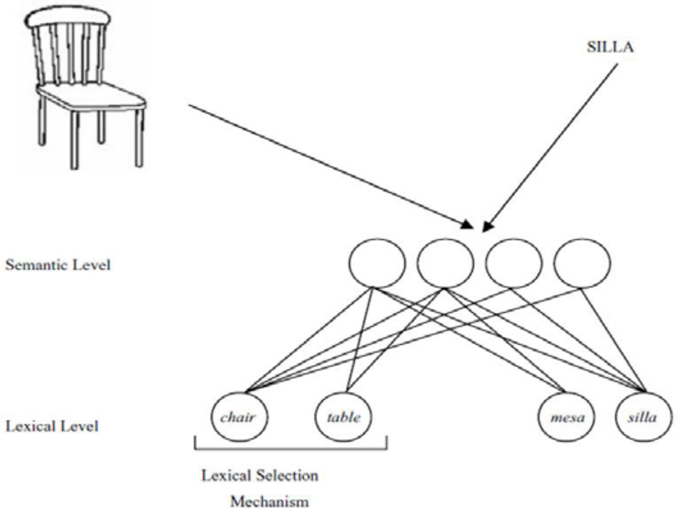


Figure 1. The language-specific selection mechanism proposed by Costa et al., (1999) (taken from Finkbeiner, Gollan & Caramazza, 2006).

The model proposed by Costa et al. (1999) received mainly support from evidence employing picture-word interference (PWI) tasks. In the monolingual version of this task, participants are presented with a target picture to be named. This target picture is presented along with a written word (distractor) and the most common finding is a delay in naming latencies when the distractor is semantically related to the name of the target picture. This result is generally taken to reflect a semantic interference effect, stemming from the competition between semantically related lexical items (e.g., Glaser & Dunglehoff, 1984; Levelt, Schriefers, Vorberg, Meyer, & et al, 1991; Roelofs, 1992). Interestingly, this effect is still present in the bilingual version of the task (e.g., Mägiste, 1984; Mägiste, 1985), that is, when bilinguals have to name in one language a picture, presented along with a distractor word in the other language. One possible explanation for this result is competition arising between the distractor word in the non-intended language and the picture to be named in the intended language (see Inhibitory control model-ICM-, Green, 1986, 1998). Alternatively, the delay in naming latencies for the picture could arise not because of the distractor word itself, but because the distractor word would activate its translation in the intended language, that would ultimately interfere with the picture to be named in the intended language.

Costa et al. (1999) demonstrated that the locus of cross-language semantic interference was the target lexicon by conducting a series of PWI experiments in which the distractor word was the translation of the name of the target picture, hence, the strongest cross-language competitor. According to the view that cross-language semantic interference is due to the interference between languages (e.g., Green, 1986, 1998), this condition would have elicited a pronounced delay in naming latencies. Conversely, according to the hypothesis that the locus of cross-language semantic interference is within the intended language, a great facilitation in naming latencies should have appeared. This is because the activation of the distractor word activates its translation word, that is, the name to be produced for the target picture. Hence, if only the lexical nodes within-language can be considered for selection, the result of the spreading of activation from the distractor word to the corresponding translation word/target response would be an extra activation of this translation word/target response. Crucially, this process was expected to result in a facilitatory effect and this is precisely what Costa et al. (1999) observed.

This evidence, interesting as it is, nevertheless received some criticism, since the facilitatory effect observed when the distractor word is the strongest cross-language competitor of the target response (Costa et al., 1999) could be embraced by alternative explanations that the PWI design does not allow to parse.

In detail, it has been questioned whether this facilitation occurs at the lexical level or rather at other processing stages, such as at the conceptual level (e.g., Abutalebi & Green, 2007; Hermans, 2004). Indeed, the facilitatory effect observed by Costa et al. (1999) might arise because the distractor primes the lexical concept. Hence, the results observed by Costa et al. (1999) might be determined by a conceptual priming effect rather than an effect occurring at the lexical level (e.g., Hermans et al., 1998). Some authors argued that this facilitatory effect may be stronger than the cost of resolving cross-language competition (see Abutalebi & Green, 2007; Hermans, 2004), therefore leaving out the possibility that cross-language competition indeed occurs but is masked by a strong facilitation induced by conceptual priming.

Beyond these considerations, evidence coming from a host of different studies suggests that the PWI paradigm might not be the better design to test how language selection is achieved in bilinguals and monolinguals (e.g., Costa, Alario, & Caramazza, 2005; Finkbeiner & Caramazza, 2006; Mahon, Costa, Peterson, Vargas, & Caramazza, 2007; Miozzo & Caramazza, 2003; Janssen, Schirm, Mahon, & Caramazza, 2008; Dhooge & Hartsuiker, 2011; Dhooge & Hartsuiker, 2010) and that rather than constraining lexical access processes, PWI paradigm would implicate general response selection processes (see Finkbeiner et al., 2006).

1.1.2 Language-non specific selection models of bilingual language production: the Inhibitory Control Model

According to other models, not only the two lexical systems are simultaneously activated during the course of bilingual language production, but also such systems enter into competition (e.g., De Bot, 1992; Green, 1986, 1998; Hermans et al., 1998; Lee & Williams, 2001; Poulisse & Bongaerts, 1994). This competition is then resolved by an inhibitory mechanism that suppresses the activation of the lexical items belonging to the non-intended language.

To date, the Inhibitory Control Model (ICM; Green, 1986, 1998) has been the one within this view receiving more experimental attention (e.g., Levy, McVeigh, Marful, & Anderson, 2007; Linck, Kroll, & Sunderman, 2009; Misra, Guo, Bobb, & Kroll, 2012; Philipp, Gade, & Koch, 2007). According to this model, language is considered an instantiation of motor action and therefore, those processes underlying language control (i.e., inhibitory control) are recruited from those of action control. Similarly, the same neural circuits are considered to underlie bilingual language control and domain-general cognitive control (see Abutalebi & Green, 2007, 2008).

As we will see, most of the experimental paradigms to explore bilingual language control have been borrowed from those employed to explore domain-general executive control (e.g., language switching paradigm). This is particularly relevant in the context of the present dissertation, since the idea that bilingual language control mechanisms are not language-specific leads to the prediction that the performance of the same bilinguals in language control and domain-general executive control tasks should be somehow related.

Before critically reviewing the evidence that supports the involvement of inhibitory processes in bilingual language control and evidence problematic for this view, we will first describe the basic assumptions of the ICM (Green, 1986, 1998).

The ICM (Green, 1986, 1998) proposes that during lexicalization processing the two languages of a bilingual become concurrently activated, and that such activation leads to lexical competition. To avoid potentially massive cross-language competition, an inhibitory control mechanism operates over the lexical representations of the non-intended language, in order to reduce or suppress their activation.

Hence, when a bilingual wants to speak in a given language (e.g., language A) the inhibition of the non-intended language (e.g., language B) is achieved through lexicon external task-schemas that allow controlling output goals (e.g., “name in language A”). The specific way in which this operation is achieved is by projecting inhibitory signals from the task-schemas to all the lexical representations that contain a language tag of the non-intended language (i.e., language B). Consequently, the level of activation of the language B representations is reduced and therefore also cross-language interference. According to the ICM, this process allows bilinguals to select the lexical items from the intended language. For example, when an English-Spanish bilingual plans to name a picture in English (e.g., *chair*), the language schemas will suppress the activation of the all lemmas with an incorrect language tag. Therefore, in our example “silla” will be inhibited, in addition to all the semantically related words in Spanish (e.g., “mesa”) (see Figure 2).

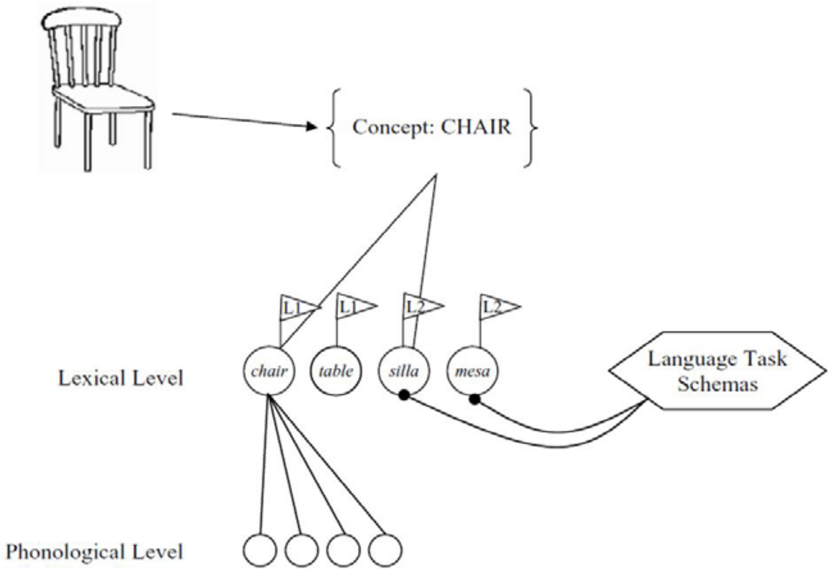


Figure 2. A simplified version of the ICM proposed by Green (1986; 1998) (taken from Finkbeiner, Gollan & Caramazza, 2006).

This view also posits two important assumptions regarding the functioning of the inhibitory control system. First, the amount of inhibition applied to a given language depends on the strength with which its representations are activated to begin with. Hence, when trying to speak in the non-dominant language (i.e., the L2), the inhibition applied to the dominant language (i.e., the L1) is higher than vice-versa. This assumption comes from the reactive nature of the inhibitory system, in the sense that inhibitory control is applied only after the lexical representations of the non-intended language have been activated. Second, the activation of previously inhibited representations (i.e., overcoming inhibition) requires time, and indeed the stronger the inhibition applied, the more time is needed to overcome it.

The large majority of experimental evidence regarding the presence of inhibitory processes in bilingual language control comes from different instantiations of the "language switching paradigm" (e.g., Costa, Santesteban, & Ivanova, 2006; Costa & Santesteban, 2004; Guo, Liu, Misra, & Kroll, 2011; Jackson, Swainson, Cunnington, & Jackson, 2001; Meuter & Allport, 1999). Despite the differences between the specific instantiations of this paradigm, they both involve speakers using their two languages, in such a way that is possible to measure the after-effects of using one language on the subsequent use of the other language. As we will see, both these instantiations have been largely employed, since both are suitable to test the assumptions of the ICM. We acknowledge that the "language switching paradigm" is not the only design able to test the assumptions of the ICM (e.g., Runnqvist, Strijkers, Alario, & Costa, 2012). Nevertheless, in the present dissertation we employed this paradigm to address our scientific questions. Thus, in the next two sections we will particularly focus on those studies that used different instantiations of the language switching paradigm to test the ICM.

1.1.2.1 Evidence from trial-by-trial language switching

The trial-by-trial language switching task (e.g., Meuter & Allport, 1999; Christoffels, Firk, & Schiller, 2007; Jackson et al., 2001; Wang, Xue, Chen, Xue, & Dong, 2007) is likely the most-used instantiation of the language switching paradigm. This version of the task comes from the domain-general task switching literature (e.g., Allport, Styles, & Hsieh, 1994; Jersild, 1927; Monsell, 2003). As previously hinted, most of the studies using this paradigm assume a tight relationship between the bilingual language control mechanisms and those involved in domain-general executive control (e.g., Meuter & Allport, 1999). In the trial-by-trial language switching task, bilinguals are required to name some pictures in one language and some other in the other language, with the presentation of these pictures mixed. The language in which a given picture has to be named is indicated by a cue (e.g., color of the picture). Generally, in these tasks there are two types of trials: trials in which the language to be used is the same as that of the previous trial (“repeat” trials; AA language sequences) and trials in which the language to be used is different, as compared to that of the previous trial (“switch” trials; BA task sequences). The difference between naming latencies of switch and repeat trials results in the “switch cost” or “n-1 shift cost”. This cost is found in switching paradigms that do not involve linguistic processes (e.g., Martin, Barcelo, Hernandez, & Costa, 2011; Meiran, 1996; Monsell, 2003; Schneider & Anderson, 2010).

One possible interpretation of the origin of this switch cost is inhibitory control applied on the non-response language (or task) (Green 1986, 1998; Meuter & Allport, 1999). For example, in a BA language sequence, naming in the language B would entail the inhibition of the language A. Hence, when the language A needs to be produced in the successive trial, more time is needed to activate the previously inhibited representations.

Despite this interpretation is consistent with the main assumptions of the ICM (Green, 1986, 1998), this is not the only possible explanation of the phenomenon (e.g., Koch, Gade, Schuch, & Philipp, 2010; see also Runnqvist et al., 2012; Yeung & Monsell, 2003).

Beyond that, other evidence has been taken as an index inhibitory control in bilingual language control. One of them is the “asymmetrical switch cost” (Meuter & Allport, 1999; Costa & Santesteban, 2004; Costa, et al., 2006; Jackson et al., 2001; Linck, Schwieter, & Sunderman, 2012; Macizo, Bajo, & Paolieri, 2012; Philipp et al., 2007; Schwieter & Sunderman, 2008; Wang et al., 2007), that refers to the observation of larger switch costs when switching to the dominant language as compared to when switching to the non-dominant language (e.g., Meuter & Allport, 1999; Jackson et al., 2001). Importantly, asymmetrical switch costs are found also in non-linguistic versions of the switching task, as long as tasks of different difficulty/strength are involved (e.g., Martin et al., 2011).

The evidence of asymmetries in linguistic switch costs is in accord with the ICM, since it proposes the amount of inhibition applied on one language is proportional to its strength (level of activation). Hence, in the case of a difference of strength between the two languages (unbalanced bilinguals), one would expect that more inhibition is necessary to inhibit L1 during L2 production, than to inhibit L2 during L1 production. Hence, since the switch cost is a measure of the after-effects of this inhibition, these after-effects are supposed to be more detrimental when the switch is to

L1 (due to the need of recovering from a strong inhibition) than when the switch is to L2. Different studies replicated this result (e.g., Meuter and Allport, 1999; Costa & Santesteban, 2004; Costa, et al., 2006; Jackson et al., 2001). Moreover, in accord with the ICM it has been found that bilinguals with equal strength in the two languages (high-proficient and balanced bilinguals) showed symmetrical switch costs, likely because the same amount of inhibition is deployed on the non-intended language when speaking in L1 or in L2 (e.g., Costa & Santesteban, 2004).

Along the same lines, electrophysiology literature provided some evidence in accord with the idea that bilingual language control is implemented through inhibition.

The critical component of the Event Related Potentials (ERPs) is a negative deflection typically observable in switch trials when compared to repeat trials (e.g., Jackson et al., 2001). This enhanced negativity peaks around 200-250 ms after stimulus presentation (N200[5]). In the context of domain-general executive control tasks (e.g., Go/NoGo tasks), this component has often been interpreted as revealing inhibitory processes, although other interpretations have been advanced (e.g., Nieuwenhuis, Yeung, van den Wildenberg, & Ridderinkhof, 2003). In a trial-by-trial language switching task, Jackson et al. (2001) found that switch trials elicited an increased N200 relative to repeat trials. Interestingly, this N200 modulation associated with language switching was only present

---

[5] The N200 ERP modulation appears somehow delayed in bilingual language control experiments (i.e., Branzi, Martin, Abutalebi, & Costa, 2014; Christoffels et al., 2007; Misra et al., 2012).

when switching into the L2. Such asymmetry was interpreted as revealing that the L1 must be strongly inhibited when accessing lexical representations in the L2. Even though in this study the asymmetrical patterns in behavioral and ERP measures appear mismatched, indeed they are not. In fact, if what leads to slower naming latencies in L1 switch trials is the need of recovering from the L1 inhibition applied during previous L2 production, this effect should be observable in the ERP responses when the L1 lexical entries are suppressed, i.e., in L2 trials. Thus, also this result is consistent with the workings of the inhibitory system.

Neuroimaging studies on language switching revealed asymmetries in the brain activations similar to those found the behavioral and electrophysiological studies. For example, in a Functional Magnetic Resonance Imaging (fMRI) study, Wang et al. (2007) tested a group of late Chinese-English bilinguals in a trial-by-trial language switching task and found a behavioral asymmetry in switch costs (i.e., larger switch costs for L1 than for L2) similar to that reported in previous studies (see Meuter & Allport, 1999; Jackson et al., 2001). Along with this finding, Wang et al. (2007) also observed that switching into L2 only activated brain areas involved in executive control and inhibition, such as frontal areas, the anterior cingulate cortex (ACC) and the supplementary motor area (SMA)[6] (e.g., Garavan, Ross, Murphy, Roche, & Stein, 2002; Garavan, Ross, & Stein, 1999). This asymmetry was interpreted as a result of increased demands on the domain-general executive

---

[6] Similarly as in the ERP study by Jackson et al. (2001), in Wang et al. (2007) the switch effect observed at the neural level (in the L2) mirrored the one observed at the behavioral level (in the L1).

control system, to allow successful L2 production and avoid competition from the L1; an explanation clearly in line with the ICM (see for similar results also Van Heuven, Schriefers, Dijkstra, & Hagoort, 2008).

Neuroimaging literature suggests also that the brain network involved in language switching overlaps with that involved in non-linguistic task switching (de Bruin, Roelofs, Dijkstra, & Fitzpatrick, 2014; Abutalebi & Green, 2007, 2008; see also Luk, Green, Abutalebi, & Grady, 2012 for a meta-analysis of brain areas involved in language switching). In other words, switching between languages and switching between non-linguistic tasks elicit similar brain activations[7]. Therefore, also these observations are in accord with the tenets of the ICM (Green, 1986, 1998), since the model states that bilingual language control functioning is achieved through the same mechanisms and brain areas of domain-general executive control. In that, bilingual language control would be just an instance of the functioning of a domain-general executive control system.

Even though the evidence reviewed above dovetails quite well with the assumptions of the ICM (Green, 1986, 1998), another series of studies report results that are hardly reconcilable with this view. To advance, one of the main problems is that in language switching tasks the asymmetries/symmetries of switch costs seem to

---

[7] This network is composed by left and right prefrontal and parietal cortices, the anterior cingulate cortex, left and right caudate nucleus, putamen and finally the right thalamus (see Abutalebi & Green, 2007, 2008; Green & Abutalebi, 2013).

be influenced by variables other than the strength of the languages (see below).

One clear example is provided in Costa and Santesteban (2004; see also Costa et al., 2006), where high-proficient bilinguals were required to switch between two languages of different strength (their L1 and a much weaker L3). Results revealed an unexpected pattern: symmetrical rather than asymmetrical switch costs (Costa & Santesteban, 2004; Costa et al., 2006). These results are problematic for the ICM, since switching between languages of different strength should lead to asymmetrical switch costs. Hence, authors proposed an explanation that represents a possible way out for the ICM: high-proficient bilinguals would be a “special case” of bilingual language control. That is, differently from low-proficient bilinguals, they would not need to resort to inhibition to control their languages. As previously described, there are other models of bilingual language control that propose mechanisms different from inhibition (see Costa et al., 1999). Hence, Costa and Santesteban (2004) argued that in high-proficient bilinguals, the simple intention to speak in the intended language would allow these “language-specific selection mechanisms” to select the intended language, while ignoring the activation of the lexicon of the non-intended language. Importantly, once that these “language-specific selection mechanisms” are developed in high-proficient bilinguals they can be applied also to languages with different strength (Costa et al., 2006; Costa & Santesteban, 2004; Schwieter & Sunderman, 2008). Unfortunately, such an interesting proposal was undermined by the observation that also high-proficient bilinguals showed asymmetrical switch costs when switching between an L3 and an L4 or between L1 and new learnt language (Costa et al., 2006).

Successively, other evidence suggested that switch costs do not vary only as a function of language proficiency. In fact, Christoffels et al. (2007) reported symmetrical switch costs in low-proficient bilinguals (see also Prior & Gollan, 2011). This unexpected result was explained in turn by appealing to the fact that these bilinguals were used to switch between languages frequently on an everyday basis. Hence, to the extent to which the activity of switching between languages increase bilingual language control abilities, these bilinguals could be considered as another “special case” of bilingual language control. In that, also these bilinguals may use language control mechanisms that do not resort to inhibition.

However, there is another set of evidence that is perhaps more problematic to be reconciled with the assumptions of the ICM. This evidence suggests that the variability of switch cost patterns depends on experimental variables that are not related to bilingualism at all, such as predictability (Gollan & Ferreira, 2009), preparation times (Verhoef, Roelofs, & Chwilla, 2009) or the type of stimuli involved in the task (Finkbeiner, Almeida, Janssen, & Caramazza, 2006).

For example, Verhoef et al. (2009) found asymmetrical or symmetrical switch costs in the same group of unbalanced bilinguals, depending on the timing of the cue-target interval[8]. These observations led the authors to conclude that low-proficient bilinguals may use inhibitory control strategically when performing the task, depending on whether the experimental setting allows applying such process.

In line with this conclusion, Finkbeiner et al. (2006) report asymmetrical switch costs and a lack of switch costs depending on the type of stimuli involved in the task. In this experiment, participants named digits either in L1 and L2, according to the language cue. Furthermore, the experiment also included some pictures that had to be named only in L1. Naming latencies for the digits revealed an asymmetrical switch cost, with longer naming latencies for switching into L1. Conversely, there was no switch cost for picture naming. In other words, picture naming in L1 was not affected by the language in which the previous digit was named (the same or not), but rather it depended on whether the items used in the experiment needed to be named in the two languages (bivalent stimulus) or not (univalent stimulus).

Beyond behavioral findings, also electrophysiological evidence is somehow inconsistent with the ICM. In various studies the modulation of the N200 behaved rather differently than what found by Jackson et al. (2001).

Sometimes the modulation of the N200 was only present for the L1 but for repeat trials, rather than for the switch trials

---

[8] In detail, when the cue-target interval was short (500 ms) bilingual participants showed asymmetrical switch costs. However, when the cue-target interval was longer (1250 ms), the switch cost was symmetrical.

(Christoffels et al., 2007). Moreover, Verhoef et al. (2009) showed that when asymmetrical behavioral switch costs were observed, the ERPs did not show any modulation of the N200 associated with switching (see also, Martin, Strijkers, Santesteban, Escera, Hartsuiker, Costa, 2013). Hence, to the extent that the N200 indexes inhibitory processes, it seems that asymmetrical switch costs can be present without inhibition. Furthermore, and perhaps more problematic is that in Verhoef et al. (2009) the enhanced N200 negativity was found to be sensitive to preparation times, but not to language switch effects. This suggests that some caution should be exercised when interpreting the N200 modulation as an unequivocal index of inhibition in bilingual speech production.

At any rate, the ERPs evidence has not helped to elucidate how the asymmetries/symmetries in the language switching tasks should be interpreted and, unfortunately, when going to the neuroimaging evidence, the same problem persists.

In fact, if in low-proficient bilinguals the asymmetrical involvement of executive control brain areas (e.g., frontal areas, the SMA and the ACC) reflects L1 inhibition in the linguistic switching task (see Wang et al., 2007), therefore, a symmetrical neural switch cost for high-proficient bilinguals should be observable. That is, we might expect to observe in high-proficient bilinguals a similar involvement of the above mentioned areas, regardless of the direction of the language switch. However, Garbin et al. (2011) found that in high-proficient bilinguals, switches from the L1 to the L2 activated the left caudate. Instead, the reverse switches activated areas involved in executive control, such as the pre-SMA. That is, the brain regions considered to underlie the switches to the L2 in low-proficient bilinguals were now observed for switches to the L1 in high-proficient bilinguals. Arguably, it is possible that the involvement of different neural substrates in language switching does not correspond directly to the magnitude of the behavioral switch cost (see Garbin et al., 2011). Moreover, it is questionable whether the described brain areas should be taken as an index of inhibition per se. Indeed, the workings of those areas are specified in terms of a network, whose functioning is thought to reflect the workings of different executive control functions, including inhibition (see Abutalebi & Green 2007).

All in all, the aforementioned observations pose some challenges to the ICM (Green, 1986, 1998) and highlight the evidence of inhibitory control based on the patterns of switch costs is rather unstable.

At some point, it has been questioned whether asymmetries of switch costs were indeed reflecting inhibitory control in linguistic switching tasks. Some authors suggested that switch costs and asymmetries do not necessarily reflect the workings of inhibitory control processes only (see Koch et al., 2010) and alternative accounts were put forward. For example, it has been proposed that switch costs might be caused by a carryover effect of the previously activated language (or task) that affects negatively the current switch trial (see Philipp et al., 2007; Yeung & Monsell, 2003). Thus, the asymmetries of linguistic switch costs could be explained by assuming that during production, the L2 needs to be over-activated as compared to the L1. This language activation might interfere during switch trials more when switching to L1 than when switching to L2 (e.g., Yeung & Monsell, 2003; see also Koch et al., 2010), leading to the same asymmetrical switch cost.

In order to shed light on the origin of asymmetrical switch costs, researchers went to test another type of switch cost, which has been proposed to measure inhibitory control only. This cost is the “n-2 repetition cost” (e.g., Mayr & Keele, 2000) and it is measured in switching tasks in which participants are required to switch among three tasks (e.g., A, B, C). The general observation is that response times (RTs) for ABA task sequences are slower than those of CBA task sequences. Hence, the presence of the n-2 repetition cost prove that the execution of the task B during an ABA task sequence elicit the inhibition of the just executed task (A). In fact, if it would not be the case, similar or faster RTs would be observed in ABA task sequences as compared to CBA ones.

The ICM hence would predict the following pattern of n-2 repetition costs: larger for the L1 than for the L2. Interestingly, Philipp et al. (2007) found an asymmetrical n-2 repetition cost, larger for the L1 rather than for the two non-dominant languages (L2 and L3). This finding is clearly consistent with the ICM. However, according to the ICM the magnitude of the n-2 repetition cost should have been larger for the L2 as compared to the L3. Indeed, authors found the opposite: the n-2 repetition cost was larger for the L3 than for the L2, a result that it is clearly at odds with the ICM.

Further attempts of detecting any modulation of the n-2 repetition cost associated with language proficiency have not produced the expected results (Guo, Liu, Chen, & Li, 2013; Philipp & Koch, 2009) or have failed to detect n-2 repetition costs at all (Guo, Ma, & Liu, 2013), leading to conclude that also the evidence of the n-2 repetition cost in support of the ICM seems to be unsteady.

All in all, the aforementioned evidence does not provide a consistent picture of the mechanisms involved in bilingual language control. Importantly, it is not clear to which extent switch cost patterns alone can really inform about them.

In the present dissertation we tried to solve this problem by conducting experiments in which we were able to measure other indices of inhibitory control, beyond the asymmetries of switch costs. This approach is relevant because at present we are not allowed to concluding that inhibitory mechanisms are not involved at all in bilingual language control. In fact, alternative mechanisms proposed for bilingual language control (see Costa et al., 1999; Costa & Santesteban, 2004; Costa et al., 2006) are hardly reconcilable with the mixed evidence coming from the trial-by-trial language switching paradigm.

Beyond these considerations, some authors have also suggested the workings of bilingual language production may better be tested by employing other kind of paradigms (e.g., Costa, La Heij, & Navarrete, 2006; Finkbeiner, Almeida, et al., 2006; Finkbeiner, Gollan, & Caramazza, 2006). These paradigms would not be those requiring continuous allocation of attention to decide the language to use, such as trial-by-trial language switching paradigms, but rather those that restrict the production to one language.

As we will see below, the mechanisms of bilingual language control have been investigated also through another instantiation of the language switching paradigm, that does not require switching continuously between languages. In the following section we provide a description of this instantiation along with the most important findings.

1.1.2.2 Evidence from blocked language switching

Beyond the switch cost that measures the after-effects of one language on the other one in a mixed context, there is a way to measure the after-effects of one language on the other one in single naming context. The "blocked design" provides several advantages as compared to the trial-by-trial switching paradigm. The first one is that it allows to measuring the workings of bilingual language control in an experimental setting which is more similar to the real contexts in which bilinguals communicate in the two languages. The second advantage is that this design allows to assessing the scope of bilingual language control, that is, to test whether bilingual language control is applied *globally* or *locally* (De Groot & Christoffels, 2006).

In this design the languages to be produced are “blocked”, in the sense that participants are typically required to name an entire block of pictures in one language and successively another block of pictures in the other language. Hence, the comparison of RTs for the same language after and before naming in the other language is generally between-participants and it allows to measuring the after-effects of one language on the other one, in single naming contexts.

Behaviorally, some evidence suggests that only L1 production is affected by previous naming in the other language. For example, Misra et al. (2012) showed that naming a set of pictures in L1 was hampered when the very same pictures were previously named in L2, as compared to naming them in L1 first. This was indicated by the absence of behavioral priming effect that is generally observed when the same pictures are repeated in a task. Conversely, this priming effect was observed when naming a set of pictures in L2 after L1, as compared to naming them in L2 first. Interestingly, these behavioral asymmetries were accompanied by ERP effects related to inhibitory control (N200 enhanced negativity; see Falkenstein, Hoormann, & Hohnsbein, 1999; Jodo & Kayama, 1992). In an fMRI study, Guo et al. (2011) implementing a similar design did not find the same asymmetries between languages in RTs. However, the lack of this effect in the behavioral responses was somehow compensated by the fact that these asymmetries were observable in the brain activations. That is, compared to naming in L1 first, naming in L1 after L2 elicited the activation of a brain network of frontal, parietal and temporal areas known to be involved in bilingual language control (see Abutalebi & Green, 2007, 2008; Green & Abutalebi, 2013). Instead, compared to naming in L2 first, naming in L2 after L1 elicited a completely different pattern of brain activations, since only visual processing areas were involved.

These results might be considered in accord with the idea that to produce the intended language bilinguals inhibit the non-intended language (e.g., Green, 1986, 1998). However, as in the case of trial-by-trial language switching tasks, the origin of this asymmetry can be embraced by alternative explanations. For example, this asymmetry could be the result of an over-activation of the non-dominant language (L2) that interferes with the successive naming in the dominant language (L1) (see Section 1.1.2.1), rather than the consequence of the inhibition of the dominant language (L1).

The first experimental study presented in this thesis (see Section 2.4) aimed to disambiguate between these two alternatives (L1 inhibition or L2 over-activation). In Section 2 we will explain in detail how we implemented a task able to dissociate between these two alternatives.

Before going to that, we will first review the available evidence on the scope of bilingual language control, that is, the studies that tried to assess whether bilingual language control mechanisms (e.g., inhibition or activation) are applied to specific linguistic representations or to the whole language.

1.2 On the scope of bilingual language control

Another relevant question to understand the bilingual language production system regards the extent to which bilingual language control mechanisms are applied. Particularly, in this section we refer to the "representational scope" of bilingual language control.

To introduce this issue with an example, let's consider the situation in which a Spanish-English bilingual wants to produce some words in Spanish and then some others in English. The question here is whether only the lexical representations activated in Spanish will be controlled when speaking in English successively, or rather whether speaking in English per se will trigger language control on the entire Spanish lexicon. The first possibility is referred to the so-called *local control*, whether instead the later one to the so-called *global control* (e.g., De Groot & Christoffels, 2006). Importantly, these two theoretical proposals have been mainly tested in relation to those models of bilingual language control assuming competition between the languages and especially in relation to the ICM (Green, 1986, 1998).

Since the scope of bilingual language control is referred to lexical representations, one possibility to test *local* and *global control* is to explore whether the effects of the use of one language on the other language are the same for repeated and for unrepeated pictures. That is, the issue is to establish whether the fact of naming set of pictures in Spanish affects the successive naming in English in the same way, whether these pictures were named before in

Spanish, or whether the naming in English involves only new pictures, seen for the first time.

There are few studies that investigated the scope of bilingual language control following this reasoning.

In one study, Van Assche, Duyck, and Gollan (2013) explored the issue of *local* and *global control* by testing a group of Dutch-English bilinguals in a "letter fluency task". Typically, in this task participants have a limited time (60 seconds) in which they must produce as much words as possible, starting with a specific letter (e.g., "say in English all the words that you can starting with the letter "A"). This task is thought to involve executive control functions, such as the inhibition of all the words that does not conform to the task instructions, along with the activation of the suitable ones (e.g., Baldo, Shimamura, Delis, Kramer, & Kaplan, 2001). In detail, the goal the study by Van Assche et al. (2013) was to see whether the production of words in one language affected the fluency, that is, the number of words produced successively, in the other language. In order to investigate this, authors used a blocked design in which one group of participants started with producing words in L1 and then in L2 and the other group with the reverse order. Importantly, there were two conditions: some letters used to trigger the verbal responses were common in the two languages. Some other letters were instead different between the two languages. The first condition meant to measure the after-effects of *local control*, whether instead the later one those of *global control*. Results revealed the performance at the letter fluency task in L1 was reduced when this was preceded by L2 production. This result was restricted to the case in which the letters used in the fluency task were the same. Hence, authors concluded that the presence of detrimental effects on L1 words production after the fluency task in L2 (with the same starting letters) was an evidence of *local control*. Nevertheless, in the same study, Van Assche et al. (2013) tested also another group of bilinguals (Chinese-English bilinguals) and besides a *local control* effect they also reported evidence of *global control*[9] on the L1.

This study meant to inform about the representational scope of bilingual language control. The result that Vann Assche et al. (2013) reported as an evidence of *local control* was the observation that producing words in L2 hampers the successive production in L1, if the starting letter to be used for both languages is the same.

However, since *local control* concerns the lexical representations of the two languages, it may be that in this study authors tested conditions referring to *global control*, rather than to *local control*. This is because it is unlikely that the words starting with the same letter produced first in one language and then in the other one, were all translation equivalents. Unfortunately, this information is not reported in Vann Assche et al. (2013). Hence, another possibility is that the results observed by authors were likely due to interference elicited by a “phonological” effect. That is, since the same letter was repeated, it is likely that in the second block, the sound of the letter automatically recalled all the words

---

[9] Note that the differences in results between the first and the second experiment were attributed to different control strategies between bilinguals with more similar (English-Dutch bilinguals) and more different languages (Chinese-English bilinguals).

previously produced in the other language (i.e., in the first block). These words hence would interfere with the successive production of words in the other language (i.e., in the second block). For these reasons, taken as interesting as they are, these findings do not clearly address the representational scope of bilingual language control. At any rate, this study provides some evidence of *global control* rather than *local control*.

Beyond that, also Finkbeiner et al. (2006) presented some evidence that tackles the *local* and *global control* issue. As previously hinted, in this study participants were presented with two different types of stimuli: digits and pictures, presented in a mixed fashion. The task was to name digits in both the two languages, according to a cue and to name pictures in L1 only. Results revealed a switch cost only for digits. This result indicates that naming in one language affects the naming in the other language only when the same items are involved in the task, an apparent evidence for *local control*.

There are other studies (Guo et al., 2011; Misra et al., 2012) that used a blocked language switching task and provided some evidence on the representational scope of bilingual language control. In these studies authors concluded that *global* inhibition was applied on the L1 during L2 production. However, since in both studies only repeated items were used, these conclusions should be taken with caution. The results from Guo et al. (2011) and from Misra et al. (2012) appear to be more in accord with a *local control* view than the *global* one.

The evidence reviewed so far approached the question on the representational scope of bilingual language control. Nevertheless, besides Finkbeiner et al. (2006) study, no other study provided results to distinguish between *local* and *global control*, leading to conclude that the available information on this issue is rather scarce.

With two experimental articles (see Section 2.4 and 2.8) presented in this dissertation, we aimed to advance the knowledge on the representational scope of bilingual language control. As it will explained below, we explored *local* and *global control* by employing blocked language switching tasks, with repeated and unrepeated pictures.

2. THEORETICAL REVIEW AND EXPERIMENTAL SECTION: the current approach and overview of the studies

The goal of the present dissertation was to advance the knowledge on the mechanisms and the representational scope of bilingual language control. We pursued this goal by realizing several experiments that made use of different methodologies. The result of this work is a compilation of three published articles in internationally recognized, peer-reviewed and indexed scientific journals, two articles under review process and one book chapter accepted for publication.

Importantly, the work presented in this dissertation was carried out by following two different approaches. In the next sections we will present them as separated, along with the description of the corresponding studies.

2.1 The after-effects of bilingual language production: the mechanisms and the scope

Research on bilingual language production and control has focused particularly on two questions: the mechanisms and the representational scope of bilingual language control. As we explained in the introductive section, even though the amount of available evidence is massive, there is substantial debate around both these issues.

The book chapter presented in Section 2.3 is a critical review of the most important findings related the mechanisms and the representational scope of bilingual language control. The aim of this chapter was to describe the state of the art on this research topic, to suggest future directions and to indicate those approaches that should be eventually abandoned.

The articles presented in Sections 2.4 and 2.8 are two experimental studies that investigated the mechanisms and the representational scope of bilingual language control. As presented in the introduction, the effects of naming in one language on the successive production of the other language can be explored at least two different ways. One is by measuring language switch costs in a trial-by-trial switching task. The other one is by measuring the cost of changing language across blocks of naming (i.e., blocked language switching task).

In this dissertation we embraced both of them, since they are both able to speak to the issue of bilingual language control mechanisms. However, the blocked language switching task is more suitable to explore the question of the scope of bilingual language control[10]. Hence, in Sections 2.4 and 2.8 we employed a “blocked language switching” design.

---

[10] In general, in trial-by-trial language switching tasks, the switch costs are measured on a large number of trials (e.g., Costa & Santesteban, 2004). Therefore, it is very common that a restricted set of items is re-presented during the task, hereby, allowing to testing *local control* effects only. This is not to say that it is impossible to create trial-by-trial language switching tasks with repeated and unrepeated items to be named in both languages. However, perhaps a better way explore the representational scope of bilingual language control is to use the blocked switching task, since it requires less trials to process these effects.

In Section 2.4, we explored the after-effects of bilingual language production in a group of young and early bilinguals, balanced and high-proficient in the two languages (i.e., Catalan/Spanish bilinguals). Besides behavioral measures, we also employed the ERP technique to shed light on the neural components behind the mechanisms and the scope of bilingual language control. Importantly, our study goes further in respect to previous ones, since we employed an experimental design that allows a clear interpretation of the patterns of switch costs (see above in Section 1.1.2.1). In fact, to reveal the mechanisms of bilingual language control we explored the after-effects of bilingual language production across three blocks of naming. Hence, a first group of participants was required to name pictures in L1 in the first block, in L2 in the second block and finally in L1 in the third block. The second group of participants was required to perform the reverse order (i.e., L2-L1-L2). We hypothesized that the comparison between the third and the first block would have been particularly informative on the mechanisms involved in bilingual language control[11], since the inhibitory account (e.g., Green, 1998) and the activation account (e.g., Yeung & Monsell, 2003) make different predictions on the performance in the third block (*see* Section 1.1.2.1).

In the same study, we also investigated the scope of bilingual language control. As reported in the introductive section, a shortcoming of previous studies was that only repeated pictures

---

[11] To recall, comparing adjacent blocks of language does not rule out the possibility that switch cost asymmetries are due to L2 over activation rather than to L1 inhibition (see Sections 1.1.2.1 and 1.1.2.2).

were used to assess bilingual language control effects (e.g., Misra et al., 2012). Our study goes a step further, since we explored whether bilingual language control is applied *locally* or *globally*, by employing not only repeated but also unrepeated pictures.

In the other study (Section 2.8) that speaks to the issues of the mechanisms and the scope of bilingual language control, we employed a similar design to that of the study in Section 2.4, that is, a blocked switching task. However, there are some differences between the two studies.

The first difference regards the participants. In fact, they were all German-Italian bilinguals recruited in South Tyrol, a bilingual region in Italy. German was the native and dominant language (i.e., L1) and Italian was the second language (i.e., L2), acquired early in life (4 years old). Despite both the languages were used before going to elementary school, German has been used consistently more than Italian across different periods of life (see Section 2.8 and Appendix B). The second difference is that we used a different technique, that is, fMRI. We employed this technique in order to reveal whether the neural network of language control was similarly involved in the control of the two languages, when the same and different items were involved in language selection. A further difference is that our initial hypotheses, to test the mechanisms and the scope of bilingual language control, were established referring to an influential model of bilingual language processing (Abutalebi & Green 2007, 2008; Green & Abutalebi, 2013). This model specifies the functional role of each area in the language control network in respect to different mechanisms, including inhibitory control. Finally, in comparison to the study in Section 2.4, in this second study (Section 2.8) we focused on different effects to tackle the questions related to the mechanisms and the scope of bilingual language control. For example, in order to investigate *local control* effects we explored the effects of *neural priming disruption* (Dobbins, Schnyer, Verfaellie, & Schacter, 2004), elicited by a change of language across blocks. These effects reveal the extent to which each brain area of the language control network (see Abutalebi & Green, 2007, 2008) is involved in the control of linguistic responses, when this language is L1 and when this language is L2. Importantly, this study might be considered an improvement compared to previous ones (e.g., Guo et al., 2011), since it can inform about which areas are specifically involved in *local control* and which instead are involved in *global control*.

2.2 The overlap between bilingual language control and executive control: domain-general vs. language-specific mechanisms

A second approach for investigating the nature of bilingual language control mechanisms is to explore the functional overlap between bilingual language control and domain-general executive control.

Since the ICM (Green 1986, 1998) postulates that the inhibition involved in language switching is a domain-general process, one would expect that the same mechanisms and brain areas are implicated when switching between different languages and when switching between different non-linguistic tasks.

We tried to answer to this question by comparing the performance of the same bilingual participants in tasks tapping bilingual language control and domain-general executive control processes.

This approach has not been introduced in detail before, since it is still relatively recent. In fact, the studies presented in this dissertation are amongst the first to be conducted to investigate to which extent the mechanisms involved in a bilingual language control are domain-general.

In detail, we assessed the overlap between bilingual language control and domain-general executive control, by looking to different effects and by using different methodologies, such as behavioral and fMRI measures. The studies presented in Sections 2.5, 2.6 and 2.7 are behavioral experiments employing trial-by-trial linguistic and non-linguistic switching tasks. The other experimental study (see Section 2.8), instead, is the same fMRI study described in the previous section, and therefore it made use of linguistic and non-linguistic blocked switching tasks.

In the article presented in Section 2.5, we explored the overlap between bilingual language control and executive control in a population of young bilinguals (Catalan/Spanish bilinguals, high-proficient and balanced in their two languages; see Appendix A). Specifically, we explored two main effects to reveal the overlap between bilingual language control and domain-general executive control: (1) the correlation of the n-1 shift cost between linguistic and non-linguistic switching tasks and (2) the patterns of the n-1 shift cost in linguistic and non-linguistic switching tasks.

In the article presented in Section 2.6, we replicated and extended previous evidence also to populations of different ages (i.e., young, middle aged, and elderly). Moreover, we deeply explored behavioral measures by means of a fine-grained analysis (ex-Gaussian distribution analysis) that decomposes the RTs in two different distributions (normal and exponential- μ and τ). This is particular relevant to test the ICM (Green, 1986, 1998), since the exponential component (τ) has been related to inhibitory control processes (e.g., McAuley, Yap, Christ, & White, 2006; Shao, Roelofs, & Meyer, 2012; Spieler, Balota, & Faust, 1996). Hence, this analysis represents a more thorough tool to evaluate the involvement of inhibitory control in bilingual language control and domain-general executive control tasks.

In the article presented in Section 2.7, we tested another group of high-proficient Catalan/Spanish bilinguals to clarify the role of inhibitory control in linguistic and in non-linguistic switching tasks. We did so by assessing not only the n-1 shift cost, but also the n-2 repetition cost, that is considered a clearer marker of inhibitory control in switching tasks (e.g., Koch et al., 2010; Mayr & Keele, 2000). Importantly, a potential shortcoming of previous studies is that the contribution of inhibitory control was measured only through the magnitude of the n-1 shift cost that, indeed, may reflect the functioning of other executive control mechanisms, beyond inhibitory control (see Koch et al., 2010).

Hence, potentially any interpretation about inhibitory processes might be distorted by the variability added by these other processes, indexed by the n-1 shift cost. Therefore, in order to see whether inhibitory control was similarly applied in bilingual language control and in executive control, we assessed the following effects. First, we correlated the two costs between tasks to evaluate whether in the same participants the performance related to inhibitory control (the magnitudes of the costs) varied similarly between tasks. Second, in order to examine the contribution of inhibitory control in bilingual language control and executive control we also focused on the patterns of the n-1 shift cost and n-2 repetition cost in the two tasks. In particular, we focused on how much the n-2 repetition cost, which is known to reflect inhibitory control specifically, departed from the n-1 shift cost.

Beyond the effects related to inhibitory control, we assessed also other effects related to what we call "cognitive control flexibility". With this term we refer to the ability of combining dynamically different control mechanisms according to task demands. Indeed, recent evidence suggests that the bilingual advantage in executive control may involve this kind of ability (e.g., Morales, Gómez-Ariza, & Bajo, 2013). Thus, in accord with previous evidence (Philipp & Koch, 2006), we hypothesized that the n-1 shift cost and that of the n-2 repetition cost, measured in both linguistic and non-linguistic switching tasks, were likely reflecting the contribution of two opposing mechanisms, that is, task activation and task inhibition processes, respectively. Hence, we explored whether task activation and task inhibition were similarly combined in linguistic and non-linguistic switching tasks, by correlating within each task the magnitudes of the n-1 shift cost and the n-2 repetition cost.

Finally, in the last study (see Section 2.8), taking into account the neurocognitive model of bilingual language processing (Abutalebi & Green 2007, 2008; Green & Abutalebi, 2013), we explored whether the selection of linguistic and non-linguistic responses recruited similarly the brain areas proposed in this model. For that, we employed a blocked switching design that required to name pictures in the linguistic version and to perform a semantic classification task (with a “yes/no” response) in the non-linguistic version. Importantly, the same pictures were used in the two tasks. In this fMRI study, we investigated the neural overlap between bilingual language control and domain-general executive control, by measuring *neural priming disruption effects* (Dobbins et al., 2004) induced by a change of (linguistic and non-linguistic) task.

In what follows, we present the individual studies for the dissertation. These studies are ordered according to the two approaches presented above[12], employed to investigate the questions of the mechanisms and the scope of bilingual language control.

In detail, one book chapter and two articles (2.3, 2.4 and 2.8) are related to the questions of the mechanisms and the scope of

---

[12] The study presented in Section 2.8 embraces both the two approaches proposed to study the mechanisms of bilingual language control. However, this study will be presented following those related to the overlap between bilingual language control and domain-general executive control.

bilingual language control in language switching tasks. The studies presented in Sections 2.5, 2.6, 2.7 and 2.8 investigated the question of the mechanisms of bilingual language control by exploring the overlap between bilingual language control and domain-general executive control.

The following articles will be presented in these sections:

2.3 Baus, C., Branzi, F.M., Costa, A. (In Press). On the mechanisms and scope of bilingual language control. *The Cambridge Handbook of Bilingual Processing*.

2.4 Branzi, F.M., Martin, C.D., Abutalebi, J., Costa, A. (2014). The after-effects of bilingual language production. *Neuropsychologia*, 52, 102-116.

2.5 Calabria, M., Hernandez, M., Branzi, F.M., & Costa, A. (2012). Qualitative differences between bilingual language control and executive control: evidence from task-switching. *Frontiers in Psychology*, 2.

2.6 Calabria, M., Branzi, F.M., Marne, P., Hernández, M., & Costa, A. (2013). Age-related effects over bilingual language control and executive control. *Bilingualism: Language and Cognition*, 1-14.

2.7 Branzi, F.M., Calabria, M., Boscarino M., & Costa A. (Under Review). Inhibitory control and cognitive control flexibility: the overlap between bilingual language control and domain-general executive control. *Journal of Experimental Psychology: Learning, Memory and Cognition*.

2.8 Branzi, F. M., Della Rosa, P.A., Canini, M., Costa, A., & Abutalebi, J. (Under Review). Language control in bilinguals: monitoring and response selection. *Cerebral Cortex*.

2.3 On the mechanisms and scope of bilingual language control

Baus, C., Branzi, F.M., & Costa, A. (In press).On the mechanisms and scope of bilingual language control. *The Cambridge Handbook of Bilingual Processing.*

Baus C., Branzi F.M., Costa A. On the mechanism and scope of language control in bilingual speech production.
Dins de: Schweiter J. W. (ed.) The Cambridge handbook of bilingual processing. Cambridge : Cambridge University Press, 2015. ISBN 9781107060586

2.4 The after-effects of bilingual language production

Branzi FM, Martin CD, Abutalebi J, Costa A. The after-effects of bilingual language production.
Neuropsychologia. 2014 Jan; 52: 102-16. DOI: 10.1016/j.neuropsychologia.2013.09.022

2.5 Qualitative differences between bilingual language control and executive control: evidence from task-switching

Calabria M, Hernández M, Branzi FM, Costa A. Qualitative Differences between Bilingual Language Control and Executive Control: Evidence from Task-Switching. Front Psychol. 2012 Jan 13; 2: 399. DOI: 10.3389/fpsyg.2011.00399

frontiers in
PSYCHOLOGY

ORIGINAL RESEARCH ARTICLE
published: 13 January 2012
doi: 10.3389/fpsyg.2011.00399

Qualitative differences between bilingual language control and executive control: evidence from task-switching

Marco Calabria[1], **Mireia Hernández**[1,2,3], **Francesca M. Branzi**[1] **and Albert Costa**[1,4]*

[1] Department of Technology, Universitat Pompeu Fabra, Barcelona, Spain
[2] Center for Mind/Brain Sciences, University of Trento, Trento, Italy
[3] Cognitive Neuropsychology Laboratory, Department of Psychology, Harvard University, Cambridge, MA, USA
[4] Institució Catalana de Recerca i Estudis Avançats, Barcelona, Spain

Edited by:
Ingrid Christoffels, University of Leiden, Netherlands

Reviewed by:
Andrea Kiesel, Julius-Maximilians-University, Germany
Rico Fischer, Technische Universität Dresden, Germany

***Correspondence:**
Albert Costa, Departament de Tecnologies de la Informació i les Comunicacions, Universitat Pompeu Fabra, C/Tanger, 122-140, 08014 Barcelona, Spain.
e-mail: costalbert@gmail.com

Previous research has shown that highly proficient bilinguals have comparable switch costs in both directions when they switch between languages (L1 and L2), the so-called "symmetrical switch cost" effect. Interestingly, the same symmetry is also present when they switch between L1 and a much weaker L3. These findings suggest that highly proficient bilinguals develop a language control system that seems to be insensitive to language proficiency. In the present study, we explore whether the pattern of symmetrical switch costs in language switching tasks generalizes to a non-linguistic switching task in the same group of highly proficient bilinguals. The end goal of this is to assess whether bilingual language control (bLC) can be considered as subsidiary to domain-general executive control (EC). We tested highly proficient Catalan–Spanish bilinguals both in a linguistic switching task and in a non-linguistic switching task. In the linguistic task, participants named pictures in L1 and L2 (Experiment 1) or L3 (Experiment 2) depending on a cue presented with the picture (a flag). In the non-linguistic task, the same participants had to switch between two card sorting rule-sets (color and shape). Overall, participants showed symmetrical switch costs in the linguistic switching task, but not in the non-linguistic switching task. In a further analysis, we observed that in the linguistic switching task the asymmetry of the switch costs changed across blocks, while in the non-linguistic switching task an asymmetrical switch cost was observed throughout the task. The observation of different patterns of switch costs in the linguistic and the non-linguistic switching tasks suggest that the bLC system is not completely subsidiary to the domain-general EC system.

Keywords: bilingualism, executive control, language control, task-switching, language switching

INTRODUCTION

A remarkable skill of bilingual speakers is the ability to confine speech to one language while preventing interference from the unintended language. The cognitive process underlying this ability is often referred to as bilingual language control (bLC; e.g., Green, 1998; Costa and Santesteban, 2004; Crinion et al., 2006; Abutalebi and Green, 2007; Christoffels et al., 2007). Although there is disagreement regarding the nature of the bLC mechanisms, there is a general consensus that certain aspects of domain-general executive control (EC) functions mediate this ability (Abutalebi et al., 2008). However, it is still unclear whether bLC is completely subsidiary to the domain-general EC system or whether it also involves mechanisms specific to language.

In fact, the relationship between bLC and domain-general EC processes can be characterized in at least two different ways. First, one could think of bLC as a set of processes that are fully subsidiary to the domain-general EC functioning. That is, a bilingual speaker producing language would engage the very same set of EC processes that are involved in other non-linguistic activities requiring EC. Under this hypothesis, when switching language as a function of the interlocutor, individuals would engage the very same control mechanisms as when they are asked to switch between different non-linguistic tasks in everyday life. Alternatively, the bLC system may be only partially subsidiary to domain-general EC processes. That is, it is possible that the continuous control that bilingual speakers exert over their two languages results in the development of control processes specific to language (Costa and Santesteban, 2004). Although they probably make use of certain aspects of the EC system, additional processes may become specifically engaged in language switch related tasks. From this viewpoint, the crosstalk between the bLC and domain-general EC would still be present, leading to the repeatedly reported bilingual advantages in EC (e.g., Bialystok et al., 2004; Costa et al., 2008, 2009; Hernández et al., 2010). At the same time, however, some aspects of the bLC system would be specific to language and not necessarily related to the EC system.

Here, we set out to gain some initial insights on this issue by exploring a phenomenon observed both in language switching and task-switching, namely, the "asymmetrical switch cost" (see below). By doing this, we hope to shed some light on the crosstalk between the processes involved in bLC and those involved in domain-general EC.

ON THE FUNCTIONING OF EC SYSTEM IN BILINGUALS AND MONOLINGUALS

A first indication revealing that bilingualism affects the EC functioning can be found in those studies comparing monolinguals and bilinguals performing EC tasks. An increasing body of literature reveals that the continuous use of two languages seems to enhance processes related to domain-general EC such as those put at play in Stroop-like tasks and non-linguistic task-switching. This has been indexed through the observation of reduced Stroop-like interference and switch costs for bilinguals relative to monolinguals (e.g., Bialystok et al., 2004, 2006, 2008, 2010; Colzato et al., 2008; Costa et al., 2008, 2009; Bialystok and Viswanathan, 2009; Hernández et al., 2010). In particular, Prior and MacWhinney (2010) assessed whether bilinguals would show an advantage over monolinguals in non-linguistic task-switching with two sorting rules (sorting by shape or by color). They found that bilinguals had a reduced switch cost compared to monolinguals. Of the multiple components involved in task-switching (e.g., goal shifting, rule activation, etc., see Rubinstein et al., 2001), the authors hypothesized that the bilingual advantage in task-switching might be related to a more efficient goal shifting. The reasoning behind this hypothesis was that bilinguals' lifelong use of language switching may lead to an enhancement of the abilities of goal shifting also in the non-linguistic cognitive control mechanisms[1].

Other indications of the crosstalk between EC and bLC come from neuroimaging studies comparing monolinguals and bilinguals. Recently, Abutalebi et al. (2011) found differences in the way the dorsal anterior cingulate cortex (ACC) was recruited during conflict resolution in the flanker task. Specifically, bilinguals revealed a smaller activation of this area than monolinguals during conflict resolution. This pattern of brain activation was consistent with the fact that behaviorally bilinguals showed a reduced magnitude of the conflict effect compared to monolinguals. These results suggest that the ACC, one area within the cognitive control network, is engaged to a different extent in bilinguals and monolinguals during EC tasks.

There are also some indications of qualitative differences in brain activation between monolinguals and bilinguals during EC tasks (Garbin et al., 2010). In the study of Garbin et al. (2010), monolinguals and bilinguals completed a task-switching experiment using two sorting rules determined by stimulus color and shape. The authors found that bilinguals recruited brain areas normally engaged during language control (left inferior frontal gyrus), whereas monolinguals did not. This suggests that bilinguals recruit different neural structures relative to monolinguals in tasks involving the EC system.

Overall, these results indicate that bilingualism has an impact on the development of EC. However, they do not exclude the possibility that bLC involves certain processes that are outside the EC system. One way to explore the crosstalk between bLC and EC is to look at the qualitative difference of performance in tasks that engaged these two systems. Let us explain in more detail these qualitative aspects, specifically the asymmetry of the switch costs in linguistic and non-linguistic task-switching.

QUALITATIVE DIFFERENCES IN SWITCH COSTS BETWEEN LINGUISTIC AND NON-LINGUISTIC TASK-SWITCHING

Abutalebi and Green (2007), in a review of neuroimaging studies, suggested that the same neural regions (the dorsolateral prefrontal cortex, the ACC and the caudate nucleus) are engaged during both language switching tasks (e.g., Price et al., 1999; Hernandez et al., 2000, 2001; for a review see Hervais-Adelman et al., 2011) and non-linguistic task-switching (e.g., Botvinick et al., 1999; Crone et al., 2006). This indirect evidence supports the hypothesis that the mechanisms for language control are subsidiary to those of the domain-general EC.

However, an fMRI study conducted by Abutalebi et al. (2008) may actually be interpreted as going against the claim of functional overlap between bLC and EC. The authors demonstrated the existence of a neural network that is specifically recruited to switch between two different linguistic registers but not between two intra-linguistic tasks. This suggests that some processes at play during bLC are "language-specific" and not recruited for any other switching task.

In this article we further explore the issue of the crosstalk between bLC and EC by assessing qualitative aspects of these two systems (see below). To do so, we employ tasks involving bLC (language switching task) and EC (non-linguistic switching task) to compare the patterns of switch costs observed within the same population of highly proficient bilinguals. These two tasks share many different cognitive components and one can argue that in fact, the language switching task is just a specific instantiation of the more general task-switching paradigm (see for example, Abutalebi and Green, 2008). If so, and according to the first hypothesis put forward above, the pattern of results in the two tasks should be similar. In contrast, if bLC is not fully subsidiary to the EC processes, one could predict that the pattern of results in the two tasks may not be identical. Let us be more specific about the pattern of results we are referring to.

One of the most robust effects in task-switching is the so-called "local switch cost" (e.g., Meiran, 1996; Monsell, 2003; Koch et al., 2010; Schneider and Anderson, 2010; Martin et al., 2011). This cost refers to the observation of slower reaction times (RTs) for trials that require a task-switch in comparison to trials that do not require such a switch. For our present purposes, it is interesting that the magnitude of the local switch cost is not constant for any given task, but rather depends on the relative difficulty of the two tasks at hand during the experiment. Given differences in task difficulty, local switch costs tend to be larger when switching into the easier task than when switching into the more difficult one. For example, consider a switching task where task 1 consists

---

[1] The question of which EC processes are involved in task-switching is a complex issue that goes beyond the purposes of the present article. Several theories have exemplified how task-switching might be mediated by separable executive control processes [e.g., attention-to-action (ATA) model by Norman and Shallice, 1986; the frontal-lobe executive (FLE) model by Duncan, 1986; and the strategic response–deferment (SRD) model, Meyer and Kieras, 1997]. For a detailed description of such theories see reviews by Rubinstein et al. (2001) and Monsell (2003). Here, we refer to Rubinstein et al.'s (2001) account discussed in Prior and MacWhinney's (2010) study on the bilingual advantage in task-switching. Rubinstein et al. (2001) proposed that at least two processes of the EC system are involved in task-switching, namely "goal shifting" and "rule activation." "Goal shifting" updates the content of the declarative working memory about the two task-sets; whereas rule activation enables the selection of the current task and disables the rules of the previous one.

in sorting cards by color and task 2 consists in sorting cards by shape, with unpredictable switches from one task (e.g., color) to the other (shape). The switch cost observed when switching to the more difficult task "sorting by shape" are usually smaller than when switching to the easier task "sorting by color" (e.g., Nagahama et al., 2001; Rubinstein et al., 2001; Martin et al., 2011). This phenomenon, often referred to as the asymmetrical switch cost, has received many different explanations in the task-switching literature (for a review see Koch et al., 2010; Schneider and Anderson, 2010). Given the focus of this article, we will only discuss briefly what is, perhaps, the most influential account of this asymmetrical switch cost.

According to Allport et al. (1994), the "task-set inertia hypothesis", part of the switching cost stems from the need to retrieve a task-set that has been inhibited in the previous trial. Furthermore, the amount of inhibition applied to a given task-set (e.g., sorting by color or shape) depends on the relative strength of the task. That is, the easier task is inhibited more strongly than the more difficult one. Given this imbalance, the asymmetrical switch cost comes about in the following way: when performing the more difficult task (i.e., sorting by shape), the system has to strongly inhibit the task-set corresponding to the easier task (sorting by color). Hence, in the following trial, retrieving the strongly inhibited task-set will incur in a large switching cost. In contrast, when performing the easier task (i.e., sorting by color), the system has to inhibit with less strength the task-set corresponding to the more difficult task (sorting by shape). Consequently, in the following trial, retrieving the not-very-much inhibited task-set will incur in a small switching cost. Therefore, switching from the easier to the more difficult task will incur in a smaller switch cost (from color to shape) than switching from the more difficult to the easier task (from shape to color)[2].

Similarly, when the task-switching involves two languages, low-proficient bilinguals show asymmetrical switch costs (i.e., larger switch costs when switching into the easier language), which parallels the pattern of the non-linguistic task-switching paradigms. That is, for low-proficient bilinguals switching into the less proficient (and hence, the more difficult task) language (L2) is easier (in terms of RTs and errors) than switching into the more proficient (and hence, the easier task) language (L1; e.g., Meuter and Allport, 1999). This linguistic asymmetrical switch cost can be explained in the same manner as domain-general asymmetrical switching costs. In fact, Meuter and Allport (1999) argued that the magnitude of the inhibition applied to two languages is dependent on the relative strength of the two languages. Therefore, when the less proficient L2 needs to be produced, the more proficient L1 needs to be inhibited more than the other way around. Thus, an asymmetrical switch cost arises because the amount of inhibition that needs to be overcome during the switch into L1 is larger than when switching into L2. This pattern of asymmetries in low-proficient bilinguals fits very well with the notion that the same control processes involved in bLC are the ones that are also at play in domain-general EC.

The framework described above makes a straightforward prediction: whenever there is a difference in the difficulty of the tasks (or languages) involved in the switching task, there should be an asymmetrical switching cost, being such cost larger when switching into the easier task. Along the same lines, symmetrical switch costs are expected for switching tasks involving tasks of similar difficulty.

Crucial for present purposes is the fact that several studies conducted with highly proficient bilinguals have given only partial support to this prediction. Highly proficient bilinguals do not seem to show asymmetrical language switching costs regardless of the difficulty of the languages involved in the task. Let us be more specific and describe the pattern of language switching cost for highly proficient bilinguals in some detail.

As expected, when highly proficient bilinguals are asked to switch between their two proficient languages (hence little difference in difficulty between the two tasks), the switching costs are comparable in both directions (from L1 to L2 and vice versa; Costa and Santesteban, 2004; Costa et al., 2006). However, and crucial for present purposes, when these bilinguals are asked to switch between languages of different difficulties (e.g., switching between their L1 and their L3), the predicted asymmetrical switch cost is not present. In a series of experiments Costa et al. (2006) showed that in highly proficient bilinguals the symmetrical switch cost was present irrespective of the age of acquisition of L2, the similarities of two languages involved in the switching task and language proficiency. Given this pattern, two questions emerge:

(a) Why highly proficient bilinguals do not show the predicted asymmetrical switch cost when switching between languages of different proficiency, as the low-proficient bilinguals do?
(b) Would these bilinguals be sensitive to task difficulty when performing a non-linguistic switching task (e.g., would they show asymmetrical switch costs)? Answering this second question is the goal of the present article.

In trying to answer the first question, Costa and Santesteban (2004) hypothesized that highly proficient bilinguals might recruit a qualitatively different bLC when performing the language switching task compared to low-proficient bilinguals. As proposed by Costa and Santesteban (2004), there might be a shift in the type of mechanisms responsible for the selection of the intended language once a certain level of proficiency is attained in an L2. That is, it is possible that at some point highly proficient bilinguals do not make use of inhibition (as low-proficient ones probably do), but instead they make use of a mechanism that restricts lexical competition to the intended language. Importantly, once highly proficient bilinguals develop such as a mechanism it would be applied also to other languages (e.g., a weaker L3).

This explanation contains the implicit assumption that bLC might be to some extent different from EC processes in general, and hence the "task-set inertia" hypothesis (Allport et al., 1994) for the performance of highly proficient bilinguals is not granted. Note

---

[2] Other authors have proposed different accounts based on long-term memory retrieval processes (e.g., Allport and Wylie, 2000; Mayr and Kliegl, 2000; Bryck and Mayr, 2008). One assumption is that the retrieval of irrelevant task traces interferes with selection of the relevant task and that more instances of the more difficult task would be encoded/retrieved into long-term memory than in the case of the easier task. Since the amount of interference is proportional to the number of irrelevant task traces in long-term memory, the interference will be larger when switching into the easier task than into the more difficult one. This leads to a larger switch cost when switching from the more difficult to the easier task than vice versa.

that this hypothesis would predict asymmetrical switch costs when switching from L3 into L1 for highly proficient bilinguals, given that one language (L3) is harder than the other (L1) – similarly to what happens when low-proficient bilinguals switch between L1 and L2. Thus, according to this hypothesis, the difference in the relative strength between L1 and L3 should involve a different amount of inhibition when speaking in one language or the other and therefore produce asymmetries in switch costs as well.

Regardless these explanations, what is relevant here is the potential generalizability of such a lack of asymmetrical switch costs of highly proficient bilinguals to non-linguistic tasks. That is, the question is whether the crosstalk between bLC and EC systems is such that the relative insensitivity of highly proficient bilinguals to task difficulty in the language switching task will also be present in a non-linguistic switching task.

If the bLC system is fully subsidiary to the EC system, it is reasonable to predict that whichever pattern is observed in the language switching task will also be present in a non-linguistic switching task. Hence, we predict that differences in task difficulty should not lead to asymmetrical switch costs in these bilinguals, in the same way that differences in language difficulty do not lead to asymmetrical switch costs for this group. On the other hand, if bLC is governed by processes that are, to some extent, independent of the EC system, then it is possible that the symmetrical switch costs observed for language switching do not generalize to non-linguistic task-switching.

We put these predictions to test by comparing the performance of highly proficient Catalan–Spanish bilinguals in a linguistic and non-linguistic switching paradigm and examining the qualitative pattern of the switch costs. Specifically, we compared the symmetry/asymmetry of the switch costs between tasks differing in their level of difficulty. We used an adaptation of the linguistic switching task previously employed by Costa and Santesteban (2004), through which we expected to replicate the typical symmetrical switch cost of highly proficient bilinguals between L1 and L2 and also between L1 and L3. Note that for the sake of completeness we present two experiments: in Experiment 1 highly proficient bilinguals switched between L1 and L2, and in Experiment 2 between L1 and L3.

Concerning the non-linguistic task, we used a task-switching where participants had to switch between two rule-sets of a card sorting task (color and shape). As previously described, sorting by color is easier than sorting by shape. This effect of task difficulty permitted us to compare the non-linguistic switching task with the language switching task. We defined the non-linguistic switching task such that it did not require changing languages and it did not require explicit verbalization of the response.

To recapitulate, we will examine the issue of the crosstalk between bLC and EC in two ways:

(a) From a qualitative point of view: by examining the pattern of the switch costs in terms of the symmetry/asymmetry in the linguistic and non-linguistic switching tasks. If highly proficient bilinguals show a symmetrical switch cost in the language switching task, the same symmetrical pattern is expected in the non-linguistic switching task if the mechanisms of bLC are completely subsidiary to the EC system.

(b) From a quantitative point of view: by examining any potential correlations between linguistic and non-linguistic switch costs. Significant correlations between switch costs in linguistic and non-linguistic switching tasks could indicate that the bilinguals' behavior in the bLC generalizes to a non-verbal domain, such as domain-general EC.

PARTICIPANTS

Fourteen bilinguals (mean age = 23.2, range = 18–27 years old) took part in Experiment 1, and 15 bilinguals did it in Experiment 2 (mean age = 20.3, range = 18–23 years old). All participants in both experiments were early and highly proficient Catalan–Spanish bilinguals. All participants had Catalan as L1 and they learned Spanish before the age of 6. Their proficiency in the two languages was tested by means of a questionnaire. Each participant self-rated on a four-point scale the abilities of speaking, comprehension, writing and reading for each language (1 = poor, 2 = regular, 3 = good, 4 = perfect). All the participants were highly proficient in both L1 and L2 (see **Table 1**). In addition, participants in Experiment 2 were low-proficient in English (L3).

EXPERIMENT 1: LINGUISTIC SWITCHING BETWEEN L1 AND L2 AND NON-LINGUISTIC SWITCHING TASK

MATERIALS AND PROCEDURE

Linguistic switching task

Eight pictures of objects were selected from Snodgrass and Vanderwart (1980). Half of them referred to cognate words [Spanish/Catalan names: "Caracol"/"Cargol" (in English, snail); "Escoba"/"Escombra" (broom); "Martillo"/"Martell" (hammer); "Reloj"/"Rellotge" (watch)], and the other half to non-cognate words ["Calcetín"/"Mitjó" (sock); "Manzana"/"Poma" (apple); "Silla"/"Cadira" (chair); "Tenedor"/"Forquilla" (fork)].

Participants were required to name the picture in Catalan or in Spanish. A Catalan or Spanish flag, which was presented along with the picture, acted as a cue to indicate in which language subjects had to name the picture.

Table 1 | Language proficiency (mean and SD) of speaking, comprehension, writing, and reading abilities for each language, self-rated on a four-point scale (1 = poor, 2 = regular, 3 = good, 4 = perfect).

Experiment 1	Catalan, mean (SD)	Spanish, mean (SD)
Speaking	4.0 (0.0)	3.9 (0.3)
Comprehension	4.0 (0.0)	4.0 (0.0)
Pronunciation	4.0 (0.0)	3.9 (0.3)
Reading	4.0 (0.0)	4.0 (0.0)
Writing	4.0 (0.0)	3.9 (0.3)
Experiment 2	**Catalan, mean (SD)**	**English, mean (SD)**
Speaking	4.0 (0.0)	2.1 (0.5)
Comprehension	4.0 (0.0)	2.9 (0.7)
Pronunciation	4.0 (0.0)	2.1 (0.7)
Reading	4.0 (0.0)	3.0 (0.4)
Writing	4.0 (0.0)	2.7 (0.5)

There were two types of trials: (a) those in which participants were required to name the picture in the same language as the preceding trial (repeat trial), (b) those in which participants were required to name in a different language with respect to the previous trial (switch trial). There were a total of 320 trials divided in two blocks with 160 trials each. The total distribution of trials was: 128 repeat trials in Catalan, 128 repeat trials in Spanish, 64 switch trials in Catalan, and 64 in Spanish.

Participants were asked to name the picture as fast as possible and they were informed that the language to be used was indicated by a flag, presented on the top of the picture. At the beginning of each series a word cue was presented for 1000 ms indicating in which language participants had to start to name ("CATALÀ," for Catalan; "ESPAÑOL," Spanish). Then the picture appeared for 1700 ms and the timeout to respond was 5000 ms. The pictures were presented in a series of three to seven trials and at the end of each series an asterisk appeared and the participants pressed the spacebar to start the next series. The experiment started with a practice session of 80 trials.

Non-linguistic switching task

Three shapes (square, circle, and triangle) and three colors (green, blue, and red) were selected for the task. The three shapes were combined with the three colors, resulting in a total of nine colored shapes (e.g., green square, blue square etc.). Participants were presented with an array containing three shapes, two at the top of the screen and one at the bottom. They were instructed to match the shape at the bottom with one of the two at the top of the display according to two possible criteria (shape or color). The criterion was indicated by a cue ("COLOR," for Color; "FORMA," for Shape) appearing in the center of the array. As in the linguistic version of the task, there were two types of trials: repeat and switch trials.

At the beginning of each series a word cue was presented for 1000 ms indicating by which rule participants must start matching each item ("COLOR," for Color; "FORMA," for Shape). Then the array appeared for 2500 ms and the timeout to respond was 3000 ms.

Participants gave the response by pressing the two keys "M" or "V" according to the position of the matched picture at the top of the array. Specifically, they had to press "M" key when the correct answer was at the top-right part of the array and the "V" key when the correct response was at the top-left part of the array. The experiment started with a practice session of 80 trials.

The experiments were controlled by the software DMDX (Forster and Forster, 2003), which recorded participants' vocal and manual responses. Responses were analyzed off-line and naming latencies were measured from the onset of the word trough Checkvocal, a program of data analysis of naming tasks in DMDX (Protopapas, 2007). Participants always performed the linguistic switching and then the non-linguistic switching task. The order of the two tasks was not counterbalanced.

RESULTS

Linguistic switching cost

The variables considered in the analyses were "type of trial" (switch vs. repeat) and "response language" (L1 and L2) which were included as within-subject factors in a repeated-measure ANOVA on naming latencies. Naming latencies 3 SD above or below a given participant's mean were excluded from the analyses. Also the naming latencies in which the participants produced a different name from what was expected were excluded from the analyses.

Reaction times. Overall participants were slower in switch trials (886 ms) compared to repeat trials [801 ms; $F(1, 13) = 55.11$, MSE = 1822.67, $p < 0.0001$, $\eta_p^2 = 0.81$], and faster to name in L1 (829 ms) than in L2 [857 ms; $F(1, 13) = 4.81$, MSE = 2318.88, $p = 0.05$, $\eta_p^2 = 0.27$]. But the cost to switch to L1 (87 ms) and to L2 (82 ms) was the same, as indexed by a non-significant "type of trial" × "response language" interaction [$F(1, 13) = 0.15$, MSE = 741.59, $p = 0.70$; see **Figure 1A**]. That is, there was a symmetrical switch cost.

Accuracy. No difference in accuracy was found between switch and repeat trials [Type of trial: $F(1, 13) = 2.29$, MSE = 9.65, $p = 0.15$] and between L1 and L2 [Response language: $F(1, 13) = 0.40$, MSE = 22.76, $p = 0.54$]. The interaction between type of trial and response language was not significant either [$F(1, 13) = 0.19$, MSE = 6.64, $p = 0.66$; see **Table 1**].

Non-linguistic switching cost

The variables considered in the analysis were "type of trial" (switch vs. repeat) and "sorting criteria" (color and shape), which were included as a within-subject factor in a repeated-measure ANOVA using RTs as a dependent variable.

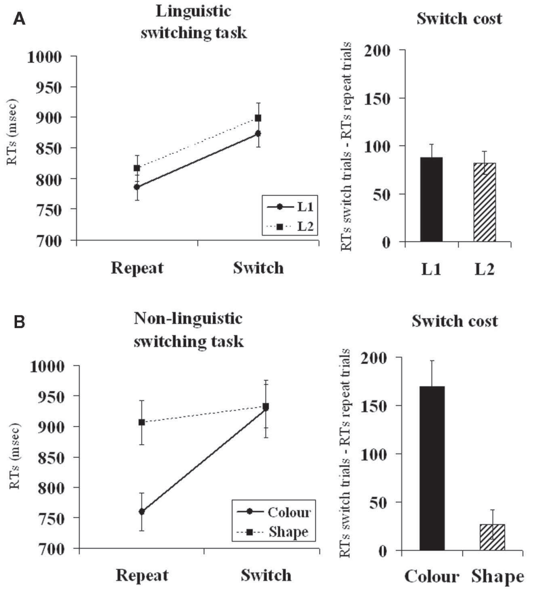


FIGURE 1 | (A) Performances on the linguistic switching task (left) and magnitude of the switch cost for L1 and L2 (right). Error bars represent SE. **(B)** Performances on the non-linguistic switching task (left) and magnitude of the switch cost for color and shape (right). Error bars represent the SE.

Reaction times. Overall participants were slower in switch trials (931 ms) compared to repeat trials [833 ms; $F(1, 13) = 38.42$, $MSE = 3505.52$, $p < 0.0001$, $\eta_p^2 = 0.75$], and faster to sort by color (843 ms) than to sort by shape [920 ms; $F(1, 13) = 40.32$, $p < 0.0001$, $MSE = 2011.41$, $\eta_p^2 = 0.76$]. In this case the switch cost interacted with "type of trial" [$F(1, 13) = 19.88$, $MSE = 3592.72$, $p = 0.001$, $\eta_p^2 = 0.61$]. That is, participants showed a cost when they switched from shape to color [169 ms, $F(1, 13) = 37.57$, $MSE = 5353.39$, $p < 0.0001$, $\eta_p^2 = 0.74$], but not from color to shape [27 ms, $F(1, 13) = 2.85$, $MSE = 1744.86$, $p = 0.11$; see **Figure 1B**].

Accuracy. There was a tendency toward lower accuracy for switch trials (91.25%) over repeat ones [94.75%; Type of trial: $F(1, 13) = 3.64$, $MSE = 17.80$, $p = 0.08$]. Also, participants were less accurate in sorting by shape (90.0%) than by color [94.7%; $F(1, 13) = 14.22$, $MSE = 22.40$, $p < 0.01$, $\eta_p^2 = 0.52$; see **Table 2**].

To summarize, we found that bilingual participants showed symmetrical switch costs in the linguistic task-switching, but in the non-linguistic one we found asymmetrical switch costs since only switching into color resulted in a cost.

EXPERIMENT 2: LINGUISTIC SWITCHING BETWEEN L1 AND L3 AND NON-LINGUISTIC SWITCHING TASK

As advanced in the Introduction, one could argue that the symmetrical switch costs between L1 and L2 of highly proficient bilinguals are due to both tasks (naming in L1 and naming in L2) being equally easy for highly proficient bilinguals. In other words, we would have a difference in difficulty between color and shape in the non-linguistic task-switching but not between L1 and L2 in the language switching task. Thus, in this experiment, bilinguals (who were still highly proficient in both Catalan and Spanish) conducted the language switching task between their L1 (Catalan) and L3 (English) for which they were low-proficient.

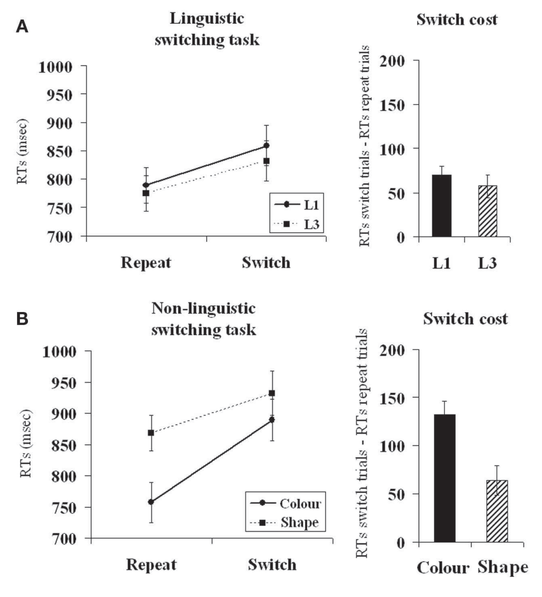


FIGURE 2 | (A) Performances on the linguistic switching task (left) and magnitude of the switch cost for L1 and L3 (right). Error bars represent SE. **(B)** Performances on the non-linguistic switching task (left) and magnitude of the switch cost for color and shape (right). Error bars represent the SE.

MATERIALS AND PROCEDURE

The procedure for the linguistic and non-linguistic switching tasks was the same as that reported for the Experiment 1. The only difference with Experiment 1 was that participants were required to name in Catalan and English, instead of Catalan and Spanish in the language switching task. The material was the same as in Experiment 1.

RESULTS

Linguistic switching cost

The variables considered in the analyses were "type of trial" (switch vs. repeat) and "response language" (L1 and L3), which were included as within-subject factor in a repeated-measure ANOVA on naming latencies.

Reaction times. Overall participants were slower in switch trials (846 ms) compared to repeat trials [783 ms; $F(1, 14) = 75.85$, $MSE = 799.13$, $p < 0.0001$, $\eta_p^2 = 0.84$], but there was no difference in naming latencies between L1 (824 ms) and L3 [804 ms; $F(1, 14) = 2.12$, $MSE = 2914.51$, $p = 0.17$]. The cost to switch to L1 (70 ms) and to L3 (57 ms) was equivalent, as indexed by a non-significant effect of "type of trial" × "response language" interaction [$F(1, 14) = 0.56$, $MSE = 1211.89$, $p = 0.47$; see **Figure 2A**], revealing a symmetrical switch cost.

Accuracy. No difference in accuracy was found between switch and repeat trials [Type of trial: $F(1, 14) = 2.81$, $MSE = 11.99$, $p = 0.12$] and between L1 and L3 [Response language: $F(1, 14) = 0.59$, $MSE = 10.92$, $p = 0.46$]. The interaction between type of trial and response language was not significant either [$F(1, 14) = 0.09$, $MSE = 13.93$, $p = 0.77$; see **Table 3**].

Table 2 | Accuracy (%) and SE in the linguistic and non-linguistic versions of the task-switching broken for trial types for the Experiment 1.

Experiment 1	Accuracy (%)	SE	Accuracy (%)	SE
	L1		**L2**	
LINGUISTIC VERSION				
Repeat	97.8	0.5	97.3	0.6
Switch	96.8	1.0	95.7	1.5
Total	97.3	0.7	96.5	1.0
	Color		**Shape**	
NON-LINGUISTIC VERSION				
Repeat	96.0	0.6	90.9	0.8
Switch	93.5	1.0	89.0	1.9
Total	94.7	0.8	90.0	1.3

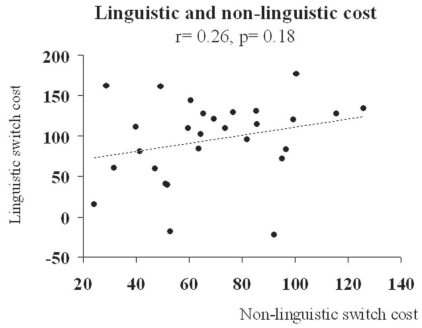


FIGURE 3 | Correlation of individuals' performances between the linguistic and non-linguistic switching tasks, for Experiment 1 and Experiment 2 ($n = 28$). In this graph we excluded one participant from Experiment 1 because his language switching cost was 2 SD above the group's mean.

Table 3 | Accuracy (%) and SE in the linguistic and non-linguistic versions of the task-switching broken for trial types for the Experiment 2.

Experiment 2	Accuracy (%)	SE	Accuracy (%)	SE
	L1		**L3**	
LINGUISTIC VERSION				
Repeat	94.5	1.1	93.4	2.1
Switch	92.6	2.1	92.2	2.1
Total	93.4	1.6	92.4	2.1
	Color		**Shape**	
NON-LINGUISTIC VERSION				
Repeat	96.0	0.8	91.2	0.8
Switch	92.2	1.5	91.7	1.3
Total	93.6	1.1	91.9	1.2

Non-linguistic switching cost

The variables considered in the analysis were "type of trial" (switch vs. repeat) and "sorting criteria" (color and form), which were included as within-subject factors in a repeated-measure ANOVA on the RTs.

Reaction times. Overall participants were slower in switch trials (911 ms) compared to repeat trials [812 ms; $F(1, 14) = 69.38$, $\text{MSE} = 2104.36$, $p < 0.0001$, $\eta_p^2 = 0.83$], and faster sorting by color (823 ms) than sorting by shape [900 ms; $F(1, 14) = 42.81$, $p < 0.0001$, $\text{MSE} = 2085.37$, $\eta_p^2 = 0.75$]. In this case the switch cost interacted with "type of trial" [$F(1, 14) = 14.11$, $\text{MSE} = 1221.76$, $p = 0.002$, $\eta_p^2 = 0.50$]. That is participants showed a larger cost when they switched from shape to color [132 ms, $F(1, 14) = 82.34$, $\text{MSE} = 1600.58$, $p < 0.0001$, $\eta_p^2 = 0.85$], than from color to shape [64 ms, $F(1, 14) = 18.22$, $\text{MSE} = 1725.55$, $p = 0.001$; see **Figure 2B**].

Accuracy. Participants were less accurate in switch trials (91.9%) than in repeat trials [93.6%; Type of trial: $F(1, 14) = 7.59$, $\text{MSE} = 5.54$, $p = 0.01$, $\eta_p^2 = 0.35$], and less accurate to sort by shape (91.4%) than by color [94.1%; $F(1, 14) = 9.44$, $\text{MSE} = 11.58$, $p < 0.01$, $\eta_p^2 = 0.40$]. A significant interaction between "type of trial" and "sorting criteria" [$F(1, 14) = 7.38$, $\text{MSE} = 9.34$, $p = 0.02$, $\eta_p^2 = 0.34$], indicated an increase of errors when participants switched from shape to color [$F(1, 14) = 12.76$, $\text{MSE} = 8.57$, $p < 0.01$, $\eta_p^2 = 0.47$] but not from color to shape [$F(1, 14) = 0.26$, $\text{MSE} = 6.31$, $p = 0.62$; see **Table 2**].

To summarize, we found that bilingual participants showed symmetrical switch costs in the linguistic version of the task, but asymmetrical switch costs in the non-linguistic version, as we did in Experiment 1.

Individuals' differences in performance: correlations

Additionally, we used a correlation analysis (Pearson's coefficient) to compare the magnitude of the switch cost between the linguistic and non-linguistic switching tasks.

In fact, if we assume that the switch cost reflects to some extent the efficiency of the bLC and EC in the same way, we may expect that the magnitude of the two switch costs (linguistic and non-linguistic) varies in the same manner in participants.

First, we obtained the correlation coefficient of the total switch cost between the linguistic task and the non-linguistic task (collapsing language in one case and the sorting criteria in the other case). In order to gain more statistical power we ran the analysis with participants of both experiments resulting in a total number of 28 (one participant from Experiment 1 was excluded because his performance was 2 SD above the group means). The switch costs of the two tasks were not significantly correlated ($r = 0.26$, $p = 0.18$; see **Figure 3**).

Then, we tested whether the cost of switching into the easier language (L1) correlated with the cost of switching into the easier sorting criteria (i.e., color), and whether the cost of switching into the difficult language (L2/L3) correlated with the cost of switching into the more difficult sorting criteria (shape). Neither the correlation between the cost of switching to L1 and to color ($r = 0.16$, $p = 0.42$), nor the correlation between the cost of switching to L2/L3 and to shape ($r = -0.15$, $p = 0.44$) were significant.

Exploratory analysis of the switch costs across blocks

Considering the overall results, we found that the switch cost was symmetrical in the linguistic switching task and asymmetrical in the non-linguistic switching task. In a further analysis we explored the pattern of the switch costs across the two experimental blocks with the aim of assessing any potential differences in task adaptation.

To do so we calculated the switch costs separately for the two blocks of the two tasks (linguistic and non-linguistic), containing 160 trials each. In the non-linguistic switching task-switch costs were asymmetrical in both blocks[3] (i.e., switching into color

---

[3] Non-linguistic switching task. In Experiment 1, the switch costs were 149 ms for color and 34 ms for shape in block 1; 162 ms for color and 24 ms for shape in block 2 [Type of trial × Block interaction: $F(1, 13) = 0.34$, $p = 0.57$]. In Experiment 2, the switch costs were 133 ms for color and 49 for shape in block 1; 134 ms for color

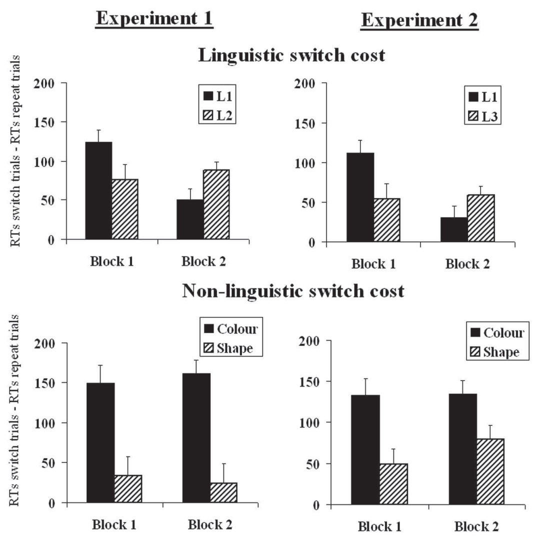


FIGURE 4 | Magnitude of the switch costs in the linguistic and non-linguistic switching tasks broken by blocks and experiments. Error bars represent SE.

was more costly than switching into shape; see **Figure 4**). However, in the linguistic switching task we found a more puzzling result. In the first block, switching into L1 was more costly than switching into L2 or L3, but this pattern reversed in the second block. Interestingly, the cost of switching into L2 or L3 was constant across both blocks, whereas the cost of switching into L1 decreased in the second block. Even though this interaction renders the interpretation of the results more complex, the interesting point here is that it suggests that there are differences between the two types of task-switching also in what regards adaptation to the task.

DISCUSSION AND CONCLUSION

In the present study we examined the relationship between the bLC and EC system. We did so by comparing the pattern of switch costs across linguistic and non-linguistic tasks within a set of highly proficient bilinguals.

We assessed the presence of the symmetrical switch cost in the linguistic task as a starting point, and then we looked at the pattern of switch cost in a non-linguistic switching task. In both experiments, bilinguals showed an asymmetrical non-linguistic switch cost: switching from shape to color was more costly than switching from color to shape. That is, switching from the more difficult task (sorting by shape) to the easier one (sorting by color) resulted in a larger switch cost than vice versa. Additionally, participants committed more errors when they sorted by shape than by color, suggesting that the shape criterion was the most difficult of the two – a finding congruent with previous studies (e.g., Koch, 2001; Martin et al., 2011). In contrast, the same participants showed a symmetrical switch cost in the linguistic task (as previously reported by Costa and Santesteban, 2004; Costa et al., 2006). That is, there seems to be a qualitative difference in the way highly proficient bilinguals perform linguistic and non-linguistic task-switching.

The relationship between the two tasks was also explored by examining the magnitude of the switch costs in the two task versions. The idea behind this analysis was to see whether the efficiency of the bLC abilities could, to some extent, be transferred to the domain-general EC system. Specifically, bilingual individuals that have developed more efficient bLC will probably show relatively small switch costs in the language switching task compared to individuals with less developed bLC. If indeed the bLC functioning depends completely on the EC system, one would expect to find smaller switch costs also in the non-linguistic task. We did not find significant correlations between the linguistic and non-linguistic switch costs, neither between L1 and color nor between L2/L3 and shape. Thus, quantitatively, the magnitude of the switch cost suggests that there is no generalizability from the bLC to the EC system.

Similar results of uncorrelated performance between linguistic and non-linguistic tasks were reported in a study by Bialystok et al. (2008). These authors correlated the performance of bilingual speakers in two language production tasks (fluency and picture naming) with their performance in EC tasks. They did not find any correlation and concluded that their results leave open the possibility that the mechanisms responsible for bLC and those of domain-general EC may have different causes.

Further evidence about differences between the patterns of results in the two versions of the task-switching comes from the different adaptation patterns across the experiment. In the non-linguistic switching task, asymmetrical switching costs (larger switch cost for the easier task) were consistently observed across the whole experiment. However, this was not the case in the language switching task, where a puzzling result was observed. The switch cost for L1, both in Experiment 1 and 2, decreased from block one to block two, whereas the switch cost for L2 and L3 remained constant across blocks. That is, while there is a modulation of the switch cost for the easier task (L1) across the experiment, switch costs for the more difficult task (L2 and L3) remain the same. An interpretation of the L1 adaptation is premature, and future studies need to replicate it. However, our observations highlight the need of exploring language switching costs across the experimental blocks. Besides any kind of interpretation, the interesting point here is that in the two versions of task-switching we found different patterns of switch costs also over time. To some extent, these results indicate that some properties of bLC, for instance a certain degree of flexibility to adapt the behavior, are peculiar to the linguistic domain and they do not transfer to other domains. Once again, this might be evidence for the fact that bLC processes are not fully subsidiary to those

---

and 79 ms for shape in block 2 [Type of trial × Block interaction: $F(1, 14) = 0.92$, $p = 0.35$]. Linguistic switching task. In Experiment 1, the switch costs were 124 ms for L1 and 76 ms for L2 in block 1; 50 ms for L1 and 88 ms for L2 in block 2 [Type of trial × Block interaction: $F(1, 13) = 19.72$, $p = 0.001$]. In Experiment 2, the switch costs were 112 ms for L1 and 54 for L3 in block 1; 31 ms for L1 and 59 ms for L3 in block 2 [Type of trial × Block interaction: $F(1, 14) = 12.96$, $p = 0.003$].

of the EC system and that there is no transfer from bLC to the domain-general EC system.

Before going into the implications of the results reported here, it is important to note a potential caveat of our study. We have argued that the instantiation of the language switching task in Experiment 2 involves languages of different difficulty, since we compared L1 and L3. In principle, the difference in proficiency between the two languages should be enough to reveal asymmetrical switch costs, as has been shown previously with low-proficient bilinguals (Costa and Santesteban, 2004). However, we do not have any independent evidence that guarantees this difference in proficiency. Indeed, one may be tempted to take the fact that L1 is slower than L3 as an indication against our assumption. However, such interpretation is not without problems. This is because in previous studies we observed a similar pattern of RTs for participants for which we did have independent evidence that L1 was much stronger than L3 (Costa and Santesteban, 2004; Costa et al., 2006). At any rate, we acknowledge that the lack of independent information about the differences in strength between the two languages is a shortcoming of the present study.

The results of the present study suggest that the set of processes engaged in bLC are not fully subsidiary to the domain-general EC processes. That is, a bilingual speaker producing language will not engage the very same set of EC processes that are involved in any other non-linguistic activity in which the executive system is required. As discussed in the Introduction, most of the available evidence from neuroimaging studies is indirect. That is, it is a result of comparing different groups of participants performing either language switching tasks (e.g., Abutalebi and Green, 2007, 2008) or non-linguistic switching tasks (Garbin et al., 2010). One exception is the study of Abutalebi et al. (2011) in which the same group of bilinguals performed a language switching task and a non-linguistic conflict resolution task. The analysis of the brain networks involved in the two tasks showed an overlap over a set of brain areas along the mesial surface, comprising the ACC (BA 32) and the pre-SMA (BA 6). However, some additional areas were recruited during the conflict resolution task that were not active during the language switching task. Thus, the general conclusion from the neuroimaging literature is that some brain areas of the bLC and EC overlap, but the small amount of direct evidence (e.g., the same group of participants tested both on linguistic and non-linguistic tasks involving EC) precludes us from drawing strong conclusions about the extent of this overlap.

Our results fit well with data on brain-damaged individuals. Studies testing bilingual aphasics have reported double dissociations between language control and domain-general control (e.g., Green et al., 2010; see also Abutalebi et al., 2000; Mariën et al., 2005). For example, in Green et al. (2010) found a relatively different impairment of language control and the EC system as a result of the brain lesion, indicating that the brain areas implicated in language control are not totally subsidiary to those implicated in EC and vice versa.

Before concluding, it is worth mentioning the lack of a correlation observed between the magnitudes of the switch costs in the linguistic and non-linguistic tasks. This also points to the direction that one cannot equate the processes involved in bLC with those involved in domain-general EC system. This approach, in which the crosstalk between bLC and EC is assessed in the same group of bilinguals by comparing the magnitude of switch costs, has started to receive some attention. Recently, Prior and Gollan (2011) looked at this issue by testing whether the bilingual advantage in EC was to some extent related to the cost of language switching. They found that those bilinguals who showed less cost in task-switching were also those who showed less cost in language switching. But this was true only for those bilinguals who reported to switch quite often in their everyday life. Second, no direct correlations of the switch costs between the two tasks were performed within the group of participants. Therefore, only based on the results of Prior and Gollan (2011) it is premature to conclude that the mechanisms underlying bLC are fully subsidiary to the EC system. And, in fact, if anything our results indicate otherwise.

To conclude, in this study we found different patterns of switch costs between a language switching task and a non-linguistic switching task. These results suggest that even if there is crosstalk between bLC and domain-general EC, there are some aspects of the bLC system that are specific to the domain of language and not necessarily related to the EC system. The relevance of our results is that they represent an attempt to investigate the crosstalk between the bLC and EC in the same group of participants. Further research is needed to investigate the exact mechanisms underlying the bLC and EC systems in bilinguals in order to eventually gain knowledge about their functional and neural relationship.

ACKNOWLEDGMENTS

This work was supported by grants from the Spanish government (PSI2008-01191, Consolider Ingenio 2010 CSD2007-00012) and the Catalan government (Consolidat SGR 2009-1521). Marco Calabria was supported by a postdoctoral fellowship from the Spanish Government (Juan de la Cierva fellowship). Francesca M. Branzi was supported by a predoctoral fellowship from the Spanish Government (FPU-2009-2013). This research was also supported by a Marie Curie International Outgoing Fellowship within the seventh European Community Framework Programme awarded to Mireia Hernández. The authors are grateful to Ian FitzPatrick, Philip Jaekl, and Elin Runnqvist for comments on previous versions of this manuscript.

REFERENCES

Abutalebi, J., Annoni, J. M., Zimine, I., Pegna, A. J., Seghier, M. L., Lee-Jahnke, H., Lazeyras, F., Cappa, S. F., and Khateb, A. (2008). Language control and lexical competition in bilinguals: an event-related FMRI study. *Cereb. Cortex* 18, 1496–1505.

Abutalebi, J., and Green, D. (2007). Bilingual language production: the neurocognition of language representation and control. *J. Neurol.* 20, 242–275.

Abutalebi, J., and Green, D. (2008). Control mechanisms in bilingual language production: neural evidence from language switching studies. *Lang. Cogn. Process.* 23, 557–582.

Abutalebi, J., Miozzo, A., and Cappa, S. (2000). Do subcortical structures control "language selection" in polyglots? Evidence from pathological language mixing. *Neurocase* 6, 51–56.

Abutalebi, J., Rosa, P. A., Green, D., Hernández, M., Scifo, P., Keim, R., Cappa, S. F., and Costa, A. (2011). Bilingualism tunes the anterior cingulate cortex for conflict monitoring. *Cereb. Cortex.* doi: 10.1093/cercor/bhr287

Allport, A., and Wylie, G. (2000). "Task-switching, stimulus–response bindings, and negative priming," in *Attention and Performance XVIII: Control of Cognitive Processes*, eds S. Monsell and J. S. Driver (Cambridge, MA: MIT Press), 35–70.

Allport, D. A., Styles, E. A., and Hseih, S. (1994). "Shifting intentional set: exploring the dynamic control of tasks," in *Attention and Performance XV: Conscious and Nonconscious Information Processing*, eds C. Umiltà and M. Moscovitch (Cambridge, MA: MIT Press), 421–452.

Bialystok, E., Barac, R., Blaye, A., and Poulin-Dubois, D. (2010). Word mapping and executive functioning in young monolingual and bilingual children. *J. Cogn. Dev.* 11, 485–508.

Bialystok, E., Craik, F., and Luk, G. (2008). Cognitive control and lexical access in younger and older bilinguals. *J. Exp. Psychol. Learn. Mem. Cogn.* 34, 859–873.

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

Bialystok, E., Craik, F. I., and Ryan, J. (2006). Executive control in a modified antisaccade task: effects of aging and bilingualism. *J. Exp. Psychol. Learn. Mem. Cogn.* 32, 1341–1354.

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

Botvinick, M., Nystrom, L. E., Fissell, K., Carter, C. S., and Cohen, J. D. (1999). Conflict monitoring versus selection-for-action in anterior cingulate cortex. *Nature* 402, 179–181.

Bryck, R. L., and Mayr, U. (2008). Task selection cost asymmetry without task s witching. *Psychon. Bull. Rev.* 15, 128–134.

Christoffels, I. K., Firk, C., and Schiller, N. O. (2007). Bilingual language control: an event-related potential study. *Brain Res.* 1147, 192–208.

Colzato, L. S., Bajo, M. T., van den Wildenberg, W., Paolieri, D., Nieuwenhuis, S., La Heij, W., and Hommel, B. (2008). How does bilingualism improve executive control? A comparison of active and reactive inhibition mechanisms. *J. Exp. Psychol. Learn. Mem. Cogn.* 34, 302–312.

Costa, A., Hernández, M., Costa-Faidella, J., and Sebastián-Gallés, N. (2009). On the bilingual advantage in conflict processing: now you see it, now you don't. *Cognition* 113, 135–149.

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

Costa, A., and Santesteban, M. (2004). Lexical access in bilingual speech production: evidence from language switching in highly proficient bilinguals and L2 learners. *J. Mem. Lang.* 50, 491–511.

Costa, A., Santesteban, M., and Ivanova, I. (2006). How do highly proficient bilinguals control their lexicalization process? Inhibitory and Language-Specific Selection mechanisms are both functional. *J. Exp. Psychol. Learn. Mem. Cogn.* 32, 1057–1074.

Crinion, J., Turner, R., Grogan, A., Hanakawa, T., Noppeney, U., Devlin, J. T., Aso, T., Urayama, S., Fukuyama, H., Stockton, K., Usui, K., Green, D. W., and Price, C. J. (2006). Language control in the bilingual brain. *Science* 312, 1537–1540.

Crone, E. A., Wendelken, C., Donohue, S. E., and Bunge, S. A. (2006). Neural evidence for dissociable components of task-switching. *Cereb. Cortex* 16, 475–486.

Duncan, J. (1986). Disorganization of behaviour after frontal-lobe damage. *Cogn. Neuropsychol.* 3, 271–290.

Forster, K. I., and Forster, J. C. (2003). A Windows display program with millisecond accuracy. *Behav. Res. Methods Instrum. Comput.* 35, 116–124.

Garbin, G., Sanjuan, A., Forn, C., Bustamante, J. C., Rodriguez-Pujadas, A., Belloch, V., Hernández, M., Costa, A., and Avila, C. (2010). Bridging language and attention: brain basis of the impact of bilingualism on cognitive control. *Neuroimage* 53, 1272–1278.

Green, D. W. (1998). Mental control of the bilingual lexico-semantic system. *Biling. Lang. Cogn.* 1, 67–81.

Green, D. W., Grogan, A., Crinion, J., Ali, N., Sutton, C., and Price, C. J. (2010). Language control and parallel recovery of language in individuals with aphasia. *Aphasiology* 24, 188–209.

Hernandez, A. E., Dapretto, M., Mazziotta, J., and Bookheimer, S. (2001). Language switching and language representation in Spanish-English bilinguals: an fMRI study. *Neuroimage* 14, 510–520.

Hernandez, A. E., Martinez, A., and Kohnert, K. (2000). In search of the language switch: an fMRI study of picture naming in Spanish-English bilinguals. *Brain Lang.* 73, 421–431.

Hernández, M., Costa, A., Fuentes, L., and Vivas, A. (2010). The impact of bilingualism on the executive control and orienting networks of attention. *Biling. Lang. Cogn.* 13, 315–325.

Hervais-Adelman, A. G., Moser-Mercer, B., and Golestani, N. (2011). Executive control of language in the bilingual brain: integrating the evidence from neuroimaging to neuropsychology. *Front. Psychol.* 2:234. doi:10.3389/fpsyg.2011.00234

Koch, I. (2001). Automatic and intentional activation of task sets. *J. Exp. Psychol. Learn. Mem. Cogn.* 27, 1474–1486.

Koch, I., Gade, M., Schuch, S., and Philipp, A. M. (2010). The role of inhibition in task switching: a review. *Psychon. Bull. Rev.* 17, 1–14.

Mariën, P., Abutalebi, J., Engelborghs, S., and De Deyn, P. P. (2005). Pathophysiology of language switching and mixing in an early bilingual child with subcortical aphasia. *Neurocase* 11, 385–398.

Martin, C. D., Barceló, F., Hernández, M., and Costa, A. (2011). The time course of the asymmetrical "local" switch cost: evidence from event-related potentials. *Biol. Psychol.* 86, 210–218.

Mayr, U., and Kliegl, R. (2000). Task-set switching and long-term memory retrieval. *J. Exp. Psychol. Learn. Mem. Cogn.* 26, 1124–1140.

Meiran, N. (1996). Reconfiguration of processing mode to task performance. *J. Exp. Psychol. Learn. Mem. Cogn.* 22, 1423–1442.

Meuter, R. F. I., and Allport, A. (1999). Bilingual language switching in naming: asymmetrical costs of language selection. *J. Mem. Lang.* 40, 25–40.

Meyer, D. E., and Kieras, D. E. (1997). EPIC – a computational theory of executive cognitive processes and multiple-task performance: part 1. Basic mechanisms. *Psychol. Rev.* 104, 3–65.

Monsell, S. (2003). Task switching. *Trends Cogn. Sci. (Regul. Ed.)* 7, 134–140.

Nagahama, Y., Okada, T., Katsumi, Y., Hayashi, T., Yamauchi, H., Oyanagi, C., Konishi, J., Fukuyama, H., and Shibasaki, H. (2001). Dissociable mechanisms of attentional control within the human prefrontal cortex. *Cereb. Cortex* 11, 85–92.

Norman, D. A., and Shallice, T. (1986). "Attention to action: willed and automatic control of behavior," in *Consciousness and Self-Regulation*, Vol. 4, eds R. J. Davidson, G. E. Schwartz, and D. Shapiro (New York: Plenum), 1–18.

Price, C. J., Green, D. W., and Von Studnitz, R. (1999). A functional imaging study of translation and language switching. *Brain* 122, 2221–2235.

Prior, A., and Gollan, T. H. (2011). Good language-switchers are good task-switchers: evidence from Spanish-English and Mandarin-English bilinguals. *J. Int. Neuropsychol. Soc.* 17, 1–10.

Prior, A., and MacWhinney, B. (2010). A bilingual advantage in task switching. *Biling. Lang. Cogn.* 13, 253–262.

Protopapas, A. (2007). Checkvocal: a program to facilitate checking the accuracy and response time of vocal responses from DMDX. *Behav. Res. Methods* 39, 859–862.

Rubinstein, J. S., Meyer, D. E., and Evans, J. E. (2001). Executive control of cognitive processes in task switching. *J. Exp. Psychol. Hum. Percept. Perform.* 27, 763–797.

Schneider, D. W., and Anderson, J. R. (2010). Asymmetric switch costs as sequential difficulty effects. *Q. J. Exp. Psychol.* 63, 1873–1894.

Snodgrass, J. G., and Vanderwart, M. (1980). A standardized set of 260 pictures: norms for name agreement, familiarity and visual complexity. *J. Exp. Psychol. Learn. Mem. Cogn.* 6, 174–215.

Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Received: 01 June 2011; accepted: 30 December 2011; published online: 13 January 2012.

*Citation: Calabria M, Hernández M, Branzi FM and Costa A (2012) Qualitative differences between bilingual language control and executive control: evidence from task-switching. Front. Psychology **2**:399. doi: 10.3389/fpsyg.2011.00399*

This article was submitted to Frontiers in Cognition, a specialty of Frontiers in Psychology.

2.6 Age-related effects over bilingual language control and executive control

Calabria M., Branzi F.M., Marne P., Hernandez M., Costa A. Age-related effects over bilingual language control and executive control. Biling (Camb Engl). 2015; 18(1):65-78. DOI: http://dx.doi.org/10.1017/S1366728913000138

Bilingualism: Language and Cognition: page 1 of 14 © Cambridge University Press 2013 doi:10.1017/S1366728913000138

Age-related effects over bilingual language control and executive control*

MARCO CALABRIA
Center for Brain and Cognition, Universitat Pompeu Fabra, Spain
FRANCESCA M. BRANZI
Center for Brain and Cognition, Universitat Pompeu Fabra, Spain
PAULA MARNE
Center for Brain and Cognition, Universitat Pompeu Fabra, Spain
MIREIA HERNÁNDEZ
Center for Brain and Cognition, Universitat Pompeu Fabra, Spain & Cognitive Neuropsychology Laboratory, Department of Psychology, Harvard University, Cambridge, MA, USA
ALBERT COSTA
Center for Brain and Cognition, Universitat Pompeu Fabra, Spain & Institució Catalana de Recerca i Estudis Avançats, Spain

(Received: July 25, 2012; final revision received: March 7, 2013; accepted: March 13, 2013)

The aim of the present study is two-fold. First, we investigate age-related changes to bilingual language control (bLC) mechanisms across lifespan. Second, we explore the relation between bLC mechanisms and those of the domain-general executive (EC) system by looking at age effects on these two systems. To do so, we compare the performances of the three age groups of bilinguals (young, middle-aged and elderly) in a language switching task to those of non-linguistic switching task. We found an age-related change in the non-linguistic switch cost but not in the language switch cost. Moreover, we did not find any correlation between the magnitudes of the switch costs. Taken together these results indicate that bLC is not affected by age as the EC system is, and interestingly, we add new evidence that the bLC mechanisms are not fully subsidiary to those of the domain-general EC system.

Keywords: bilingualism, aging, executive control, bilingual language control

1. Introduction

Language production is the set of processes that allows individuals to translate thoughts into speech. These processes include the selection of a concept to be expressed, the lexical retrieval of the words and their morphological properties, and the planning and the monitoring of the articulatory aspects of the speech output. Although unimpaired individuals appear to conduct all these processes effortlessly and with high reliability, it requires the participation of executive control (EC) processes (Roelofs & Piai, 2011; Strijkers, Holcomb & Costa, 2011; Ye & Zhou, 2009). Hence, the domain-general EC system is constantly interacting with the language production system to guarantee successful communication. A particular instance in which this interaction becomes very apparent is that of bilingual speech production, since bilingual speakers, beyond mastering all the processes involved in lexicalization, also have to learn how to prevent cross-language interference. That is, bilinguals need not only to select the language in which they want to conduct verbalization (according to the communicative setting), but they also need to avoid the potential interference from the irrelevant language. Furthermore, on some occasions bilinguals have to switch between the two languages according to the given interlocutor. The cognitive processes involved in this ability are usually referred to as bilingual language control

---

* This work was supported by grants from the Spanish government (PSI2008-01191, PSI2011-23033, Consolider Ingenio 2010 CSD2007-00012, IMSERSO 48/2010) and the Catalan government (Consolidat SGR 2009-1521). Marco Calabria was supported by a postdoctoral fellowship from the Spanish Government (Juan de la Cierva fellowship). Francesca M. Branzi was supported by a predoctoral fellowship from the Spanish Government (FPU-2009-2013). This research was also supported by a Marie Curie International Outgoing Fellowship within the 7th European Community Framework Programme awarded to Mireia Hernández. We thank three anonymous reviewers for their comments.

Address for correspondence:
Albert Costa, Departament de Tecnologies de la Informació i les Comunicacions, Universitat Pompeu Fabra, C/ Tanger, 122-140, 08014-Barcelona, Spain
costalbert@gmail.com

(bLC) (e.g., Abutalebi & Green, 2007; Green, 1986, 1998; Soveri, Rodriguez-Fornells & Laine, 2011). The goal of the present investigation is to explore whether and how bLC is affected by aging. To do so, we compare the performance of three age groups of bilingual speakers (young, middle-aged and elderly) on a typical bLC task called the language switching task.

Most of the current evidence regarding bLC comes almost exclusively from studies in which young university students have been tested (Calabria, Hernandez, Branzi & Costa, 2011; Costa & Santesteban, 2004; Costa, Santesteban & Ivanova, 2006; Garbin, Costa, Sanjuan, Forn, Rodriguez-Pujadas, Ventura, Belloch, Hernandez & Ávila, 2011; Hernandez, Dapretto, Mazziotta & Bookheimer, 2001; Hervais-Adelman, Moser-Mercer & Golestani, 2011; Magezi, Khateb, Mouthon, Spierer & Annoni, 2012). To date, the few studies that have investigated the effects of aging on the functioning of the bLC have shown moderate effects. For instance, Gollan, Sandoval and Salmon (2011) showed that the number of cross-language intrusions during verbal fluency tasks increases little with age. Moreover, Weissberger, Wierenga, Bondi and Gollan (2012) showed a complex pattern of switching costs in which some of such costs were affected by aging and others were not. For example, while language mixing costs were relatively unaffected by aging, local-switch costs were affected. Thus, the current evidence is not sufficient to argue in favour of detrimental effects of aging on bLC.

Furthermore, there are also reasons to suspect age-related changes over bLC. First, to the extent that bLC depends on the efficient functioning of the EC system, one might expect that the decline of the EC system associated with aging (Greenwood, 2000; Rhodes, 2004; Tisserand & Jolles, 2003; Verhaeghen & Cerella, 2002; Verhaeghen, Steitz, Sliwinski & Cerella, 2003; Wasylyshyn, Verhaeghen & Sliwinski, 2011) affects the functionality of the bLC system as well. Indeed, some authors have proposed that some of the age-related changes in language production are due to defective functioning of EC mechanisms, such as the weakness of the inhibitory control and/or the reduction of working memory abilities. Second, it has been reported that aging affects a bilingual's performance in language production tasks. For example, Bialystok, Craik and Luk (2008) reported that bilingual elderly adults compared to young bilinguals have deficits in lexical access when tested in a verbal fluency task. Gollan et al. (2011) also found an increase in cross-language intrusions (e.g., an English word when speaking Spanish) in elderly bilinguals in verbal fluency. These results suggest that there are age-related changes in bilingual language production that are probably due to a loss in efficiency of bLC.

The available evidence for the age effects of bLC comes from language switching studies (Gollan & Ferreira, 2009; Hernandez & Khonert, 1999; Weissberger et al., 2012). A typical example of this task is the following: participants are required to name a series of pictures in different language conditions and the language to use in each trial is cued. There are two kinds of trials: those in which, in a given trial and in the immediately preceding trial, the naming language does not change (repeat trials), and those in which the language changes from one trial to the successive one (switch trials). Participants are slower and less accurate on switch trials than repeat trials, thus the difference in reaction times between these two types of trials is named language switch cost. Two main findings have been reported in this context (Gollan & Ferreira, 2009; Hernandez & Khonert, 1999; Weissberger et al., 2012): (i) elderly bilinguals are overall slower and more error-prone than young bilinguals; (ii) there is an age-related increase in the magnitude of switch costs.

In the present study we further explore the age-related changes on bLC across the lifespan using language switching in Catalan–Spanish bilinguals of three age groups: young, middle-aged and elderly adults.

A second goal of this article is to advance our knowledge of how the bLC relates to the domain-general EC system. Although at present few can deny that these two systems interact (for reviews, see Abutalebi & Green, 2007; Hervais-Adelman et al., 2011) we are far from understanding in which way they do so. Perhaps one way to gain more knowledge on this issue is to address whether the performances in linguistic and non-linguistic switching tasks suffer from a similar decline due to aging. To assess this issue, in the present study we also test the three age groups of participants in a non-linguistic switching task, in which bilinguals are cued to judge a series of pictures according to two sorting criteria based on their colour or their shape. Next, we discuss a series of studies that are relevant in this context.

In a recent article, Prior and Gollan (2011) assessed the relationship between the EC and bLC by testing bilinguals and monolinguals using a non-linguistic switching task and bilinguals in a language switching task. Interestingly, the group of bilinguals that reported switching languages frequently showed a smaller language switch cost than the group of bilinguals that claimed not to switch languages so frequently. Furthermore, those that switched often showed a smaller switch cost in the non-linguistic task as compared to the monolinguals, suggesting a link between bLC and EC system.

Somewhat in contrast with these observations, Calabria et al. (2011) failed to observe a correlation between the magnitude of switch costs observed in language switching and in non-linguistic switching tasks. The results revealed that the two types of switch cost were uncorrelated, suggesting that the bLC mechanisms are not fully subsidiary to those of the domain-general EC system.

A recent study by Weissberger et al. (2012) has addressed the issue of the cross-talk between the bLC and EC system by studying the performance of elderly bilinguals. Weissberger et al. (2012) observed an age-related increase in the magnitude of the language switch cost, that is, the magnitude of the switch cost was smaller for younger than elderly bilinguals. Interestingly, however, the performance in the non-linguistic switch task was much less affected by aging, showing significant effects only for error rates. This pattern was interpreted as revealing differential effects of aging on the bLC and EC systems.[1]

1.1 The present study

The aim of the present study is two-fold: first, to further explore to what extent and how bLC is affected by aging, and second, to assess the interaction of the bLC and EC mechanisms across the lifespan.

To achieve these goals, sixty Catalan–Spanish highly-proficient bilinguals of three age groups (young, middle-aged and elderly) were tested in a language switching task and in a non-linguistic switching task (sorting by colour and shape) (see Calabria et al., 2011). We pay attention to both the quantitative and qualitative aspects of the switch costs. Quantitatively, we assess the presence of correlations between the two tasks in terms of overall speed and in terms of the magnitude of the switch costs, paying special attention to how these magnitudes are affected by aging. The qualitative analysis assesses whether the pattern of switch costs in the two tasks is affected by aging. Here, it is not so much important whether the two tasks elicit the same pattern of switching costs, but rather whether such a pattern is affected by aging in both tasks.

The asymmetry of the switch costs is defined as the degree to which the magnitude of the costs to switch between two tasks is similar. One variable that affects switch cost is, for example, the relative difficulty of the two tasks at hand during the experiment (e.g., Calabria et al., 2011; Martin, Barcelo, Hernandez & Costa, 2011). For instance, the switching costs tend to be larger when switching into the easier task than when switching into the more difficult one (for theoretical explanation see the review by Koch, Gade, Schuch & Philipp, 2010). Similarly, when the task switching involves two languages, low-proficient bilinguals show asymmetrical switch costs (i.e., larger switch-costs when switching into the easier language) which parallel the pattern of the non-linguistic task-switching paradigms. That is, for low-proficient bilinguals switching into the less proficient (and hence, the more difficult task) language (L2) is easier (in terms of RTs and errors) than switching into the more proficient (and hence, the easier task) language (L1) (e.g., Meuter & Allport, 1999). This linguistic asymmetrical switch cost can be explained in the same manner as domain-general asymmetrical switching costs. In fact, Meuter and Allport (1999) argued that the magnitude of the inhibition applied to two languages is dependent on the relative strength of the two languages. Therefore, when the less proficient L2 needs to be produced, the more proficient L1 needs to be inhibited more than the other way around. Thus, an asymmetrical switch cost arises because the amount of inhibition that needs to be overcome during the switch into L1 is larger than when switching into L2. However, several studies conducted with highly-proficient bilinguals revealed no asymmetrical language switching costs. That is, when highly-proficient bilinguals are asked to switch between their two proficient languages (hence little difference in difficulty between the two tasks), the switching costs are comparable in both directions (from L1 to L2 and vice versa) (Calabria et al., 2011; Costa & Santesteban, 2004; Costa et al., 2006).

Interestingly, this pattern of switching costs in highly-proficient bilinguals is restricted to the linguistic domain. In a previous study, we found symmetrical switching costs for highly-proficient young bilinguals when switching between languages, and asymmetrical switching costs when they switched from colour to shape, that is, in a non-linguistic switching task (Calabria et al., 2011). What is important in the present context is whether these different patterns of switching costs would vary across the life span. That is, whether the linguistic switching symmetry and the non-linguistic switching asymmetry would be affected by aging.

To recapitulate, we examine the issue of the integrity of bLC and its relation with the EC system in several ways.

First, we will evaluate the integrity of bLC by looking at the speed of processing, the accuracy and the magnitude of the language switch costs in the three age groups. For instance, a slowing of the reaction times, an increase in errors and the switch costs across groups would indicate age-related changes over bLC. Moreover, we will also look at the qualitative aspect of the language switch cost, such as the symmetry, in the three age groups of bilinguals as an index of the efficiency of bLC functioning.

---

[1] To some extent, Gollan et al. (2011) reported a similar result by comparing the age-related effects in verbal fluency task and in an EC task (flanker task). Gollan et al. (2011) took the cross-language intrusions as a measure of the defective functioning of the bLC and the magnitude of the conflict effect as a measure of the efficiency of the EC system. Then, the authors correlated the two measures in elderly English–Spanish bilinguals and actually they found a positive correlation. However, the few number of cross-language intrusions (about 1%) experienced by elderly people suggested that language control in bilinguals is not affected with the same severity by aging as the domain-general EC system is. Consequently, this unequal decline of bLC and EC systems led the authors to conclude that the overlapping of bLC and EC mechanisms is to some extent partial.

Table 1. *Participant characteristics for the three age groups.*

	Young		Middle-aged		Elderly	
	Mean	SD	Mean	SD	Mean	SD
Age	21.8	2.2	45.7	5.1	70.5	4.0
Education	16.5	2.5	18.6	2.6	15.1	2.4
Age of L2 acquisition	1.7	2.1	1.8	2.0	1.1	1.9
Self-rating						
Catalan						
Comprehension	4.0	0.0	4.0	0.0	4.0	0.0
Speaking	4.0	0.0	4.0	0.0	4.0	0.0
Pronunciation	3.9	0.4	4.0	0.0	4.0	0.0
Writing	4.0	0.0	3.6	0.5	2.0	1.5
Reading	4.0	0.0	4.0	0.0	3.1	1.1
Spanish						
Comprehension	4.0	0.0	4.0	0.0	4.0	0.0
Speaking	3.9	0.3	4.0	0.0	3.7	0.4
Pronunciation	4.0	0.0	4.0	0.0	3.8	0.3
Writing	3.9	0.3	3.8	0.4	3.6	1.6
Reading	4.0	0.0	4.0	0.0	4.0	0.0

Second, to explore the relationship between bLC and EC, we will examine:

(a) From a quantitative point of view, the magnitude of linguistic and non-linguistic switch costs and any potential correlations between the two switch costs. A similar age-related increase in the switch costs and significant correlations between switch costs in linguistic and non-linguistic switching tasks would suggest similar age-related effects, and to some extent, demonstrate that the bLC mechanisms are fully subsidiary to those of the EC system.

(b) From a qualitative point of view, we examine the pattern of switch costs in terms of the symmetry/asymmetry within the linguistic and non-linguistic switching tasks across three age groups. The presence of similar age-related changes in the pattern of switch costs in both tasks would suggest that the mechanisms of bLC are completely subsidiary to the EC system.

2. Methods

2.1 Participants

Sixty bilinguals took part in the experiment. All participants were early and highly-proficient Catalan–Spanish bilinguals with Catalan as L1, having learned Spanish before the age of six. Their proficiency in the two languages was tested by means of a questionnaire at the end of the experiment. Each participant self-rated on a four-point scale the abilities of speaking, pronunciation, comprehension, writing and reading for each language (1 = poor, 2 = regular, 3 = good, 4 = perfect).

The whole sample of participants was divided into three age groups, such as: young (n = 20; mean age = 21.8 years, range = 19–27 years), middle-aged (n = 20; mean age = 45.7, range = 38–53), and elderly bilinguals (n = 20, mean age = 70.5, range = 62–77). The characteristics of the three age groups of participants (age, education, age of acquisition of L2, and language proficiency) are reported in the Table 1.

2.2 Materials and procedure

The experiment was conducted in a soundproof room. Participants performed the linguistic and non-linguistic versions of the tasks in the same session. The experiments were controlled by the software DMDX (Forster & Forster, 2003), which recorded participants' vocal and manual responses. Responses were analysed offline and naming latencies were measured from the onset of the word through Checkvocal, a data analysis program for naming tasks in DMDX (Protopapas, 2007). The order of the two tasks was counterbalanced across participants, meaning that half of the participants started with the language switching task and the other half with the non-linguistic switching task. Each experiment started with a practice session of 80 trials.

Linguistic switching task

Eight pictures of objects were selected from Snodgrass and Vanderwart (1980). Half of them referred to cognate words (Spanish/Catalan names: *Caracol*/*Cargol* (in English, “snail”); *Escoba*/*Escombra* (“broom”); *Martillo*/*Martell* (“hammer”); *Reloj*/*Rellotge* (“watch”)), and the other half to non-cognate words (*Calcetín*/*Mitjó* (“sock”); *Manzana*/*Poma* (“apple”); *Silla*/*Cadira* (“chair”); *Tenedor*/*Forquilla* (“fork”)). Note that in all analyses the two categories were collapsed since there was no difference between cognate and non-cognate words.

Participants were required to name the picture in Catalan or in Spanish. A Catalan or Spanish flag, which was presented along with the picture, acted as a cue to indicate in which language subjects had to name the picture.

There were two types of trials: (i) those in which participants were required to name the picture in the same language as the preceding trial (repeat trial), and (ii) those in which participants were required to name in the other language with respect to the previous trial (switch trial). There were a total of 320 trials divided in two blocks with 160 trials each. The total distribution of trials was: 128 repeat trials in Catalan, 128 repeat trials in Spanish, 32 switch trials in Catalan and 32 in Spanish.

Participants were asked to name the picture as fast as possible and they were informed that the language to be used was to be indicated by a flag, presented on the top of the picture. The pictures were presented in a series of between three and seven trials and at the end of each series an asterisk appeared, and the participants pressed the spacebar to start the next series. At the beginning of each series a word cue was presented for 1000 ms indicating in which language participants had to start to name in (CATALÀ, for Catalan; ESPAÑOL, for Spanish) and for the other trials of the series the cue appeared along with the picture to name. The picture appeared for 1700 ms and the timeout to respond was 5000 ms.

Non-linguistic switching task

Three shapes (square, circle, and triangle) and three colours (green, blue, and red) were selected for the task. The three shapes were combined with the three colours, resulting in a total of nine coloured shapes (e.g., green square, blue square etc.). Participants were presented with an array containing three shapes, two at the top of the screen and one at the bottom. They were instructed to match the shape at the bottom with one of the two at the top of the display according to two possible criteria (shape or colour). The criterion was indicated by a cue (COLOR, for Colour; FORMA, for Shape) appearing in the centre of the array. As in the linguistic version of the task, there were two types of trials: repeat and switch trials.

At the beginning of each series a word cue was presented for 1000 ms indicating by which rule participants must start matching each item (COLOR, for Colour; FORMA, for Shape). Then the array appeared for 2500 ms and the timeout to respond was 3000 ms.

Participants gave the response by pressing one of the two keys, M or V, according to the position of the matched picture at the top of the array. Specifically, they had to press the M key when the correct answer was at the top-right part of the array and the V key when the correct response was at the top-left part of the array.

3. Results

First, we analysed the data for RTs and accuracy (percentage of correct responses). RTs exceeding three standard deviations above or below a given participant’s mean were excluded from the analyses. Second, we performed a distributional analysis of the RTs by fitting the data to an ex-Gaussian distribution. All the details of this second analysis are reported below.

3.1 Omnibus ANOVA

We first ran an omnibus ANOVA on RTs including the following variables: “type of trial” (switch vs. repeat) and “task version” (linguistic vs. non-linguistic) as within-subject variables and “group” (young, middle-aged and elderly) as between-subject factor.

All main effects were significant, that is “task version” (F(1,57) = 11.21, MSE = 21084.52, $p = .001$, $\eta p^2 = .16$), “type of trial” (F(1,57) = 230.27, MSE = 1651.42, $p < .0001$, $\eta p^2 = .80$) and “group” (F(1,57) = 14.26, MSE = 55519.71, $p < .0001$, $\eta p^2 = .33$). The interaction between “type of trial” and “group” was marginally significant (F(1,57) = 2.49, MSE = 1651.42, $p = .09$, $\eta p^2 = .09$).

Importantly, the interaction between “task version” and “group” was significant (F(1,57) = 8.69, MSE = 21084.52, $p = .001$, $\eta p^2 = .23$), revealing that the performance in the two tasks was affected differently by age (see Table 2). To further explore how age affected the switching tasks differently, the results from the linguistic and the non-linguistic switching task were further analysed separately.

3.2 Linguistic switching task

The variables considered in the analyses were “type of trial” (switch vs. repeat) and “response language” (L1 vs. L2) as within-subject factors and “group” (young, middle-aged and elderly) as between-subject factor which were included in a repeated-measure ANOVA on naming latencies and accuracy.

Table 2. *Mean RTs and SEs of the linguistic and non-linguistic switching tasks broken down by conditions and age groups.*

		L1		L2	
		Mean	SE	Mean	SE
Young	Repeat	822	21.6	837	20.0
	Switch	902	22.5	912	22.7
Middle-aged	Repeat	877	21.6	914	20.0
	Switch	961	22.5	974	22.7
Elderly	Repeat	939	21.6	927	20.0
	Switch	1016	22.5	1010	22.7
		Colour		**Shape**	
		Mean	SE	Mean	SE
Young	Repeat	749	36.7	873	39.1
	Switch	866	42.4	895	43.1
Middle-aged	Repeat	878	36.8	1008	39.1
	Switch	971	43.4	1049	43.1
Elderly	Repeat	992	36.8	1174	39.1
	Switch	1138	42.4	1253	43.1

Reaction times

The main effect of "group" was significant (F(1,57) = 6.77, MSE = 32742.16, p = .002, ηp^2 = .19). Post-hoc analysis revealed significant differences only between young participants and the other two groups (all ps < .03). The main effect of "type of trial" was significant (F(1,57) = 167.21, MSE = 2083.70, p <.0001, $\eta p^2 = .75$) indicating that participants responded slower to switch trials (962 ms) than to repeat trials (886 ms). The main effect of "response language" was not significant (F(1,57) = 2.93, MSE = 1803.18, p = .10). The interaction between "group" and "response language" was also significant (F(1,57) = 3.22, MSE = 1803.18, p = .05, $\eta p^2 = .11$), indicating that the difference between the latencies in the two languages were only present for the middle-aged group.

Interestingly, no other interactions were significant. First, in quantitative terms, this means that the magnitude of the linguistic switch cost is not modulated by age. Indeed, as it can be appreciated in Figure 1, the magnitude of the switch costs was very similar for all three groups, and far from ceiling or floor effects. Second, qualitatively, we can conclude that the pattern of switch costs is not affected by age, since it appears to be symmetrical across all ages. That is, switching from L1 into L2 and vice versa has the same cost irrespective of the age of the bilingual speakers.

These conclusions are further supported by a regression analysis in which age and age of L2 acquisition

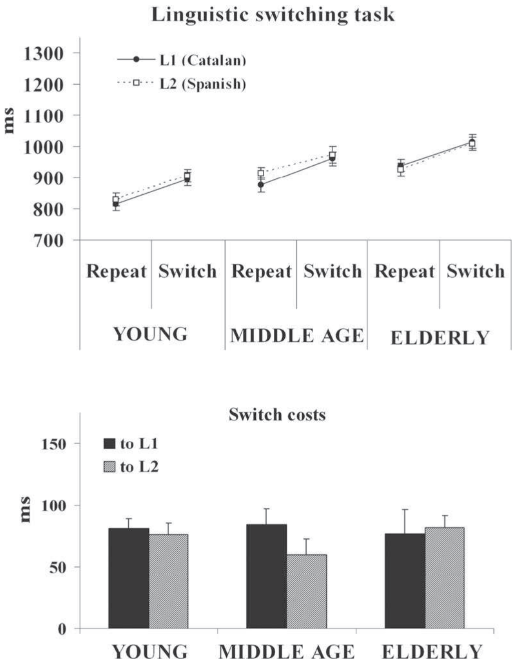


Figure 1. Performances on the linguistic switching task for the three age groups of participants. Error bars represent standard errors.

are taken into account. In this analysis the magnitude of the linguistic switch costs (in L1 and L2, separately, and also with collapsing both costs) was not modulated by these two variables, regardless of whether the fit was linear (all ps > .41), logarithmic (all ps > .91) or quadratic (all ps > .68).

Accuracy
There was no effect of age in accuracy ("group": F(2,57) = 1.89, MSE = 11.37, $p = .16$). Participants were less accurate in switch trials (95.9%) than repeat trials (97.2%) ("type of trial": F(1,57) = 9.18, MSE = 11.17, $p = .004$; $\eta p^2 = .14$). No interaction was statistically significant.

3.3 Non-linguistic switching task

The results of this task were submitted basically to the same analysis as in the previous task. The variables considered in the analysis were "group" as a between-subject factor, "type of trial" (switch vs. repeat) and "sorting criterion" (colour and form), which were included as a within-subject factor in a repeated-measure ANOVA using RTs and accuracy as dependent variables.

Reaction times
The main effect of "group" was significant (F(1,57) = 14.34, MSE = 120466.30, $p < .001$, $\eta p^2 = .34$) (see Figure 2). Post-hoc analysis showed that the young group was the faster one and the elderly group the slower one, and the middle-aged group in the middle of the other two groups (all ps < .02).

Overall, participants were faster to sort by colour (932 ms) than by shape (1042 ms) (F(1,57) = 167.21, MSE = 2083.70, $p < .0001$, $\eta p^2 = .75$), and faster to respond in repeat trials (945 ms) compared to switch trials (1028 ms) (F(1,57) = 94.72, MSE = 4354.45, $p < .0001$, $\eta p^2 = .79$). Moreover, the interaction between "sorting criterion" and "type of trial" was significant (F(1,57) = 28.95, MSE = 2665.73, $p < .0001$, $\eta p^2 = .34$), meaning that the switch cost interacted with criterion. That is, participants showed higher costs when they switched from shape to colour (118 ms) (F(1,59) = 101.23, MSE = 4183.64, $p < .0001$, $\eta p^2 = .63$), than when they switched from colour to shape (47 ms) (F(1,59) = 21.49, MSE = 3111.93, $p < .0001$, $\eta p^2 = .27$).

Finally, the non-linguistic switch cost interacted with the main effect of "group" (interaction between "type of trial" and "group" : F(2,59) = 2.99, MSE = 4354.45, $p = .05$, $\eta p^2 = 0.10$), being significantly higher in the elderly group (112 ms) compared to the other two age groups (young = 69 ms and middle-aged = 68 ms).

The analysis performed here was the same as the analysis for the language switching task when age and age of L2 acquisition are taken into account as continuous variables. In this case, participants' age, but not age of L2 acquisition (all ps > .42), accounted for a significant amount of the variance associated with switching cost for shape ($R^2 = .13$, B = 1.42, $p = .004$), and combined cost ($R^2 = .11$, B = 1.13, $p = .009$), but not for the cost for colour ($p = .25$). Interestingly, the effect of age on the combined non-linguistic cost was also present when the data were modelled as logarithmic ($p = .02$) and quadratic ($p = .005$), confirming the effect of age on the non-linguistic switch cost.

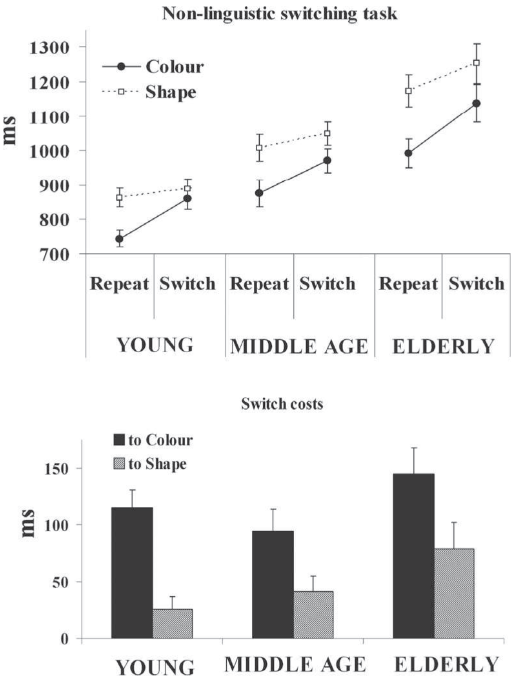


Figure 2. Performances on the non-linguistic switching task for the three age groups of participants. Error bars represent standard errors.

Accuracy
There was no effect of age in accuracy ("group": (F(2,57) = 0.61, MSE = 18.93, $p = .55$). Participants were less accurate in switch trials (89.9%) than repeat trials (93.2%) ("type of trial": F(1,57) = 56.87, MSE = 12.14, $p < .0001$) and they were less accurate in sorting by shape (90.6%) than by colour (92.5%) (F(1,57) = 10.22, MSE = 20.84, $p = .002$, $\eta p^2 = .15$). Also, the interaction between "sorting criterion" and "type of trial" was significant (F(1,57) = 32.80, MSE = 16.22, $p < .0001$, $\eta p^2 = .36$), revealing that the difference in accuracy between repeat and switch trials was only significant when sorting by colour ($p < .0001$) but not by shape ($p > .05$).

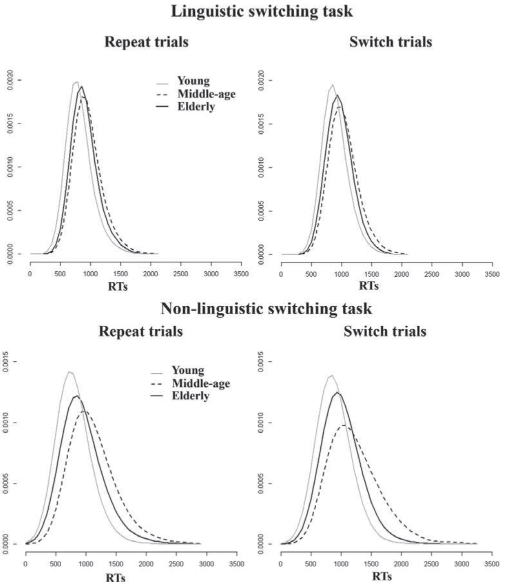


Figure 3. RT distributions of repeat and switch trials broken by age groups and task versions.

3.4 *Ex-Gaussian analysis*

In the present section we present the distribution analysis we performed on the data. These analyses provide a more detailed description of the differences in performance between groups and task, and could potentially help address the effects of aging over the bLC and the EC system. A quick look at the distributions (see Figure 3) gives an overall impression of the differences between groups. Firstly, for the linguistic task there are differences on overall RTs both for switch and repeat trials. However, the general shapes of the distributions are very similar across groups. Secondly, for the non-linguistic task, one can appreciate also differences in RTs for switch and repeat trials. Interestingly, however, for the switch trials one can see that the tail of the distribution for the elderly group is more pronounced. In other words, very long RTs contribute considerably to the overall switch cost for this group.

To assess whether this visual impression is statistically meaningful, we performed a distributional analysis fitting the data to an ex-Gaussian distribution. This fitting decomposes the overall RT distribution into two distributions, the normal and the exponential one. The normal distribution is characterized by two parameters, such as mu (μ) and sigma (σ). μ is the mean of the fitted normal distribution, and σ corresponds to the variance. The exponential distribution corresponds to the tail of the RT distribution, and it is characterized by the parameter tau (τ). The question here is whether the differences between the groups in the magnitude of the switching costs (both linguistic and non-linguistic) are captured by the normal component of the RT distribution or by the exponential one. This is important since according to some authors the cognitive processes behind differences in these components might be different (see Discussion).

The raw data was sorted by type of trial (switch and repeat) and by age group (young, middle-aged and elderly) and separately for the two tasks. The parameters of the ex-Gaussian distribution (μ and τ) were obtained for each participant using the quantile maximum likelihood (QML) estimation procedure in QMPE 2.18 (Cousineau, Brown & Heathcote, 2004). The estimation results into a value for each parameter (μ and τ) and for each participant per condition.

We then ran repeated-measures ANOVAs separately for μ and τ, separately for each task.

Linguistic switching task

The variables considered in the analyses were "type of trial" (switch vs. repeat) and "response language" (L1 and L2) as within-subject factors and "group" (young, middle-aged and elderly) as between-subject factor.

For μ, the main effect of "group" was significant (F(1,57) = 13.56, MSE = 24855.77, $p < .0001$, $\eta p^2 = .32$) and the post-hoc analysis revealed that the young group had the smaller μ values (721 ms) than the middle-aged group (811 ms, $p = .002$) and the elderly group (847 ms, $p < .0001$). In other words, the older the participants are, the slower the normal component of the RT distribution is.

Participants were slower in the switch trials (851 ms) than in the repeat trials (742 ms) ("type of trial": F(1,57) = 144.06, MSE = 5048.89, $p < .0001$, $\eta p^2 = .72$), but naming latencies for μ were not modulated by language ("response language": F(1,57) = 0.17, MSE = 3680.44, $p = .68$). Interestingly, the interaction between "type of trial" and "response language" was not significant, meaning that the linguistic switch cost was the same when switching into the L1 and the L2. Moreover, the non-significant interactions with "group" also indicate that the magnitude of the switch cost for μ was not modulated by age (see Table 3).

For τ, only the main effect of "type of trial" was significant (F(1,57) = 18.57, MSE = 4011.32, $p < .0001$, $\eta p^2 = .25$), indicating that overall the participants had smaller τ values in the switch trials (111 ms) than in the repeat trials (146 ms).

Non-linguistic switching task

The variables considered in the analysis were "group" as a between-subject factor, "type of trial" (switch vs. repeat) and "sorting criterion" (colour vs. form) as within-subject factors.

Table 3. *Means and SEs of the mu and the tau values in the linguistic (panel A) and non-linguistic (panel B) switching tasks.*

(A)

		L1		L2	
Mu values		Mean	SE	Mean	SE
Young	Repeat	664	17.5	687	17.6
	Switch	805	23.8	780	25.1
	Switch cost	141	20.6	93	18.3
Middle-aged	Repeat	747	17.5	767	17.6
	Switch	862	23.7	860	25.1
	Switch cost	115	20.7	93	18.7
Elderly	Repeat	797	17.5	788	17.6
	Switch	892	23.8	902	25.1
	Switch cost	95	20.6	114	18.9
Tau values					
Young	Repeat	158	13.9	150	13.4
	Switch	97	16.8	122	16.6
	Switch cost	−61	15.2	−28	15.2
Middle-aged	Repeat	130	14.0	157	13.4
	Switch	99	16.7	114	16.6
	Switch cost	−31	15.5	−43	15.4
Elderly	Repeat	142	14.0	139	13.4
	Switch	124	16.8	108	16.6
	Switch cost	−18	15.4	−31	15.3

(B)

		Colour		Shape	
Mu values		Mean	SE	Mean	SE
Young	Repeat	565	24.9	701	29.2
	Switch	761	42.1	736	36.6
	Switch cost	196	32.9	47	32.3
Middle-aged	Repeat	644	24.8	796	29.2
	Switch	784	42.0	817	36.8
	Switch cost	140	32.8	21	32.4
Elderly	Repeat	781	24.9	968	29.2
	Switch	934	42.2	996	36.8
	Switch cost	153	33.1	28	32.6
Tau values					
Young	Repeat	183	18.8	172	21.5
	Switch	105	23.4	159	22.9
	Switch cost	−78	21.0	−13	22.3
Middle-aged	Repeat	234	18.9	222	21.6
	Switch	187	23.4	232	23.0
	Switch cost	−48	21.1	10	22.6
Elderly	Repeat	211	18.9	206	21.5
	Switch	204	23.6	257	23.0
	Switch cost	−7	21.3	51	22.4

For μ, the main effect of "group" was significant (F(1,57) = 16.99, MSE = 67932.97, $p < .0001$, $\eta p^2 = .73$), indicating that the elderly group had higher μ values (920 ms) than the middle-aged group (761 ms, $p = .001$) and the young group (691 ms, $p < .0001$). Overall the participants were slower in the switch trials (838 ms) than in the repeat trial (742 ms) ("type of trial": F(1,57) = 58.33, MSE = 10686.94, $p < .0001$, $\eta p^2 = .51$), and slower when they matched for shape (836 ms) than for colour (745 ms) ("sorting criterion": F(1,57) = 65.93, MSE = 8400.26, $p < .0001$, $\eta p^2 = .54$). Moreover, the interaction between "type of trial" and "sorting criterion" was also significant (F(1,57) = 50.11, MSE = 4519.96, $p < .0001$, $\eta p^2 = .47$), indicating that the non-linguistic switch cost for μ was asymmetrical. However, the non-significant interactions with group indicate than for μ the magnitude of the switch cost was not affected by age.

For τ, the main effect of "group" was significant (F(1,57) = 5.66, MSE = 19631.93, $p = .006$, $\eta p^2 = .16$) and post-hoc analysis revealed that the young group had smaller τ values (154 ms) than the middle-aged group (218 ms, $p = .01$) and the elderly group (219 ms, $p = .01$). Participants were slower to match for shape (208 ms) than for colour (187 ms) ("sorting criterion": F(1,57) = 4.16, MSE = 6021.14, $p = .05$, $\eta p^2 = .07$), whereas there was not any effect of "type of trial" (F(1,57) = 1.73, MSE = 6966.63, $p = 0.19$). However, the interaction between "type of trial" and "sorting criterion" was significant (F(1,57) = 10.34, MSE = 5270.70, $p = .002$, $\eta p^2 = .15$), suggesting that the non-linguistic switch cost was asymmetrical. Finally, the non-linguistic switch cost was modulated by age (interaction between "type of trial" and "group": F(1,57) = 3.31, MSE = 6966.63, $p = .04$, $\eta p^2 = .10$). To further explore this interaction we submitted the τ values for the switch cost to a one-way ANOVA with group as between-subject factor. Indeed, we found that only the young group had smaller τ values (–45 ms) than the elderly group (22 ms, $p = .01$).

3.4 *On the correlation between the two tasks*

In the present set of analysis, we further explore the potential relationship between age and the switching costs in the two tasks.

The first relevant observation is that overall speed in both switching tasks is correlated with age; namely the older the participant is the slower he/she performs the linguistic task (r = .46, $p < .001$) and the non-linguistic task (r = .58, $p < .001$) (see Figure 4A). However, while the magnitude of the non-linguistic switch cost positively correlated with age (r = .29, $p = .03$) (see Figure 4B), the magnitude of the language switch cost did not (r = .03, $p = .80$).

Additionally, we used a correlation analysis to compare the magnitude of the switch costs between the linguistic and non-linguistic switching tasks. In fact, if we assume that the switch cost reflects to some extent the efficiency of the bLC and EC in the same way, we may expect that the magnitude of the two switch costs (linguistic and non-linguistic) varies in the same manner in participants. To do so, we correlated the total switch cost between the linguistic task and the non-linguistic task (collapsing language in one case and the sorting criteria in the other case) for each age group. We first ran the correlation separately for each group because of the difference in the variability of the switch cost across groups, especially in the elderly group. The correlations between the two switch costs were not significant in any age group (young: r = −.12, $p = .61$; middle-aged: r = −.21, $p = .35$, elderly: r = .22, $p = .34$).

In order to gain more statistical power we ran the analysis with all the participants resulting in a total number of 60. The switch costs of the two tasks were not significantly correlated (r = .04, $p = .75$) (see Figure 5).

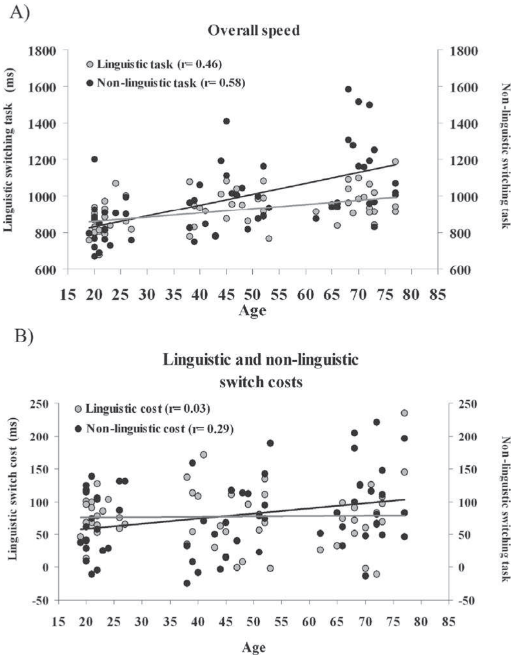


Figure 4. Correlation of individuals' performances on overall speed (panel A) and switch costs (panel B) as a function of age of participants.

4 Discussion and conclusion

The main goal of the present study was to investigate the age-related changes of bLC. To do so we compared

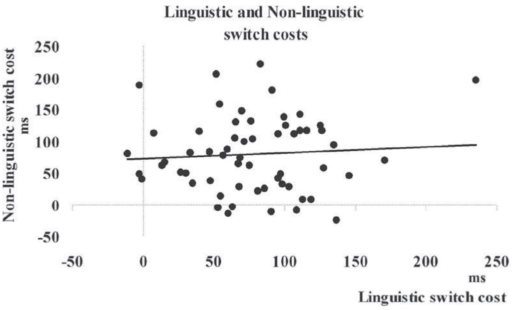


Figure 5. Correlation of individuals' performances between the linguistic and non-linguistic switching tasks.

the performances of three age groups of Catalan–Spanish highly-proficient bilinguals in the language switching task. The results show several interesting findings.

First, we found an age-related effect on the overall speed of processing for elderly adults when compared to young adults, probably suggesting a general effect of aging on cognition. However, when we looked at the language switching cost, we did not find any difference in the magnitude of such a cost among the three age groups. Indeed, the age of the participants was not correlated with the magnitude of the language switch cost. Moreover, the distributional analysis confirmed that the magnitude of the language switch cost was not affected by age in neither the exponential nor normal components. This is an interesting result because it suggests that the language control abilities of bilinguals are, to some extent, protected against the cognitive decline associated with aging.

Second, the pattern of the language switch cost was symmetrical for the three age groups. As highlighted in the Introduction, highly-proficient bilinguals generally show a symmetrical language switch cost, that is the same cost when switching from L1 into L2 and vice versa (Calabria et al., 2011; Costa & Santesteban, 2004; Costa et al., 2006), a pattern of switch cost that is not usually found in low-proficient bilinguals (e.g., Meuter & Allport, 1999). This has been explained as a qualitative difference in the recruitment of the bLC mechanisms related to proficiency. For instance, low-proficient bilinguals could make use of inhibitory control to get rid of the interference of L1 when speaking in L2, that is, to prevent the interference of the strong language over the weak language. On the other hand, highly-proficient bilinguals behave differently and in the same condition they show a symmetrical switch cost. Regardless of the merits of such an explanation, our contribution here is the observation that the bLC system does not seem to be affected by age-related decline. This appears to be so, from both quantitative and qualitative points of view, namely in terms of the magnitude of the switch cost and in terms of the symmetrical switch costs for the two languages.

This conclusion contrasts with that reached by Weissberger et al. (2012), where an aging effect on the magnitude of language switch costs was observed. Although quantitative differences were observed in this study, it is worth noticing that the same symmetrical pattern of switch costs was observed for young and elderly individuals. Hence, qualitatively the same pattern was observed regardless of aging. At present, it is difficult to account for the differences between the two studies in terms of the quantitative effects given the many differences between the two studies. Further research needs to be conducted to clarify this issue.

The second aim of the study was to explore the nature of the cross-talk between bLC and the domain-general EC system by focusing on age-related changes in linguistic and non-linguistic switching tasks. In the non-linguistic switching task participants had to judge a series of pictures according to two sorting criteria: their colour, or their shape according to a cue. In this task, we actually found an age-related change both in the speed of processing and in the magnitude of the switch cost. That is, the three age groups were different in overall speed, with the elderly group the slowest and the young group the fastest, and the magnitude of the switch cost was larger for the elderly compared to young adults.[2] We also found that age, considered as a continuum variable, positively correlated with the magnitude of the non-linguistic switching cost. These results contrast sharply with those observed in the linguistic switching task, in which the magnitude of the language switch cost was not affected by aging. In fact, the correlation analyses revealed weak associations between performances in the two tasks. Although the speed with which the tasks were performed correlated with age, only the non-linguistic switch cost was correlated with aging. Crucially, linguistic and non-linguistic switch costs were uncorrelated for any of the three groups of participants. That is, the cost of switching languages cannot be predicted by the cost of switching tasks.

Taken together, the results from the linguistic and non-linguistic switching tasks suggest that aging affects, in

---

[2] This result contrasts with that of Weissberger et al. (2012) in which the age-related effect in non-linguistic switching task was confined to an increase in errors in the mixed condition. In fact, in many studies of switching task with elderly adults, the switch cost is not consistently reported. However, the mixing cost, which is the difference in reaction times between the repeat trials of the mixed condition and those in non-mixed one, is the measure that is most sensitive to age effects (for a recent review see Wasylyshyn et al., 2011). However, it is noteworthy to say that some other studies have shown age-related effects of switch cost, for instance in some conditions in which the task is more demanding in terms of alternative of responses (Reimers & Maylor, 2005).

a relatively different manner, bLC and the EC systems. Hence, to the extent that such a differential effect of aging can be understood as revealing different underlying mechanisms for the two systems, we should conclude that the bLC cannot be reduced to a specific instance of the EC system.

Interestingly, and despite the number of differences between our study and that of Weissberger et al. (2012), the authors reached similar conclusions to the ones drawn above. Indeed, they found an instructive dissociation: a subset of elderly bilinguals was able to perform the language switching task but not the non-linguistic switching task. Thus, the relative sparing of the processes involved in the bLC in the presence of a deficient EC system, suggests that the bLC and the EC systems are only partially shared and that some of the bLC mechanisms are protected against aging (for similar conclusions see Gollan et al., 2011).

These conclusions do not necessarily conflict with the information provided by the neuroimaging literature. Indeed, there is a growing body of evidence revealing that bLC and EC share some common neural substrate. For instance, Abutalebi and Green (2007) suggested that the same neural regions (the dorsolateral prefrontal cortex, the anterior cingulate cortex and the caudate nucleus) are engaged during both language switching tasks (e.g., Abutalebi, Della Rosa, Ding, Weekes, Costa & Green, 2013; Abutalebi, Della Rosa, Green, Hernandez, Scifo, Keim, Cappa & Costa, 2012; Garbin et al., 2011; Hernandez et al., 2001; for a review see also Hervais-Adelman et al., 2011) and non-linguistic switching tasks (e.g., Botvinick, Braver, Barch, Carter & Cohen, 2001; Botvinick, Cohen & Carter, 2004). This evidence supports the hypothesis that the mechanisms for language control are subsidiary to those of the domain-general EC. However, there is also evidence going against the claim of functional overlap between bLC and EC (e.g., Abutalebi, Annoni, Zimine, Pegna, Seghier, Lee-Jahnke, Lazeyras, Cappa & Khateb, 2008). In an fMRI study those authors demonstrated the existence of a neural network that is specifically recruited to switch between two different linguistic registers but not between two intra-linguistic tasks. This suggests that some of bLC mechanisms are specific to language and not involved in any other switching task.

Thus, the issue here is to determine which components are specific to bLC and which are shared with the domain-general EC. The fitting of the data to the ex-Gaussian distribution can help provide a tentative answer. This analysis revealed that the normal and exponential components of the distribution differentially captured age related variability for the two tasks. Empirically, the parameter estimation of these two components (μ and τ) is usually used as a tool to better describe the distribution of the RTs. However, some authors suggest that group differences in the parameters also indicate the different degree to which cognitive processes are recruited during task execution (for a review see Matzke & Wagenmakers, 2009).

In this context, the results of the ex-Gaussian distribution analysis may help us to identify which are the shared and specific processes of the two systems. This is a complex issue that goes beyond the scope of this article. However, we can put forward the following tentative account.

The EC system includes a set of mechanisms, such as inhibitory control, monitoring, shifting, and working memory, etc. (e.g., Miyake, Friedman, Emerson, Witzki & Howerter, 2000) and aging affects some of these EC processes. Actually, in the non-linguistic task we found that the switch cost increased in the elderly group (as compared to the young group) and, interestingly, this relative increase was indexed by the exponential component of the distribution for switch trials (τ), and not by a general shift in the normal component of the distribution (μ). That is, the larger switch costs for elderly people do not stem from an overall slowing down in switch trials, but rather for a disproportionately presence of very slow RTs in such condition (the exponential component, τ values). So, then the question is: what cognitive process leads to such an increment of the exponential component in the switch trials? One possibility is that inhibitory control deficits are behind these long RTs, therefore reducing the ability of elderly people to switch smoothly between different tasks. Indeed, some researchers suggest that the exponential component captures the efficiency of the inhibitory control system (e.g., Penner-Wilger, Leth-Steensen & LeFevre, 2002; Schmiedek, Oberauer, Wilhelm, Suss & Wittmann, 2007; Spieler, Balota & Faust, 1996). Regardless of the merits of this tentative interpretation of this distributional analysis, what is relevant here is the contrastive distribution observed in the language switching task. In this task, there were no differences in the exponential component of the distribution neither for the comparison between groups nor for conditions. Hence, whatever the cognitive process that is behind the age-related decline in the ability to switch between non-linguistic tasks, it does not seem to be involved (at least to the same degree) in the language switch task.

In accordance with this view, some authors have argued that in the case of high-proficient bilingualism, the bLC would not resort in inhibitory mechanisms but rather in a language-specific selection mechanism that is built into the linguistic system of the speaker, and relatively independent of the EC system. Under this language-specific selection account, one could predict that a reduction in the efficiency of the inhibitory mechanism would leave relative unaffected the ability of bilingual speakers to perform language control.

Interestingly, this view leads to the further hypothesis that bLC should be affected by aging in low-proficient bilinguals. Further research should be carried out to test this hypothesis.

To conclude, our study adds new evidence to a differential age-related change over bLC and the domain-general EC system in highly-proficient bilinguals. Specifically, our results show that bLC is not totally affected by age despite the fact the EC system was impaired in elderly bilinguals. Moreover, the increase in the switch cost during the EC task was not correlated to switch costs during bLC task. Taken together, this suggests that the underlying mechanisms of bLC and EC systems are not totally shared. Further research is needed to explore in more detail which mechanisms are more affected by age within the EC system by, for instance, using tasks that involve the different processes of domain-general EC system.

References

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

Abutalebi, J., Della Rosa, P. A., Ding, G., Weekes, B., Costa, A., & Green, D. W. (2013). Language proficiency modulates the engagement of cognitive control areas in multilinguals. *Cortex, 49,* 905–1011.

Abutalebi, J., Della Rosa, P. A., Green, D. W., Hernandez, M., Scifo, P., Keim, R., Cappa, S. F., & Costa, A. (2012). Bilingualism tunes the anterior cingulate cortex for conflict monitoring. *Cerebral Cortex, 22,* 2076–2086.

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

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

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

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

Calabria, M., Hernandez, M., Branzi, F. M., & Costa, A. (2011). Qualitative differences between bilingual language control and executive control: Evidence from task-switching. *Frontiers in Psychology, 2,* 399.

Costa, A., & Santesteban, M. (2004). Lexical access in bilingual speech production: Evidence from language switching in highly proficient bilinguals and L2 learners. *Journal of Memory and Language, 50,* 491–511.

Costa, A., Santesteban, M., & Ivanova, I. (2006). How do highly proficient bilinguals control their lexicalization process? Inhibitory and language-specific selection mechanisms are both functional. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 32,* 1057–1074.

Cousineau, D., Brown, S., & Heathcote, A. (2004). Fitting distributions using maximum likelihood: Methods and packages. *Behavior Research Methods, Instruments, & Computers, 36,* 742–756.

Forster, K. I., & Forster, J. C. (2003). DMDX: A windows display program with millisecond accuracy. *Behavior Research Methods, Instruments, & Computers, 35,* 116–124.

Garbin, G., Costa, A., Sanjuan, A., Forn, C., Rodriguez-Pujadas, A., Ventura, N., Belloch, V., Hernandez, M., & Ávila, C. (2011). Neural bases of language switching in high and early proficient bilinguals. *Brain and Language, 119,* 129–135.

Gollan, T. H., & Ferreira, V. S. (2009). Should I stay or should I switch? A cost-benefit analysis of voluntary language switching in young and aging bilinguals. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 35,* 640–665.

Gollan, T. H., Sandoval, T., & Salmon, D. P. (2011). Cross-language intrusion errors in aging bilinguals reveal the link between executive control and language selection. *Psychological Science, 22,* 1155–1164.

Green, D. W. (1986). Control, activation, and resource: A framework and a model for the control of speech in bilinguals. *Brain and Language, 27,* 210–223.

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

Greenwood, P. M. (2000). The frontal aging hypothesis evaluated. *Journal of the International Neuropsychological Society, 6,* 705–726.

Hernandez, A. E., Dapretto, M., Mazziotta, J., & Bookheimer, S. (2001). Language switching and language representation in Spanish–English bilinguals: An fMRI study. *NeuroImage, 14,* 510–520.

Hernandez, A. E., & Khonert, K. (1999). Aging and language *switching* in bilinguals. *Aging, Neuropsychology and Cognition, 6,* 69–83.

Hervais-Adelman, A. G., Moser-Mercer, B., & Golestani, N. (2011). Executive control of language in the bilingual brain: Integrating the evidence from neuroimaging to neuropsychology. *Frontiers in Psychology, 2,* 234.

Koch, I., Gade, M., Schuch, S., & Philipp, A. M. (2010). The role of inhibition in task switching: A review. *Psychonomic Bulletin & Review, 17,* 1–14.

Magezi, D. A., Khateb, A., Mouthon, M., Spierer, L., & Annoni, J. M. (2012). Cognitive control of language production in bilinguals involves a partly independent process within the domain-general cognitive control network: Evidence from task-switching and electrical brain activity. *Brain and Language, 122,* 55–63.

Martin, C. D., Barcelo, F., Hernandez, M., & Costa, A. (2011). The time course of the asymmetrical "local" switch cost: Evidence from event-related potentials. *Biological Psychology, 86,* 210–218.

Matzke, D., & Wagenmakers, E. J. (2009). Psychological interpretation of the ex-Gaussian and shifted Wald parameters: A diffusion model analysis. *Psychonomic Bulletin Review, 16,* 798–817.

Meuter, R. F. I., & Allport, A. (1999). Bilingual language switching in naming: Asymmetrical costs of language selection. *Journal of Memory and Language, 40,* 25–40.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., & Howerter, A. (2000). The unity and diversity of executive functions and their contributions to complex “Frontal lobe” tasks: A latent variable analysis. *Cognitive Psychology, 41,* 49–100.

Penner-Wilger, M., Leth-Steensen, C., & LeFevre, J. A. (2002). Decomposing the problem-size effect: A comparison of response time distributions across cultures. *Memory and Cognition, 30,* 1160–1167.

Prior, A., & Gollan, T. H. (2011). Good language-switchers are good task-switchers: Evidence from Spanish–English and Mandarin–English bilinguals. *Journal of the International Neuropsychological Society, 17,* 682–691.

Protopapas, A. (2007). CheckVocal: A program to facilitate checking the accuracy and response time of vocal responses from DMDX. *Behavior Research Methods, 39,* 859–862.

Reimers, S., & Maylor, E. A. (2005). Task switching across the life span: Effects of age on general and specific switch costs. *Developmental Psychology, 41,* 661–671.

Rhodes, M. G. (2004). Age-related differences in performance on the Wisconsin card sorting test: A meta-analytic review. *Psychology and Aging, 19,* 482–494.

Roelofs, A., & Piai, V. (2011). Attention demands of spoken word planning: A review. *Frontiers in Psychology, 2,* 307.

Schmiedek, F., Oberauer, K., Wilhelm, O., Suss, H. M., & Wittmann, W. W. (2007). Individual differences in components of reaction time distributions and their relations to working memory and intelligence. *Journal of Experimental Psychology: General, 136,* 414–429.

Snodgrass, J. G., & Vanderwart, M. (1980). A standardized set of 260 pictures: Norms for name agreement, image agreement, familiarity, and visual complexity. *Journal of Experimental Psychology: Human Learning and Memory, 6,* 174–215.

Soveri, A., Rodriguez-Fornells, A., & Laine, M. (2011). Is there a relationship between language switching and executive functions in bilingualism? Introducing a within-group analysis approach. *Frontiers in Psychology, 2,* 183.

Spieler, D. H., Balota, D. A., & Faust, M. E. (1996). Stroop performance in healthy younger and older adults and in individuals with dementia of the Alzheimer’s type. *Journal of Experimental Psychology: Human, Perception and Performance, 22,* 461–479.

Strijkers, K., Holcomb, P., & Costa, A. (2011). Conscious intention to speak proactively facilitates lexical access during overt object naming. *Journal of Memory and Language, 65,* 345–362.

Tisserand, D. J., & Jolles, J. (2003). On the involvement of prefrontal networks in cognitive ageing. *Cortex, 39,* 1107–1128.

Verhaeghen, P., & Cerella, J. (2002). Aging, executive control, and attention: A review of meta-analyses. *Neuroscience and Biobehavioral Reviews, 26,* 849–857.

Verhaeghen, P., Steitz, D. W., Sliwinski, M. J., & Cerella, J. (2003). Aging and dual-task performance: A meta-analysis. *Psychology and Aging, 18,* 443–460.

Wasylyshyn, C., Verhaeghen, P., & Sliwinski, M. J. (2011). Aging and task switching: A meta-analysis. *Psychology and Aging, 26,* 15–20.

Weissberger, G. H., Wierenga, C. E., Bondi, M. W., & Gollan, T. H. (2012). Partially overlapping mechanisms of language and task control in young and older bilinguals. *Psychology and Aging, 27,* 959–974.

Ye, Z., & Zhou, X. (2009). Executive control in language processing. *Neuroscience and Biobehavioral Reviews, 33,* 1168–1177.

2.7 Inhibitory control and cognitive control flexibility: the overlap between bilingual language control and domain-general executive control

Branzi, F.M., Calabria, M., Boscarino, M. L., & Costa, A. (Under review).Inhibitory control and cognitive control flexibility: the overlap between bilingual language control and domain-general executive control. *Journal of Experimental Psychology: Learning, Memory and Cognition*.

Inhibitory control and cognitive control flexibility: the overlap between bilingual language control and domain-general executive control

Francesca M. Branzi[1], Marco Calabria [1], Maria Lucrezia Boscarino[1], Albert Costa[1,2]

[1]Center for Brain and Cognition (CBC), Universitat Pompeu Fabra, Barcelona, Spain.
[2]Institució Catalana de Recerca i Estudis Avançats (ICREA), Barcelona, Spain.

Address for correspondence:

Francesca Martina Branzi
Universitat Pompeu Fabra
C. Tanger, 122-140 (room 55102)
tf. (34) 93 5421381
email francesca.branzi@gmail.com

Abstract

We explored the overlap between bilingual language control (bLC) and domain-general executive control (EC) by focusing on *inhibitory control* processes and on a general control ability that allows combining different EC mechanisms (i.e., *cognitive control flexibility*). We tested 62 bilinguals in linguistic and non-linguistic switching tasks for two types of costs, such as the “n-1 shift cost” and the “n-2 repetition cost”. In order to evaluate *inhibitory control* in bLC and EC, we assessed the pattern of switch costs in the two tasks and then we correlated them between tasks. In order to evaluate *cognitive control flexibility* in bLC and EC, we correlated the “n-1 shift costs” and the “n-2 repetition costs” within each task. We did so because the two costs have been proposed to rely on opposing mechanisms (i.e., “task activation” and “task inhibition processes” respectively). Hence, we assessed whether these mechanisms were similarly “related” in the two tasks. Results showed reduced “n-2 repetition costs” as compared to “n-1 shift costs” in the linguistic task only. Moreover, neither the “n-1 shift costs” nor the “n-2 repetition costs” were correlated between tasks. However, a negative correlation between these two costs was found both in linguistic and in non-linguistic switching tasks, suggesting that bilinguals adjust “task activation” and “task inhibition” similarly in tasks involving language control or non-linguistic control, when the context demands to adjust these mechanisms. We conclude that the overlap between bLC and EC systems goes beyond *inhibitory control* and regards *cognitive control flexibility* that allows combining different EC mechanisms.

Keywords: Bilingual language control, domain-general executive control, inhibitory control, cognitive control flexibility, task switching.

1. Introduction

The issue of how bilingual speakers manage to restrict lexicalization to one of their languages while preventing massive interference from their other language has prompted a great amount of research in the last decade (e.g., Branzi, Martin, Abutalebi & Costa, 2014; Costa & Santesteban, 2004; Costa, Santesteban & Ivanova, 2006; Christoffels, Firk, & Schiller, 2007; Jackson, Swainson, Cunnington, & Jackson, 2001; Misra, Guo, Bobb, & Kroll, 2012). As a result of this research, there is agreement in assuming that the bilingual language control (bLC) system makes use of various processes of the domain-general executive control (EC) system (e.g., Abutalebi & Green, 2007). However, the precise nature of the overlap between bLC and EC processes is still an open issue. The aim of this article is to provide new evidence regarding the relationship between these two cognitive systems.

Recent research on this issue has focussed on different strategies. One of them correlates participants' behaviour in comparable tasks that either involved bLC or domain-general EC processes (e.g., Calabria, Hernández, Branzi, & Costa, 2012; Calabria, Branzi, Marne, Hernández, & Costa, 2013). The argument made is that to the extent that these tasks tap into comparable processes, there should be a correlation between the effects observed in them. For example, Calabria et al. (2012; 2013) compared groups of bilinguals of different ages in a linguistic switching task and in a non-linguistic switching task. In the linguistic version of the task, participants are typically required to name some pictures in a language and other pictures in the other language according to a cue (e.g., the color of the pictures). The non-linguistic version of the task, instead, requires performing a non-linguistic task, such as classifying pictures according to a non-linguistic classification rule (for example, classify pictures by their color and by their shape). In these tasks, reaction times (RTs) for “repeat” trials (AA task sequences) are faster than those for “switch trials” (AB task sequences), this is the so called “n-1 shift cost”, a measure of the efficiency of bLC and EC functioning. In general, the current evidence suggests there is not a correlation between “n-1 shift costs” across these tasks (Calabria et al., 2012; 2013; Prior & Gollan, 2013), which suggests a partial overlap between the two systems[17] (see also Weissberger, Wierenga, Bondi, & Gollan, 2012).

However, there are other studies that provided evidence of a direct link between bilingual language use and EC processing (e.g., Prior & Gollan, 2011; Soveri, Rodriguez-Fornells, & Laine, 2011). For example, Soveri et al. (2011) revealed that the frequency rate with which bilinguals switched between languages on a daily basis

---

[17] In Calabria et al. (2012) the lack of correlation between bLC and EC tasks was also accompanied by other evidence concerning the overlap between bLC and EC. This evidence was the different pattern of switch costs in the bLC and EC tasks. Generally, in linguistic and in non-linguistic switching tasks, larger switch costs are observed when switching into the more simple (or the stronger) of a pair of tasks, than into the more difficult (or the weaker) one (e.g., Meuter & Allport, 1999). Importantly, despite some inconsistencies (see Bobb & Wodniecka, 2013), the asymmetry of switch costs has been taken as reflecting the involvement of inhibitory control in the task (see Allport, Styles, & Hsieh, 1994; Meuter & Allport, 1999). Crucially, Calabria et al. (2012) found that the patterns of switch costs in the non-linguistic task were asymmetrical, whereas instead those in the linguistic one were symmetrical. This was true when bilinguals were required to switch between their dominant language (i.e., L1) and their less dominant ones (L2 or L3).

predicted the magnitude of mixing costs in error rates in a set shifting task. Moreover, Prior and Gollan (2011) showed that Mandarin–English bilinguals with higher fluency scores in Mandarin incurred smaller switch costs in a non-linguistic switching task. Note, however, that this result was not replicated in another group of bilinguals (Spanish-English bilinguals) tested in the same study.

At present, the available evidence is contradictory regarding the existence of a substantial overlap between the bLC and EC processes, at least as to when such overlap is measured by correlating effects across tasks.

In the present study, we further explore this issue by examining the performance of 62 high-proficient bilinguals in linguistic and in non-linguistic switching tasks. As in previous studies (e.g., Calabria et al., 2012), we explore the correlation of “n-1 shift costs” elicited in these tasks. However, the present study goes beyond previous ones in a crucial respect, namely, the assessment of an effect that is supposed to be a signature of *inhibitory control*, that is, the “n-2 repetition cost” (see below). This is relevant since domain-general *inhibitory control* has been postulated to be at the basis of bLC (e.g., Green, 1998). Under the assumption that the “n-2 repetition cost” is a reliable index of *inhibitory control* applied over the representations that are not relevant for the current task, we can hypothesize that participant’s variability of their inhibitory ability should be revealed by differences in the magnitude of the “n-2 repetition cost”. Moreover, if bLC makes use of the same inhibitory processing as the domain-general EC system, then participant's variability in their inhibitory abilities should be similarly evident in linguistic and in non-linguistic switching tasks. In other words, the magnitude of the "n-2 repetition costs" should correlate across tasks.

1.1. On "n-1 shift cost" and "n-2 repetition cost" effects

As advanced above, "n-1 shift costs" do not show any correlation between linguistic and non-linguistic switching tasks (Calabria et al., 2012; 2013; Prior & Gollan, 2013).

Informative as this lack of correlation might be, indeed, it does not tackle specifically whether participant's *inhibitory control* abilities in bLC can be related to performance in EC tasks. This is because the "n-1 shift cost" is supposed to reveal not only inhibitory processes, but also other EC mechanisms involved in switching between tasks (e.g., set-shifting, goal retrieval, task-set reconfiguration processes; see Kiesel, Steinhauser, Wendt, Falkenstein, Jost, & Philipp, 2010). Hence, the lack of correlation between linguistic and non-linguistic switching tasks might be due to the variability added by these other processes indexed by the "n-1 shift cost". Nevertheless, it is possible that a more direct index of *inhibitory control* can actually reveal a stronger correlation between the two tasks. Crucially, it has been argued that the "n-2 repetition cost" (e.g., Mayr & Keele, 2000; Philipp, Gade, & Koch, 2007; see also Koch, Gade, Schuch, & Philipp, 2010) might be such an index. This effect refers to the slower RTs observed when participants have to switch into a recently performed task (in an n-2 trial) as compared to when they have to switch into a not-recently performed task. To give an example, let’s consider a switching experiment in which participants have to switch between three different tasks (sort pictures by color, size and shape). This task affords the calculation of the cost of switching into a recently performed task (ABA – classify by color, classify by size, classify by color), and that of switching into a not recently performed task (CBA, classify by shape, classify by size, classify by color). As it happens, RTs from the former type of trials are slower than those of the later, the so-called “n-2 repetition cost” (e.g., Mayr & Keele, 2000; Philipp et al., 2007). As said above, the magnitude of this cost is argued to be a signature of the amount of inhibition applied to the repeated task. In other words, the inhibition applied to task A when performing task B would determine an increase of RTs when performing again task A, because of the need to overcome previous inhibition (e.g., Arbuthnott & Frank, 2000; Mayr & Keele, 2000).

In this study, we use an experimental design that affords exploring the “n-1 shift cost” and the “n-2 repetition cost” simultaneously. This is important because it allows us not only to assess the overlap between bLC and EC in relation to *inhibitory control*, but also to assess the participant’s ability to adjust the performance in relation to context demands (see below, *cognitive control flexibility*).

We will do so by examining the functional relationship between the “n-1 shift cost” and the “n-2 repetition cost” within each task; since it has been argued that these two costs may reflect the functioning of different EC mechanisms that need to be integrated in a switching task (see Philipp & Koch, 2006). Specifically, Philipp and Koch (2006) proposed that if measured within the same context, the “n-1 shift cost” and the “n-2 repetition cost” are likely to reflect the functioning of two contrasting and different processes: “task activation” (“n-1 shift cost”) and “task inhibition” (“n-2 repetition cost”) processes. This argument comes from the observation that the magnitude of the “n-2 repetition cost” is almost eliminated when repetitions (i.e., CAA sequences) are also present in the experiment (e.g., Experiment 1 in Philipp & Koch, 2006). Since the switching experiment involves “task inhibition” (for switching trials) but also persistent “task activation” (for repeated trials) (e.g., Arbuthnott & Frank, 2000; Philipp & Koch, 2006), the “n-2 repetition cost” reduction is likely due to the fact that with the presence of repetitions the deployment of “task inhibition” is not a useful strategy. Rather “task activation” might become more useful.

Hence, “task activation” and “task inhibition” appear to be maladaptive to each other, since the “n-2 repetition cost” is almost eliminated when repetitions are included in the task. Nevertheless, in some situations (i.e., when the number of repetitions -CAA task sequences- is very reduced as compared to the CBA and ABA task sequences) the presence of repetitions, that triggers “task activation” processes, does not break down the “n-2 repetition cost” (“task inhibition” processes) completely. In these circumstances, these two processes can be integrated for interference resolution, in a balance between “task inhibition” and “task activation” (see Experiment 2 in Philipp & Koch, 2006).

To the extent that it is possible to test within the same experimental context “task activation” and “task inhibition” at play, it would be interesting to see whether they are functionally integrated in the same way in linguistic and non-linguistic switching tasks.

Exploring this flexibility could help to confirm recent proposals suggesting that the bilingual advantage in respect to monolingual counterparts may go beyond the single control mechanism (e.g., Bialystok, Craik, & Luk, 2012; Morales, Gómez-Ariza and Bajo, 2013). For example, Morales et al. (2013) compared bilinguals and monolinguals in the AX-CPT task (a version of the Continuous Performance Task employed by Ophir, Nass, & Wagner, 2009) and observed that bilinguals outperformed monolinguals in the condition with the higher requirement of proactive (monitoring) and reactive (inhibition) control. These observations led authors to conclude that as compared to monolinguals, bilinguals have an advantage in combining different types of EC mechanisms. Since the cognitive control system must be flexible in order to achieve that, henceforth, we refer to this ability as “*cognitive control flexibility*”.

In the present study, we aim to assess whether *cognitive control flexibility* can be similarly present in a linguistic switching task and in a non-linguistic switching task.

1.2. The present study

In the present study, we investigate the functional overlap between bLC and EC systems, by assessing different effects in a linguistic and in a non-linguistic switching task. We focus on two main questions.

First, to what extent do bLC and EC systems rely on the same *inhibitory control* mechanisms? Three different contrasts will help to answer this question. First, we compare the magnitude of "n-1 shift costs" and "n-2 repetition costs" within tasks. If bLC and EC rely on the same processes, the relationship between magnitudes of the two costs should be similar in the two tasks, regardless of the overall magnitude of these effects across tasks. Hence, we explore how much the magnitude of the "n-2 repetition cost" departs from that of the "n-1 shift cost" in a linguistic and in a non-linguistic switching task, separately. In fact, based on the assumption that inhibition measured as "n-2 repetition costs" contribute also to "n-1 shift costs" (e.g., Mayr & Keele, 2000), we will be able to reveal the involvement of *inhibitory control* in the two tasks. Our hypothesis is that, if high-proficient bilinguals do not control their language production through *inhibitory control* (see Costa et al., 2004; 2006), in the linguistic switching task we should find reduced "n-2 repetition costs" as compared to "n-1 shift costs". Moreover, if a reduction of *inhibitory control* is something specific to bLC (see Costa et al., 2004; 2006), we should find different patterns of "n-2 repetition costs" and "n-1 shift costs" in the linguistic and in the non-linguistic switching tasks. That is, to the extent to which the "n-2 repetition cost" reflects *inhibitory control*, we expect to see this cost in the linguistic switching task as reduced in comparison with the "n-1 shift cost", since our bilinguals are balanced and equally proficient in the two languages. However, the pattern might be different in the non-linguistic switching task: It might reveal more similar "n-2 repetition" and "n-1 shift" costs, if *inhibitory control* is the type of control required to perform the non-linguistic switching task.

Second, as in previous studies (e.g., Calabria et al., 2012; 2013), we hypothesize that a correlation of the two switch costs across tasks would be informative about the degree of the overlap between the bLC and EC systems. Specifically, we hypothesize that if *inhibitory control* is the specific mechanism shared between the two systems, the "n-2 repetition cost" should be correlated between tasks.

Third, in order to further explore the overlap between bLC and EC systems we conduct an ex-Gaussian distribution analysis of RTs to see whether there are differences between the two tasks in the components (normal and exponential) of the RT distribution. We also use this analysis to test whether there are components of RT distribution that might be correlated across tasks, therefore more sensitive to capture the relationship between bLC and EC.

The second question of the present study regards whether bilinguals combine different EC mechanisms in the same fashion in a linguistic and in a non-linguistic switching task. For this question we explore the functional link between the "n-1 shift cost" and the "n-2 repetition cost" to reveal a general control strategy that globally “calibrates” the need of activating a task during task repetitions and the need of suppressing the just executed task during task switches.

In the present study, we hypothesize that if to some extent the presence of repetitions affects the deployment of “task inhibition” processes, it is likely that the “n-1 shift cost” is measuring the efficiency of “task activation” processes. That is, we hypothesize that in this context much of the magnitude of the “n-1 shift cost” reflects the proactive interference (e.g., Allport, Styles & Hiesh., 1994) of the previous “task activation” rather than that of “task inhibition”. Moreover, since the application of these activation processes should be indirectly related to the application of “task inhibition” ones, the larger the “n-1 shift cost” is, the smaller the “n-2 repetition cost” should be (and vice versa). For example, in the case in which for a given participant “task activation” dominates and the inhibition deployed is small, this participant might benefit from task repetition trials, such as the “n-1 shift cost” reflects the effort taken to overcome residual task priming when asked to switch to a different task. In other words, our hypothesis is that if “task activation” and “task inhibition” are integrated for interference resolution in a switching task, the functional link between “n-1 shift costs” and “n-2 repetition costs” should result in a negative correlation.

In the present study, we test whether interference resolution strategy (i.e., *cognitive control flexibility*) is similarly adopted in bLC and EC domains, by correlating the “n-1 shift cost” and the “n-2 repetition cost” within each task. In order to deeply explore this issue, we correlate not only the magnitude of the costs in terms of mean, but also the different components estimated from the RT distribution (see above).

2. Materials and Methods

2.1. Participants

Sixty-two high-proficient Catalan/Spanish bilinguals (46 females, mean age = 21 years ± 2) took part in the study. All participants were right-handed and had normal or corrected-to-normal vision. Self-assessed language proficiency for bilinguals is reported in Table 1.

	L1	**L2**	**L3**
	Language Proficiency	***Language Proficiency***	***Language Proficiency***
Reading	7 (0.3)	7 (0.4)	5 (0.9)
Writing	6 (0.7)	6 (0.8)	5 (1.1)
Speaking	7 (0.6)	6 (0.7)	4 (1.1)
Comprehension	7 (0.3)	7 (0.3)	5 (1.1)

Table 1. Self-assessed language proficiency in bilinguals. Language proficiency scores were on a 7 point scale, in which 7 represents a very high level and 1 a very low level of proficiency. The self-assessed index is an average of participants' responses relative to each domain (reading, writing, speaking, and comprehension). In parentheses are reported SD.

2.2. Materials and procedure

In the present experiment all participants were presented with a linguistic switching task and a non-linguistic switching task. The two tasks were administered in different days (order of presentation was counterbalanced; the interval between the first and the second experiment was approximately of one week). After having filled a language proficiency questionnaire, each participant was tested individually in a soundproof room. At the beginning participants received written and oral experimental instructions and then they took part in the experiment through a single session of approximately 45 minutes. Instructions emphasized speed and accuracy. Subjects were informed about the tasks and the responses, but we did not mention the presence or absence of repetitions. Before being tested in both experiments, all participants were trained with a practice session.

2.2.1. Linguistic switching task

Before the experiment started, participants were familiarized with the pictures used in the experiment in order to verify that they could produce the wanted names for each one of the pictures.

In the linguistic switching task, participants were presented with eight pictures of concrete objects (Snodgrass & Vanderwant, 1980). These pictures were all non-cognate words, that is, words with the same meaning but distinct phonology in three naming languages (i.e., Catalan, Spanish and English): carrot [*zanahoria (Spanish), pastanaga* (*Catalan*)]; sock [*calcetín, mitjó*]; cage [*jaula, gàbia*]; duck [*pato, ánec*]; butterfly [*mariposa, papallona*]; pillow [*almohada, coixí*]*;* apple [*manzana, poma*]; cheese [*queso, formatge*].

Participants were required to name pictures aloud by alternating between the three languages (Catalan=L1; Spanish=L2 and English=L3). Stimuli were presented one at time in a white frame at the centre of a white screen. The naming language was indicated by four cue-signs (flags) surrounding the frame. Responses were given verbally and were recorded through a microphone.

Before the experiment, participants were trained with a practice session (39 trials). The experiment consisted of 6 blocks of 108 trials each. In both the practice and experiment, each trial started with a blank screen followed by the cue (i.e., a white square surrounded by four cue signs). After 100 ms (CSI), the stimulus was presented in the middle of the cue frame, simultaneously with a tone. Stimulus and cue remained on the screen until the response was given (or with a maximum delay of 7000 ms). The response-stimulus interval (RSI) was maintained constant (1100 ms) as well as the cue-stimulus interval[18] (CSI) (100 ms). At the end of each block participants could take a break and the start of the successive block was self-paced.

As reviewed in the introduction, the magnitude of the "n-2 repetition cost" might be affected by the presence of repetitions. This appears to be true at least when the number of *n-1 repetition* sequences (CAA) is equivalent to that of the *n-2 switch* (CBA) and *n-2 repetition* (ABA) sequences (see Experiment 1 in Philipp & Koch 2006). However, if the number of repetitions (CAA task

---

[18] In previous studies (Mayr & Keele, 2000; Philipp & Koch 2006; Prior, 2012; Schuch & Koch, 2003) it has been shown that the "n-2 repetition cost" is not dramatically influenced by preparation time. Therefore, we saw no important theoretical implication to manipulate the CSI, thus we kept the CSI constant at 100 ms.

sequences) is notably reduced as compared to the other two conditions (CBA and ABA task sequences), the “n-2 repetition cost” is not eliminated (see Experiment 2 in Philipp & Koch 2006). Hence, since we aimed to measure the two costs within the same experimental design, as in Philipp and Koch (2006), we decided to introduce fewer repetitions (CAA task sequences) in both tasks as compared to the other two conditions (CBA and ABA task sequences).

The ABA (or *n-2 repetition*) sequence occurred with a probability of 39 %, the CBA (or *n-2 switch*) sequence with a probability of 39 %, and the CAA sequence (or *n-1 repetition*) with a probability of 11 % (note that the sum of probabilities is lower than 100 % because trials following a repetition were not analyzed). In the present study, we refer to A, B, C as indicating each task (i.e., name in L1, L2 and L3) that occurred in the experiment with an equal probability.

2.2.2. Non-linguistic switching task

In the non-linguistic switching task participants were presented with visual stimuli and were required to switch among three perceptual classification tasks. As in a previous study (Philipp & Koch, 2006), participants were required to classify each stimulus for the “type” (A vs. 4), the “size” (big vs. small) and the “color” (red vs. blue) accordingly with the specific cue-signs. Stimuli were presented in a white frame at the centre of a white screen. The task was indicated by four cue-signs surrounding the frame. The cues were paragraph signs for the “type” task, small yellow squares for the “color” task and up-down pointing arrows for the “size” task. Responses were given manually on an external keyboard with three response keys for each hand[19]. The procedure was identical to that of the linguistic switching task, with the only difference that at the end of each block participants received a feedback relative to their performance, in terms of the percentage of correct responses.

3. Results

As in previous studies (e.g., Philipp & Koch, 2006), each *n* trial was assigned to one of the three conditions (CAA, CBA and ABA) depending on the nature of the two preceding trials (the n-1 and the n-2 trials). For example, in the CBA sequence the *n* trial A is preceded by the n-1 trial B and by the n-2 trial C. In this case, the *n* trial A would be assigned to the condition *n-2 switch,* given that the trial n-1 and the trial n-2 are both different from A. In the ABA sequence instead, the *n* trial A is preceded by the n-1 trial B and by the n-2 trial A. In this case, the *n* trial A would be assigned to the condition *n-2 repetition,* given that the n-2 trial and the *n* trial require to performing the same task (i.e., A). In the CAA sequence the *n* trial A would be assigned to the *n-1 repetition* condition, given it is preceded by an identical trial, that is, the n-1 trial A.

---

[19] In the present study we adopted this response setting in order not to have response overlapping across tasks. Hence, three keys were used to respond to ‘A’, ‘big’ and ‘red’ and three other keys were used to respond to ‘4’, ‘small’ and ‘blue’. Note also that responses were labeled on the keyboard.

First, in order to explore potential difference between the two tasks we ran two omnibus ANOVAs: one for RTs and one for error rates, in which we compared the linguistic and the non-linguistic switching task. Further, since we aimed to explore the pattern of the “n-1 shift cost” and the “n-2 repetition cost” in the two tasks, we ran two separate paired t-tests (one for the linguistic switching task and the other for the non-linguistic switching task) in which we compared the magnitudes of the two costs.

Second, we explored by means of the ex-Gaussian distribution analysis the parameter estimates of the different components of RT distribution in the two tasks.

Third, we ran a correlation analysis between the two tasks in order to see whether the “n-2 repetition cost” and/or the “n-1 shift cost” were correlated between tasks (RTs and ex-Gaussian parameters).

Finally, in order to assess *cognitive control flexibility*, that is, the general control strategy for interference resolution adopted in the linguistic and in the non-linguistic switching tasks, we correlated within each task the “n-1 shift cost” and the “n-2 repetition cost”.

In the ANOVAs’ Post-hoc analyses, we consistently applied the *Bonferroni* correction for multiple comparisons.

In both the linguistic and the non-linguistic switching tasks, the first two trials of each block were excluded from the analyses, as well as the trials after repetitions (e.g., CAA sequences).

Hence, every error and the two trials following an error[20] were discarded from the analyses. RTs exceeding three standard deviations above or below a participant's mean were also excluded from the analyses. Thus, we excluded from the behavioral analyses the 18 % (SD = ± 9) of the data for the linguistic switching task and the 12 % (SD = ± 6) of the data for non-linguistic switching task.

3.1. *RTs and Error rates*

First, we analyzed RTs and error rates for the three types of sequence, such as CAA (or *n-1 repetition*), CBA (or *n-2 switch*) and ABA (or *n-2 repetition*). Hence, for RTs and error rates we ran two repeated-measures ANOVAs with "types of task" (linguistic switching task and non-linguistic switching task) and "types of sequence" (CAA or *n-1 repetition,* CBA or *n-2 switch* and ABA or *n-2 repetition*) as within-subject factors.

For RTs, the main effect of "types of task" was not significant [F (1, 61) = .019, p = .891, $p\eta^2 < .001$], indicating that overall RTs for the linguistic and the non-linguistic switching tasks were not different (see Figure 1 and Figure 2). The main effect of "types of sequence" was significant [F (2, 122) = 81.963, p < .001, $p\eta^2 = .573$] suggesting that CAA conditions (991 ms) were significantly faster that the other two [CBA (1034 ms, p < .001) and ABA (1060 ms, p < .001)] and that ABA conditions were slower than the CBA ones (p < .001). Interestingly, the interaction between

---

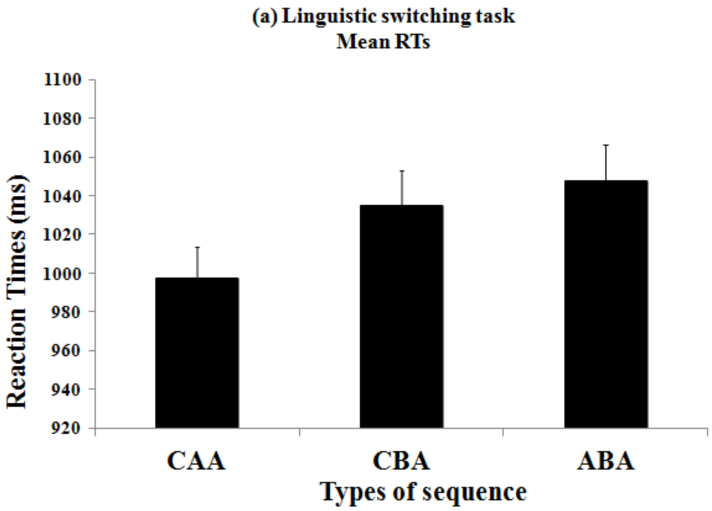
[20] In the linguistic task, we considered as "errors" all the following cases: incorrect names and verbal disfluencies or hesitations.

“types of task” and “types of sequence” was significant [F (2, 122) = 7.447, p = .001, $p\eta^2 = .109$], suggesting that the magnitudes of the costs were modulated by the type of task.

In order to explore this interaction we compared the magnitudes of the “n-1 shift cost” and “n-2 repetition cost” within each task separately. Hence, we performed two paired t-tests -one for the linguistic switching task and the other for the non-linguistic switching task- to compare the two “types of cost” (“n-1 shift cost”, “n-2 repetition cost”). The “n-1 shift cost” was calculated by subtracting the RTs of the CAA sequences from those of the CBA sequences. The “n-2 repetition cost” was calculated by subtracting RTs of the CBA sequences from those of the ABA sequences.

In the linguistic switching task, results revealed that there was a significant difference between the “n-1 shift cost” (37 ms) and the “n-2 repetition cost” (13 ms) [t (61) = 2.728, p = .008] and both costs were different from zero [“n-1 shift cost”: t (61) = 5.589, p < .001; “n-2 repetition cost”: t (61) = 3.134, p = .003] (see Figure 1).

In the non-linguistic switching task, results revealed that the “n-1 shift cost” (49 ms) and the “n-2 repetition cost” (41 ms) were not different [t (61) = .586, p = .56]. Moreover, they were both different from zero [“n-1 shift cost”: t (61) = 4.708, p < .001; “n-2 repetition cost”: t (61) = 6.049, p < .001] (see Figure 2).



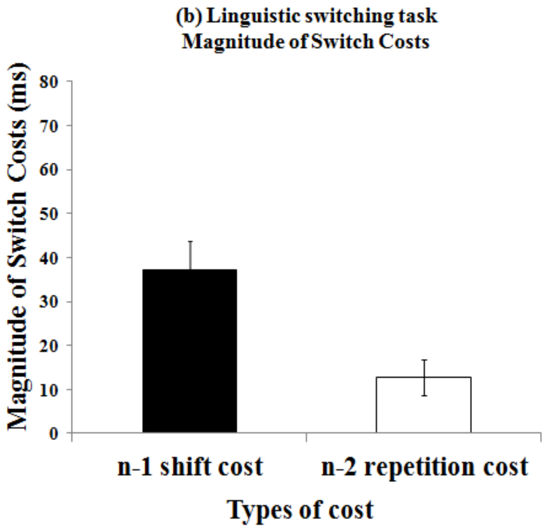
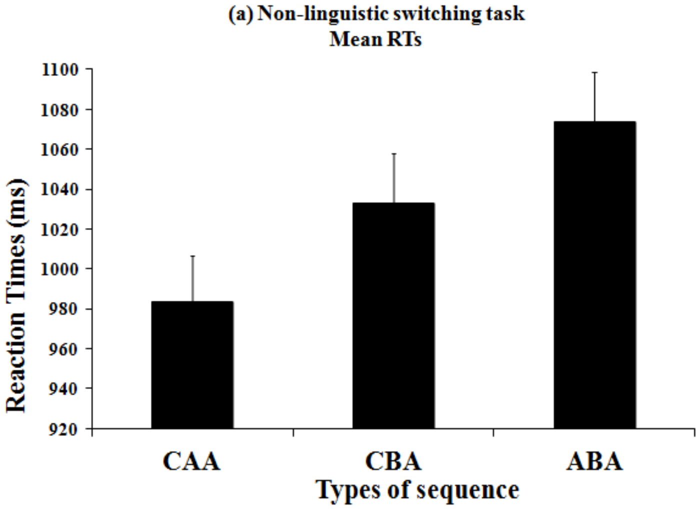


Figure 1. Linguistic switching task. **(a)** Mean RTs relative to the three different types of sequence (CAA, CBA and ABA) and **(b)** Magnitude of the switch costs (“n-1 shift cost” and “n-2 repetition cost”)**.** Errors bars refer to SE.



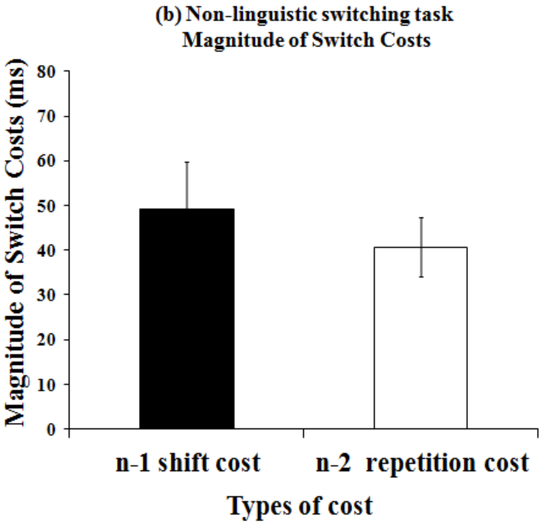


Figure 2. Non-linguistic switching task. **(a)** Mean RTs relative to the three different types of sequence (CAA, CBA and ABA) and **(b)** Magnitude of the switch costs ("n-1 shift cost" and "n-2 repetition cost")**.** Errors bars refer to SE.

For error rates, the main effect of “types of task” was significant [F (1, 61) = 14.731, $p < .001$, $p\eta^2 = .195$], suggesting a larger proportion of errors in the linguistic switching task (5.2 %) as compared to the non-linguistic switching task (3.1 %).

Also the main effect of “types of sequence” was significant [F (2, 122) = 12.339, $p < .001$, $p\eta^2 = .168$], indicating that the CBA conditions (4.5 %) and the ABA conditions (4.4 %) were more error prone than the CAA conditions (3.5 %) ($p < .001$ and $p = .002$, respectively). However, the CBA and ABA conditions were not different ($p > .05$). The interaction between “types of task” and “types of sequence” was not significant [F (2, 122) = .741, $p = .479$, $p\eta^2 = .012$].

3.2. Ex-Gaussian analysis of RTs

When the RTs for the three conditions (CAA, CBA and ABA) were compared between the two tasks (linguistic and non-linguistic switching tasks) there was no statistically significant difference (see above).

However, given that the mean captures only one parameter of the RT distribution, it is possible that differences are still present for other parameters of the distribution.

For this reason, we further explored these potential differences by running an ex-Gaussian analysis, a more fine-grained analysis of the RT distribution that allows the estimation of more parameters than the mean. The ex-Gaussian fitting decomposes the overall RT distribution into two components, the normal and the exponential one. The normal distribution is characterized by two parameters, such as mu (μ) and sigma (σ). In detail, μ is the mean of the fitted normal distribution, and σ corresponds to the variance. The exponential distribution corresponds to the tail of the RT distribution and it is characterized by the parameter tau (τ).

The question here is whether the differences between the task conditions in the linguistic and non-linguistic switching tasks are captured by the normal component of the RT distribution and/or by the exponential one. The application of the ex-Gaussian distribution analysis is not only a more fine-grained tool for data analysis, but also relevant at a theoretical level. Indeed, according to some authors the cognitive processes behind these two components (μ, τ) might be different (see Matzke & Wagenmakers, 2009).

The raw data were sorted by "types of sequence" (CAA, CBA and ABA) separately for the two tasks. The parameters of the ex-Gaussian distribution (μ and τ) were obtained for each participant using the quantile maximum likelihood (QML) estimation procedure in QMPE 2.18 (Cousineau, Brown, & Heathcote, 2004). The estimation results into a value for each parameter (μ and τ) and for each participant per condition.

3.2.1. ***Ex-Gaussian parameters (μ and τ)***

We performed two omnibus ANOVAs for μ and τ values separately, considering "types of task" (language switching task and non-linguistic switching task) and “types of sequence” (CBA, ABA and CAA) as two within-subject factors.

For μ, the main effect of “types of task” was significant [F (1, 61) = 30.638, $p < .001$; $p\eta^2 = .334$], indicating that overall the participants had smaller μ values in the non-linguistic switching task (653 ms) than in the linguistic switching task (740 ms) (see Figure 3). Also, the main effect of “types of sequence” was significant [F (2, 122) = 6.901, $p = .001$, $p\eta^2 = .102$], but the interaction between the two main factors was not [F (2, 122) = .479, p= .620, $p\eta^2 = .008$). Post-hoc analysis revealed that the CAA condition had smaller values of μ (689 ms) than the ABA condition (707 ms, $p = .003$), but not different from the CBA condition (692 ms, $p > .05$). Indeed, the “n-1 shift cost” was not different from zero in both tasks [linguistic switching task: 4 ms; t (61) = .530, p = .598; non-linguistic switching task: 3 ms; t (61) = .348, p = .729] (see Figure 4). The ABA condition had bigger values of μ than the CBA condition ($p = .007$). Indeed, the “n-2 repetition cost” was different from zero in the non-linguistic switching task (20 ms; t (61) = 2.913, $p = .005$) and marginally different from zero in the linguistic switching task (10 ms; t (61) = 1.682, $p = .098$) (see Figure 4).

For τ, the main effect of “types of task” was significant [F (1, 61) = 32.202, $p < .001$, $p\eta^2 = .346$] indicating that overall the participants had smaller τ values in the linguistic switching task (286 ms) than in the non-linguistic switching task (376 ms) (see Figure 3). Also, the main effect of “types of sequence” was significant [F (2, 122) = 58.545, $p < .001$, $p\eta^2 = .49$]. Post-hoc analyses revealed that all the conditions were significantly different among them ($p_s < .05$): the CAA condition showed the smallest τ values (300 ms), the ABA condition the largest ones (352 ms) and the CBA condition between these two conditions (341 ms).

Interestingly, the interaction between "types of task" and "types of sequence" was also significant [$F(2, 122) = 3.523$, $p = .033$, $p\eta^2 = .055$]. To further explore this significant interaction we performed two paired t-tests –one for the linguistic switching task and the other for the non-linguistic switching task- between the two "types of cost" ("n-1 shift cost", "n-2 repetition cost") for τ values.

In the linguistic switching task, for τ, the "n-1 shift cost" (35 ms) was different from zero [$t(61) = 4.464$, $p < .001$]. Instead, the "n-2 repetition cost" (2 ms) was not different from zero [$t(61) = .406$, $p = .686$].

These results suggest that the "n-1 shift cost" was captured by the exponential component (τ values) of the RT distribution only. Interestingly, it appears that the "n-2 repetition cost" was not captured by neither the exponential nor the normal component of the RT distribution (see above). This is likely due to the fact that the linguistic "n-2 repetition cost" is too small to be decomposed in the two different components of the RT distribution.

In the non-linguistic switching task, for τ, results revealed that both the "n-1 shift cost" (48 ms) and the "n-2 repetition cost" (20 ms) were different from zero ["n-1 shift cost": $t(61) = 5.291$, $p < .001$; "n-2 repetition cost": $t(61) = 2.987$, $p = .004$]. Paired t-test between the two costs revealed that the "n-1 shift cost" and the "n-2 repetition cost" were significantly different [t (61) = 2.133, p = .037].

These results suggest that in the non-linguistic switching task the "n-1 shift cost" was captured by the exponential component, whereas the "n-2 repetition cost" was captured by both the normal and the exponential components.

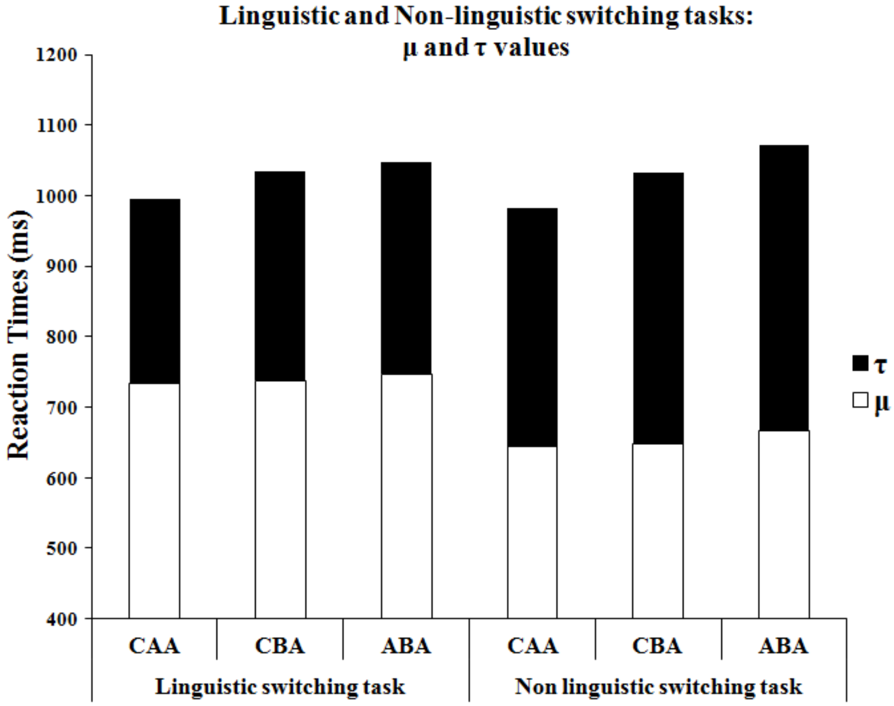
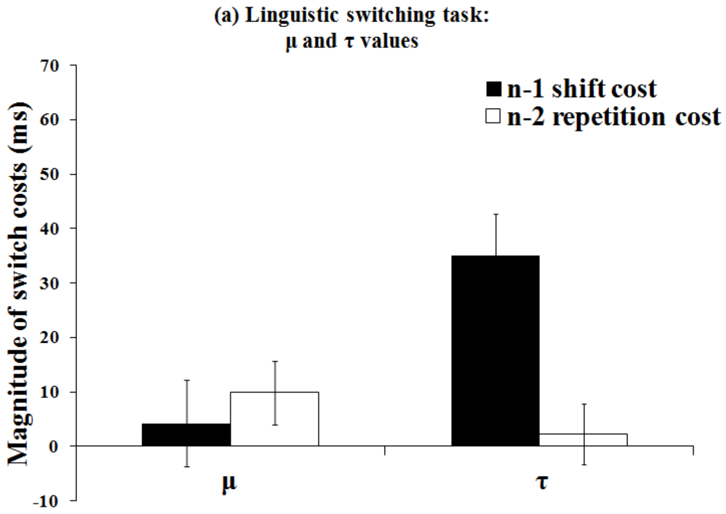


Figure 3. Ex-Gaussian analysis. μ and τ values relative to the three different types of sequence (CAA, CBA and ABA) in the Linguistic switching task and in the Non-linguistic switching task.



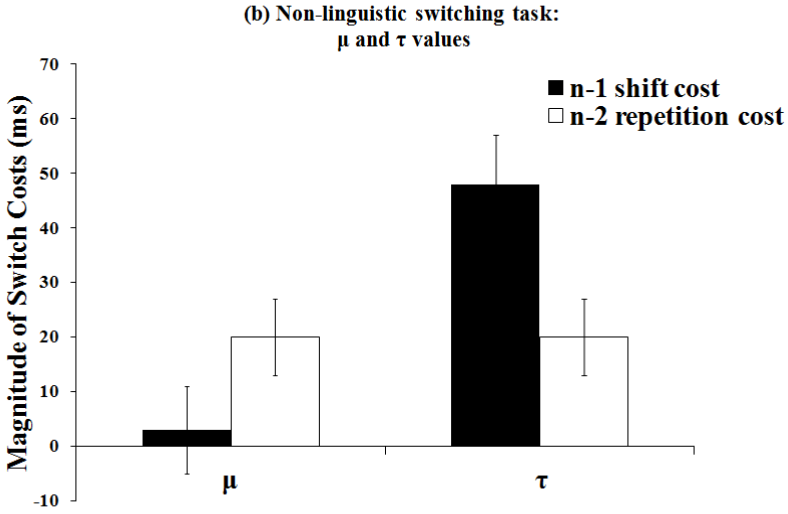


Figure 4. Ex-Gaussian analysis. μ and τ values relative to the two costs ("n-1 shift cost" and "n-2 repetition cost") in the **(a)** Linguistic switching task and in the **(b)** Non-linguistic switching task. Errors bars refer to SE.

3.3. Correlation analysis of the switch costs between tasks (RTs and ex-Gaussian parameters)

3.3.1. RTs.

In order to evaluate the overlap between bLC and EC systems, we ran a correlation analysis (Pearson's coefficient) between the linguistic and the non-linguistic switching tasks, for the "n-1 shift cost" and the "n-2 repetition cost". As in previous studies (e.g., Calabria et al., 2012; 2013), we hypothesized that if the two switch costs reflect the efficiency of the bLC and EC systems we may expect that the magnitudes of the switch costs (linguistic and non-linguistic) vary in similar manner in the same group of participants.

Results revealed that neither the "n-1 shift cost" ($r = -.023$, $p = .856$) nor the "n-2 repetition cost" ($r = -.051$, $p = .695$) were correlated across tasks.

3.3.2. Ex-Gaussian parameters: μ and τ.

In order to explore more deeply the overlap between bLC and EC systems, we ran also a correlation analysis (Pearson's coefficient) between the linguistic and the non-linguistic switching tasks for each of the two costs, for μ and τ separately.

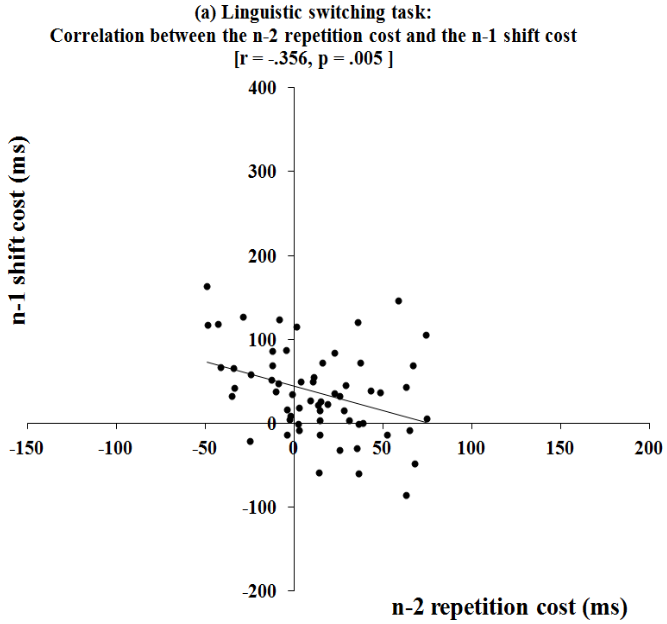
For μ, the "n-1 shift cost" was not correlated across tasks [$r = -.057$, $p = .658$] and neither was the "n-2 repetition cost" [$r = .088$, $p = .495$].

For τ, the “n-1 shift cost” was not correlated across tasks [r = -.135, p = .297] and neither was the “n-2 repetition cost” [r = .001, p = .997].

3.4. Correlation analysis of the switch costs within tasks (RTs and ex-Gaussian parameters)

3.4.1. RTs.

In order to evaluate the overlap between bLC and EC systems of a control strategy for interference resolution (i.e., *cognitive control flexibility*), we correlated the “n-1 shift cost” and the “n-2 repetition cost” within each task. We found negative correlations between the two costs, both in the linguistic [r = -.356, p = .005] and in the non-linguistic switching tasks [r = -.413, p = .001] (see Figure 5).



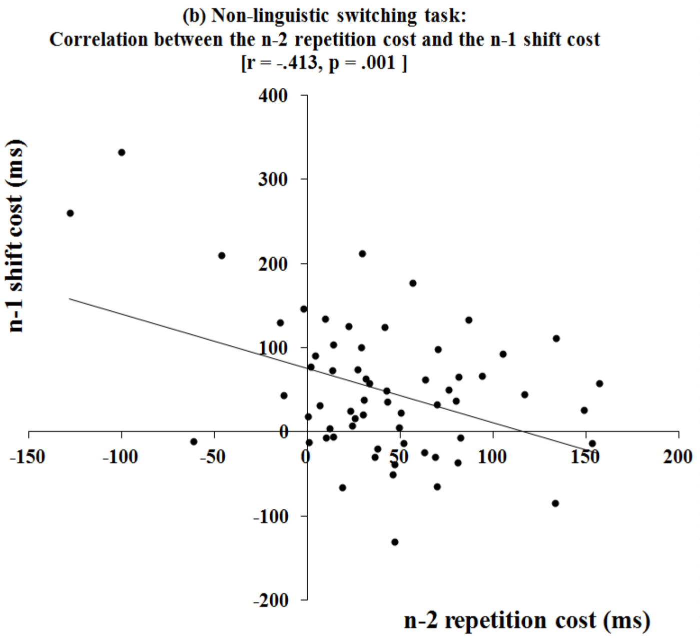


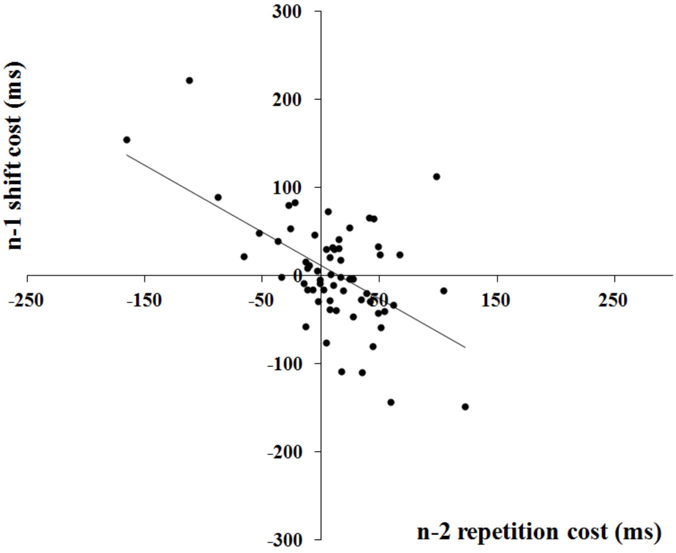
Figure 5. Correlations between the "n-2 repetition cost" and the "n-1 shift cost" (RTs). (a) Linguistic switching task and **(b)** Non-linguistic switching task.

3.4.2. Ex-Gaussian parameters: μ and τ.

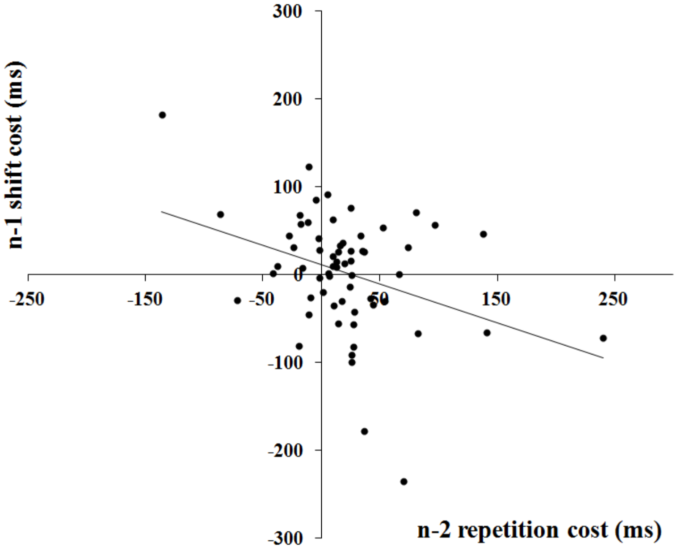
In order to reveal whether these correlations could affect the different components of the RT distribution similarly, we also explored the correlation between the "n-2 repetition cost" and the "n-1 shift cost", for μ and τ separately. In fact, it could be interesting to explore whether the correlation between the costs in the two tasks is mainly driven by one or both of these parameters.

For μ, we found negative correlations between the two costs, both in the linguistic [r = -.558, p < .001] and in the non-linguistic switching tasks [r = -.354, p = .005] (see Figure 6).

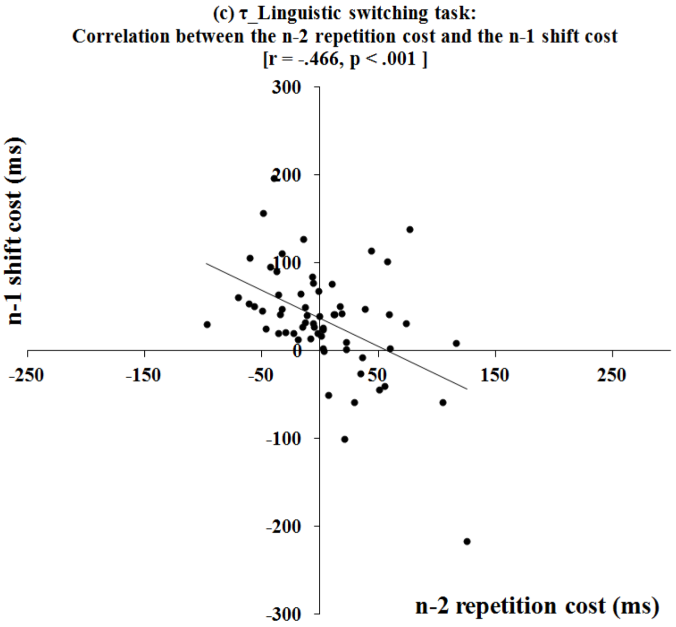
For τ, we found negative correlations between the two costs, both in the linguistic [r = -.466, p < .001] and in the non-linguistic switching tasks [r = -.368, p = .003] (see Figure 6).



(a) µ_Linguistic switching task:
Correlation between the n-2 repetition cost and the n-1 shift cost
[r = -.558, p < .001]



(b) µ_Non-linguistic switching task:
Correlation between the n-2 repetition cost and the n-1 shift cost
[r = -.354, p = .005]


(c) τ_Linguistic switching task:
Correlation between the n-2 repetition cost and the n-1 shift cost
[r = -.466, p < .001]

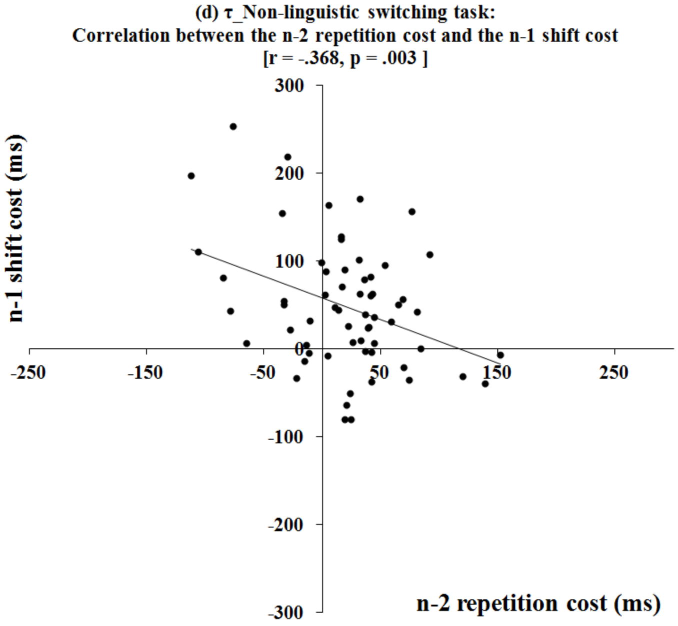

(d) τ_Non-linguistic switching task:
Correlation between the n-2 repetition cost and the n-1 shift cost
[r = -.368, p = .003]

Figure 6. Correlations between the “n-2 repetition cost” and the “n-1 shift cost” (μ and τ values). (a) μ values of the Linguistic switching task, **(b)** μ values

of the Non-linguistic switching task, **(c)** τ values of the Linguistic switching task and **(d)** τ values of the Non-linguistic switching task.

4. Discussion

In the present study we investigated the overlap between bLC and EC systems, by exploring the performance of 62 high-proficient bilinguals in a linguistic and in a non-linguistic switching task. First, we examined whether *inhibitory control* is similarly involved in bLC and EC tasks. Second, we evaluated whether different EC processes ("task activation" and "task inhibition") are similarly combined in bLC and EC tasks (i.e., *cognitive control flexibility*).

Various critical results were observed.

First, while the magnitudes of the "n-1 shift costs" and "n-2 repetition costs" were very similar in the non-linguistic switching task, the latter effect was significantly reduced as compared to the former in the linguistic switching task. Crucially, this difference between tasks in the pattern of switch costs cannot be attributable to differences in task difficulty between the linguistic and the non-linguistic switching task, since RTs were similar across them. Indeed, it seems that the "n-2 repetition cost", a potential index of *inhibitory control*, is very much reduced in the linguistic switching task only.

Second, the magnitude of the two costs reported here did not correlate across tasks (RTs and ex-Gaussian parameters). That is, performance in the non-linguistic switching task was not related to performance in the linguistic switching task. This result replicates previous observations regarding the "n-1 shift cost" (e.g., Calabria et al., 2012), but most importantly, it shows that a potential index of *inhibitory control* (Mayr & Keele, 2000), that is, the "n-2 repetition cost" does not correlate across tasks. Therefore, to the extent to which these correlations should be informative regarding the overlap between bLC and EC systems, it seems that the mechanisms behind the two costs and especially *inhibitory control* did not vary in the same way across bLC and EC tasks.

These results can be considered among all the evidence problematic to be reconciled with those models assuming domain-general *inhibitory control* (see Inhibitory Control Model-ICM; Green, 1998) as the key mechanism that regulates bLC (e.g., Philipp et al., 2007; Runnqvist & Costa, 2012; Runnqvist, Strijkers, Alario, & Costa, 2012). However, regarding the present study in particular, it is still possible to find an explanation to reconcile this result with the tenets of the ICM. This explanation is based on the assumption that high-proficient bilinguals would represent a "special" case in the context of bLC functioning. In fact, it has been proposed that high-proficient bilinguals, differently from low-proficient bilinguals, may use language-specific selection mechanisms and not *inhibitory control* to control their languages (see Costa et al., 2004; 2006). Hence, this finding is accord with the proposal by Costa et al. (2004; 2006), as it indicates that *inhibitory control*, as compared to other EC mechanisms, is less involved in bLC only. Since this result suggests that "task inhibition" does not play a crucial role in the linguistic task, it is likely that the "n-1 shift cost" here is due to an advantage in “task activation” during task repetitions, rather than to a disadvantage of *inhibitory control* during switching trials.

Overall, these results indicate that different amount of *inhibitory control* is involved when switching among three different languages and when switching among three different non-linguistic tasks. Therefore, it seems that at least *inhibitory control* is not the mechanism that overlaps between bLC and EC systems.

Along the same lines, the results from the ex-Gaussian analysis support the hypothesis proposing a partial overlap between the two systems. Indeed, despite the fact that participants performed the two tasks with the same overall speed of processing, we found some differences in the components of the RT distributions between the two tasks. Indeed, “μ” that is, the normal component of the distribution, had larger values in the linguistic as compared to the non-linguistic switching task, whereas for “τ”, the exponential component, we found the reversed pattern. Moreover, when we look at the distribution of the two types of switch costs (“n-1 shift cost” and “n-2 repetition cost”), the exponential component (“τ”) captured the effects differently. That is, for the “n-1 shift cost” to the same extent in both tasks, whereas for the “n-2 repetition cost” only in the non-linguistic switching task.

It has been proposed that “τ” might reflect processes related to EC, such as *inhibitory control* (McAuley, Yap, Christ, & White, 2006; Shao, Roelofs, & Meyer 2012; Spieler, Balota, & Faust, 1996). Even though many authors refrained from interpreting the effects of this component as related to specific cognitive processes

(Matzke & Wagenmakers, 2009), the *inhibitory control* interpretation is in accord with our data, as it shows that τ values in the linguistic switching task are reduced as compared to those in the non-linguistic switching task.

In accord with our results, Calabria et al. (2013) reported a change in the exponential component ("τ" values) in the context of the non-linguistic switching task for the effect of aging. That is, the "n-1 shift cost" increased in the bilingual older adults as compared to the young group and, interestingly, this relative increase was indexed by the exponential component of the distribution for switch trials ("τ" values). Importantly, this age-related change was not observed in the same participants when they performed the linguistic switching task. Given that aging is also associated with a decline of the *inhibitory control* system (Greenwood, 2000; Rhodes, 2004; Verhaeghen & Cerella, 2002), some researchers suggested that the exponential component captures the efficiency of this EC process (e.g., Penner-Wilger, Leth-Steensen, & LeFevre, 2002; Schmiedek, Oberauer, Wilhelm, Süß, & Wittmann, 2007; Spieler et al., 1996).

Therefore, taken together these results suggest *inhibitory control* is less involved in bLC than in EC, at least for what concerns bilinguals equally proficient in both the languages.

Finally, beyond the question about the specific involvement of *inhibitory control* in bLC and EC tasks, we tested another form of control that is related to the context in which these two costs are processed. In fact, another possibility to look at the overlap between the linguistic and the non-linguistic domain of control can regard the dynamic combination of different EC processes (see Morales et al., 2013).

Hence, we investigated whether the “n-1 shift cost” and the “n-2 repetition cost” were functionally related in the same way in a linguistic and in a non-linguistic switching task. We did so by correlating the two costs within each task.

We had a specific prediction about this relationship. It has been showed that the size of the “n-2 repetition cost” (*inhibitory control*) is reduced when task repetitions (i.e., CAA sequences), from which the “n-1 shift cost” is measured, are presented within the same switching task. Philipp and Koch (2006) suggested that this effect could be due to a change of strategy for interference resolution in a switching task. That is, in absence of repetitions, “task inhibition” is likely the dominant strategy applied to solve interference and these effects are observable in the size of the “n-2 repetition cost”. However, the presence of repetitions causes the “n-2 repetition cost” reduction (e.g., Philipp & Koch, 2006), that suggests less involvement of *inhibitory control* in the task. Interestingly, this effect is modulated by the ratio between repetitions (i.e., CAA sequences) and the other two switching conditions (CBA and ABA sequences) in the task. That is, when the number of repetitions is equal to that of the other two conditions, the “n-2 repetition cost” almost disappears (see Experiment 1 in Philipp & Koch, 2006). Instead, if the number of repetitions (CAA task sequences) is much lower as compared to that of the other conditions (CBA and ABA task sequences), the “n-2 repetition cost” is not drastically affected (see Experiment 2 in Philipp & Koch, 2006). Hence, it has been proposed that repetitions (CAA task sequences) cause a lowering of *inhibitory control* to favor another mechanism for interference resolution in a switching task, that is, “task activation”. Hence, “task inhibition” and “task activation” are two opposing processes for interference resolution that in some specific circumstances (i.e., unbalanced ratio between repetitions and the two other conditions) can be integrated (see Experiment 2 Philipp & Koch, 2006).

To the extent to which the presence of the two costs requires to find a strategy to balance “task inhibition” (“n-2 repetition cost”) and “task activation” (“n-1 shift cost”), we were expecting to see a negative correlation between the two costs. Specifically, our hypothesis was that if this control strategy was similarly adopted in the linguistic and in the non-linguistic switching task, we should have observed a similar correlation between the two costs in the two tasks, and this is precisely what we found.

A significant negative correlation between the two costs (“n-1 shift cost” and “n-2 repetition cost”) was observable in both the linguistic and the non-linguistic switching tasks.

Note that this result might be seen as at odds with the lack of the between tasks correlation of the “n-1 shift cost” and the “n-2 repetition cost”. In fact, on one hand, we suggest that the control processes behind the two costs do not vary in the same way across bLC and EC tasks. Previously, similar results have been taken as reflecting a partial overlap between bLC and EC systems (Calabria et al., 2012; 2013). On the other hand, we suggest that these mechanisms, even though they do not vary singularly in the same way across tasks (i.e., they are not correlated), nevertheless, they can be similarly combined in the two tasks. Importantly, this latter effect refers to the general setting of which process is applied to solve the interference within a given experimental context and not to the amount of “task activation” and “task inhibition” that is applied to resolve the interference in each single trial. Hence, even if the amount of inhibition and activation varies differently across tasks, leading to a lack of correlation of the two costs between tasks, it is still possible to observe a similar control strategy in the two tasks to combine “task activation” and “task inhibition” (i.e., negative correlation between the “n-1 shift cost” and the “n-2 repetition cost”).

In summary, we found a negative correlation between the “n-2 repetition cost” and the “n-1 shift cost” and we argue that it reflects the ability of adjusting the performance according to the need of applying different but complementary EC mechanisms (“task activation” and “task inhibition”) during a switching task. For the first time, with the present study we provide evidence that this ability is similarly involved in the linguistic and in the non-linguistic domains of control.

These results are in accord and reinforce the conclusions of a recent study (Branzi, Calabria, Gade, Fuentes, & Costa, Under Review) in which we compared bilinguals and monolinguals in the same non-linguistic switching task and in which we found that only bilinguals showed the negative correlation between the “n-2 repetition cost” and the “n-1 shift cost”, associated with a faster performance. Indeed, this ability of combining different EC mechanisms might be what differentiates bilinguals from monolinguals and, at the same time, what is transferred from bLC to EC.

All in all, these results suggest that some aspects, such as the amount of *inhibitory control* involved in a task, are specific to the domain of language and not necessarily related to the EC system. Instead, other aspects such as the general control strategy to combine different EC processes (i.e., *cognitive control flexibility*) seem to be shared between the bLC and EC systems.

5. Conclusion

The contribution of the present study is two-fold. First, we provide additional support to previous findings showing that specific control mechanisms are differently involved in linguistic and in non-linguistic control domains (e.g., Calabria et al., 2012; 2013; Weissberger et al., 2012). Crucially, we extended these conclusions to the role of *inhibitory control*. That is, at least for high-proficient bilinguals, *inhibitory control* is less involved in the bLC than in the domain-general EC system. Second, we provide the first evidence of an overlap between bLC and EC systems regarding a general control strategy that allows combining different EC processes in a switching task.

Future research is needful to reveal whether or not these results might reflect control strategies that are modulated by bilingualism experience and language proficiency.

Acknowledgments

This work was supported by grants from the Spanish Government (PSI2008-01191, PSI2011-23033, Consolider Ingenio 2010 CSD2007-00012) and the Catalan Government (Consolidat SGR 2009-1521). Francesca M. Branzi was supported by a predoctoral fellowship from the Spanish Government (FPU-2009-2013). Marco Calabria was supported by a postdoctoral fellowship from the Spanish Government (Juan de La Cierva Fellowship)

References

Abutalebi, J., & Green, D. (2007). Bilingual language production: The neurocognition of language representation and control. *Journal of Neurolinguistics*, *20*(3), 242-275.

Allport, D. A., Styles, E. A., & Hsieh, S. (1994). Shifting intentional set: Exploring the dynamic control of tasks. In C. Umilta & M. Moscovitch (Eds.), Conscious and nonconscious information processing: Attention and performance XV (pp.421-452). Cambridge, MA: MIT Press.

Arbuthnott, K., & Frank, J. (2000). Executive control in set switching: Residual switch cost and task-set inhibition. *Canadian Journal of Experimental Psychology/Revue canadienne de psychologie expérimentale*, *54*(1), 33.

Bialystok, E., Craik, F. I., & Luk, G. (2012). Bilingualism: Consequences for mind and brain. *Trends in cognitive sciences*, *16*(4), 240-250.

Bobb, S. C., & Wodniecka, Z. (2013). Language switching in picture naming: What asymmetric switch costs (do not) tell us about inhibition in bilingual speech planning. *Journal of Cognitive Psychology*, *25*(5), 568-585.

Branzi, F. M., Martin, C. D., Abutalebi, J., & Costa, A. (2014). The after-effects of bilingual language production. *Neuropsychologia*, *52*, 102-116.

Branzi, F. M., Calabria, M., Gade, M., Fuentes, L. & Costa, A. (Under Review).Beyond the switch cost: flexible strategies in bilingual minds. *Journal of Memory and Language*.

Calabria, M., Branzi, F. M., Marne, P., Hernandez, M., & Costa, A. (2013). Age-related effects over bilingual language control and executive control. *Bilingualism: Language and Cognition*, 1-14.

Calabria, M., Hernández, M., Branzi, F. M., & Costa, A. (2012). Qualitative differences between bilingual language control and executive control: evidence from task-switching. *Frontiers in Psychology, 2*.

Christoffels, I. K., Firk, C., & Schiller, N. O. (2007). Bilingual language control: An event-related brain potential study. *Brain research*, *1147*, 192-208.

Costa, A., & Santesteban, M. (2004). Lexical access in bilingual speech production: Evidence from language switching in highly proficient bilinguals and L2 learners. *Journal of memory and language*, *50*(4), 491-511.

Costa, A., Santesteban, M., & Ivanova, I. (2006). How do highly proficient bilinguals control their lexicalization process? Inhibitory and language-specific selection mechanisms are both functional. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *32*(5), 1057.

Cousineau, D., Brown, S., & Heathcote, A. (2004). Fitting distributions using maximum likelihood: Methods and packages. *Behavior Research Methods, Instruments, & Computers*, *36*(4), 742-756.

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

Greenwood, P. M. (2000). The frontal aging hypothesis evaluated. *Journal of the International Neuropsychological Society, 6,* 705–726.

Jackson, G. M., Swainson, R., Cunnington, R., & Jackson, S. R. (2001). ERP correlates of executive control during repeated language switching. *Bilingualism: Language and Cognition*, *4*(02), 169-178.

Kiesel, A., Steinhauser, M., Wendt, M., Falkenstein, M., Jost, K., Philipp, A. M., & Koch, I. (2010). Control and interference in task switching—A review. *Psychological bulletin*, *136*(5), 849.

Koch, I., Gade, M., Schuch, S., & Philipp, A. M. (2010). The role of inhibition in task switching: A review. *Psychonomic bulletin & review*, *17*(1), 1-14.

Mayr, U., & Keele, S. W. (2000). Changing internal constraints on action: the role of backward inhibition. *Journal of Experimental Psychology: General*, *129*(1), 4.

Matzke, D., & Wagenmakers, E. J. (2009). Psychological interpretation of the ex-Gaussian and shifted Wald parameters: A diffusion model analysis. *Psychonomic Bulletin & Review, 16*(5), 798-817.

McAuley, T., Yap, M., Christ, S. E., & White, D. A. (2006). Revisiting inhibitory control across the life span: Insights from the ex-Gaussian distribution. *Developmental neuropsychology*, *29*(3), 447-458.

Meuter, R. F., & Allport, A. (1999). Bilingual language switching in naming: Asymmetrical costs of language selection. *Journal of Memory and Language*, *40*(1), 25-40.

Misra, M., Guo, T., Bobb, S. C., & Kroll, J. F. (2012). When bilinguals choose a single word to speak: Electrophysiological evidence for inhibition of the native language. *Journal of Memory and Language*, *67*(1), 224-237.

Morales, J., Gómez-Ariza, C. J., & Bajo, M. T. (2013). Dual mechanisms of cognitive control in bilinguals and monolinguals. *Journal of Cognitive Psychology*, *25*(5), 531-546.

Ophir, E., Nass, C., & Wagner, A. D. (2009). Cognitive control in media multitaskers. *Proceedings of the National Academy of Sciences*, *106*(37), 15583-15587.

Penner-Wilger, M., Leth-Steensen, C., & LeFevre, J. A. (2002). Decomposing the problem-size effect: A comparison of response time distributions across cultures. *Memory and Cognition*, *30*, 1160–1167.

Philipp, A. M., Gade, M., & Koch, I. (2007). Inhibitory processes in language switching: Evidence from switching language-defined response sets. *European Journal of Cognitive Psychology*, *19*(3), 395-416.

Philipp, A. M., & Koch, I. (2006). Task inhibition and task repetition in task switching. *European Journal of Cognitive Psychology*, *18*(4), 624-639.

Prior, A. (2012). Too much of a good thing: Stronger bilingual inhibition leads to larger lag-2 task repetition costs. *Cognition*, *125*(1), 1-12.

Prior, A., & Gollan, T. H. (2011). Good language-switchers are good task-switchers: Evidence from Spanish–English and Mandarin–English bilinguals. *Journal of the International Neuropsychological Society*, *17*(04), 682-691.

Prior, A., & Gollan, T. H. (2013). The elusive link between language control and executive control: A case of limited transfer. *Journal of Cognitive Psychology, 25*(5), 622-645.

Rhodes, M. G. (2004). Age-related differences in performance on the Wisconsin card sorting test: A meta-analytic review. *Psychology and Aging, 19,* 482–494.

Runnqvist, E., & Costa, A. (2012). Is retrieval-induced forgetting behind the bilingual disadvantage in word production. *Bilingualism: Language and Cognition*, *15*(2), 365-377.

Runnqvist, E., Strijkers, K., Alario, F., & Costa, A. (2012). Cumulative semantic interference is blind to language: Implications for models of bilingual speech production. *Journal of Memory and Language*, *66*(4), 850-869.

Schmiedek, F., Oberauer, K., Wilhelm, O., Süß, H. M., & Wittmann, W. W. (2007). Individual differences in components of reaction time distributions and their relations to working memory and intelligence. *Journal of Experimental Psychology: General*, *136*(3), 414.

Schuch, S., & Koch, I. (2003). The role of response selection for inhibition of task sets in task shifting. *Journal of Experimental Psychology: Human Perception and Performance*, *29*(1), 92.

Shao, Z., Roelofs, A., & Meyer, A. S. (2012). Sources of individual differences in the speed of naming objects and actions: The contribution of executive control. *The Quarterly Journal of Experimental Psychology*, *65*(10), 1927-1944.

Snodgrass, J. G., & Vanderwart, M. (1980). A standardized set of 260 pictures: norms for name agreement, image agreement, familiarity, and visual complexity. *Journal of experimental psychology: Human learning and memory, 6*(2), 174.

Soveri, A., Rodriguez-Fornells, A., & Laine, M. (2011). Is there a relationship between language switching and executive functions in bilingualism? Introducing a within-group analysis approach. *Bilingualism and cognitive control*, 138.

Spieler, D. H., Balota, D. A., & Faust, M. E. (1996). Stroop performance in healthy younger and older adults and in individuals with dementia of the Alzheimer's type. *Journal of Experimental Psychology: Human Perception and Performance*, *22*(2), 461.

Verhaeghen, P., & Cerella, J. (2002). Aging, executive control, and attention: A review of meta-analyses. *Neuroscience and Biobehavioral Reviews, 26,* 849–857.

Weissberger, G. H., Wierenga, C. E., Bondi, M. W., & Gollan, T. H. (2012). Partially overlapping mechanisms of language and task control in young and older bilinguals. *Psychology and aging*, *27*(4), 959.

2.8 Language control in bilinguals: monitoring and response selection

Branzi FM, Della Rosa PA, Canini M, Costa A, Abutalebi J. Language Control in Bilinguals: Monitoring and Response Selection. Cereb Cortex. 2015 Apr 1. pii: bhv052. [Epub ahead of print]. doi: 10.1093/cercor/bhv052

Language control in bilinguals: monitoring and response selection

Francesca M. Branzi[1*], Pasquale A. Della Rosa[2*], Matteo Canini [2,3], Albert Costa[1,4], & Jubin Abutalebi [3, 5]

[*]These authors equally contributed to the work.

[1] Center for Brain and Cognition (CBC), Universitat Pompeu Fabra, Barcelona, Spain.
[2] IBFM-CNR (National Research Council), Milan, Italy
[3] Centre of Cognitive Neurosciences, San Raffaele University & San Raffaele Scientific Institute, Milan, Italy
[4] ICREA, Spain
[5] Division of Speech & Hearing Sciences, University of Hong Kong, Hong Kong

Address for correspondence:

Dr. Jubin Abutalebi

Faculty of Psychology

University San Raffaele

Via Olgettina 58,

20132 Milano, Italy,

abutalebi.jubin@hsr.it

Abstract

Language control refers to the cognitive mechanism that allows bilinguals to correctly speak in one language avoiding interference from the non-requested language. Bilinguals achieve this feat by engaging brain areas closely related to cognitive control. However, two questions still await resolution: whether this network is specific for control of linguistic representations, and whether this network is differently engaged when control is exerted upon a restricted set of lexical representations that were previously used (i.e., *local control*) as opposed to control of the entire language system (i.e., *global control*).

In the present study, we employed er-fMRI to investigate these two questions by employing linguistic and non-linguistic blocked switching tasks in the same bilingual participants. We first report that the left PFC is driven similarly for control of linguistic and non-linguistic representations suggesting a general key role in the implementation of response selection. Second, we propose that language control in bilinguals is hierarchically organized with the dACC/pre-SMA acting as the *supervisory attentional system* recruited for increased monitoring demands such as *local control* specifically for a second language, and prefrontal-inferior parietal areas and the caudate as the *effector system* of language control, tailored for response selection purposes for both *local* and *global control*.

Keywords: bilingual, language control, cognitive control, fMRI, response selection,

1. Introduction

Language control refers to a set of cognitive abilities, which allows bilinguals to utter a word in an intended language avoiding interference from the non-requested language (Abutalebi & Green, 2007, 2008; Green & Abutalebi, 2013). The cognitive processes underlying language control entail the intention to speak in a given language, selection of the target response (the word in the intended language), inhibition of words from the non-target language, and monitoring speech for potential intrusions (viable candidate words in the other language) (Costa et al., 1999; Kroll et al., 2006; Abutalebi & Green, 2007) as well as language disengagement and engagement (i.e., stop speaking in one language and switching to another language (Green & Abutalebi, 2013). According to a prominent neurocognitive model of bilingual language processing (Abutalebi & Green, 2007, 2008; Green & Abutalebi, 2013), the above-mentioned processes are orchestrated by a network of cortical and subcortical brain areas, tightly related to executive control. Chief among these areas is the ACC/pre-SMA complex (i.e., anterior cingulate cortex/pre-supplementary motor area) involved in monitoring potential conflicts between languages and detection of potential errors (Abutalebi et al., 2012). A further critical area is the left prefrontal cortex (LPFC), generally associated with control of interference and conflict resolution. Inferior parietal lobules (left and right, i.e., LIPL, RIPL) are also a part of this language control network and are associated to the maintenance of task representations. Among subcortical structures, the left caudate (LC) is associated to inhibitory processes in order to control for verbal interference (Abutalebi et al., 2008; Ali et al., 2010) when switching between languages (e.g., Abutalebi et al., 2013). In a recent update of the model (i.e., Green & Abutalebi, 2013) other regions in the right hemisphere were included, namely the right prefrontal frontal cortex (RPFC) for response inhibition, right thalamus and basal ganglia (Caudate\Putamen) entailed for the detection of salient cues.

Despite a certain agreement regarding the neural groundings of this language control network, two main questions regarding its functioning remain to be fully elucidated.

The first issue is whether this language control network is similarly involved when applying control processes to non-linguistic representations. Hence, the issue here is whether these areas respond differently when exerting control over linguistic representations as to when exerting control over other types of representations. In other words, it needs to be established if different types of responses (i.e., linguistic vs. non-linguistic responses) would differentially affect the neural regions involved in the language control network (e.g., Green, 1986; Green, 1998). The second question concerns the scope at which language control is exerted (see De Groot & Christoffels, 2006). The issue here is whether language control acts at the level of the specific stimulus to be selected, such as a lexical item (i.e., *local contro*l), or rather acts upon the entire language system (i.e., *global control*). Likewise, from a neural perspective, are similar brain systems engaged for *local* and *global control*, and if yes, whether to the same degree when controlling specific language response (S-LR) bindings (i.e., *local control*) as compared to when engaging\disengaging the whole language set (S-LS) (i.e., *global control*)?

The majority of the studies that investigated the above mentioned questions have relied upon the so-called "language-switching paradigm" (e.g., Meuter & Allport, 1999; Christoffels et al., 2007; Garbin et al., 2011; Misra et al., 2012; Branzi et al., 2014). Despite differences between the specific instantiations of this paradigm, they all involve speakers using their two languages in such a way that is possible to measure the after-effects of using one language on the subsequent use of the other language. These after-effects are generally observable in the so-called "switch cost". This "cost", measurable in response times (RTs) and in neural effects, arises since switching between languages requires shifting between two different stimulus language-response (S-LR) sets (e.g., Waszak et al., 2003). Therefore, switching requires time and cognitive effort to establish new S-LR bindings overcoming the binding established before. As to its neural counterpart, following the aforementioned neurocognitive model of bilingual language processing (Abutalebi & Green, 2007, 2008; Green & Abutalebi, 2013), during language switching, the PFC would work together with the ACC and the basal ganglia in order to achieve this new S-LR bindings and overcome potential interference from the bindings established before. Specifically, the ACC would signal potential response conflicts to the PFC that in turn would trigger control of the non-target S-LR bindings through inhibition driven by LC. This is the loop (PFC-LC loop) that allows language planning and language selection in the intended language.

The first aim of the present study is to assess whether this language control network is similarly involved when applying control processes over linguistic and non-linguistic representations. In particular, we assess whether switching S-LR bindings modulate this network in the same manner, when such switching is performed over linguistic and non-linguistic representations (e.g., Green, 1986, 1998; Abutalebi & Green, 2007, 2008; Green & Abutalebi, 2013). In detail, changes of brain activity will be investigated during linguistic and non-linguistic task performance by exploring neural "repetition priming" and "priming disruption" effects (e.g., Dobbins et al., 2004). Behaviorally, "repetition priming" effect refers to the faster reaction times (RTs) observed for the second repetition of the very same item (e.g., picture of a DOG, produce the word "dog"). This behavioral effect is accompanied by a decrease of neural responses for repeated stimuli in areas related to the stimulus processing (i.e., neural repetition priming or repetition suppression). This effect seems to reveal the reinforcement of S-R bindings set in the previous presentation of the stimulus (e.g., Stimulus: Picture / Response: Classification of the picture according to a semantic criteria A) (see Dobbins et al., 2004). Interestingly, however, when the same stimulus is repeated, but the task to be performed is not the same as previously conducted (e.g., Stimulus: Picture / Response: Classification of the picture according to a semantic criteria B), there is a disruption of neural priming (i.e., "priming disruption effect"). In other words, changing the task at hand disrupts neural priming (e.g., Dobbins et al., 2004). In the present study, we take the "neural priming disruption" effect as a measure of the control of

S-R bindings in two distinct tasks (a semantic classification task with two different criteria and a language naming task with two different languages). This measure may be referred to as to *local control*. Hence, we will assess differential *local control* effects between different tasks in brain areas associated to language control in bilinguals. Previously, the presence of *local control* effects has been taken to reflect that stimulus repetition automatically retrieves the task-set previously associated with that stimulus, which can interfere with the establishment of any new task-set. Hence, "priming disruption" most likely is a consequence of an increased necessity to engage cognitive control resources in order to remap the new S-R bindings (stimulus: Picture; response: Semantic classification of the picture according to criteria B, according to the previous example) and reject the one used when performing the previous task (Stimulus: Picture; Response: Semantic classification of the picture according to criteria A) (e.g., Henson & Rugg, 2003; Dobbins et al., 2004; Wig et al., 2009; Henson et al., 2014). Noteworthy, among other brain areas, the PFC has been found to be sensitive to the above-described changes in the S-R bindings (e.g., Dobbins et al., 2004; Race et al., 2009) with priming effects "disrupted" in the PFC potentially revealing its key role in the control of S-LR representations.

In our present investigation, we will compare changes of brain activity elicited when processing the same stimuli after and before either a linguistic or a semantic classification task change. We expect a similar network of brain areas to be involved in a similar fashion in the control of S-R bindings between the linguistic task and the semantic classification task. That is, similar changes will be observed when changing languages than when changing semantic classification criteria.

However, to the extent to which S-R bindings may be established to different strength degrees, we may also expect control processes to be entailed differently in contexts where a change of language or of semantic classification task occurs.

We expect therefore to observe differential changes in brain activity between the linguistic and the semantic classification task, in terms of increases or decreases of the measured BOLD signal, in the same cortical and subcortical aforementioned areas, with a particular emphasis for the LPFC for the abovementioned reasons (i.e., its key role in the control of S-LR representations).

The second aim is more specifically related to language processing and refers to the involvement of the brain areas underlying language control (Abutalebi & Green, 2007) in *local* and *global* language control (De Groot & Christoffels, 2006). As advanced earlier, *local control* refers to how a previous S-R binding affects a successive S-R remapping. In other words, *local* control refers to the after-effects of naming a given picture in one language upon subsequent naming of that very same picture in the other language. On the other hand, *global control* refers to how the task instruction of naming in a given language (i.e., language A) affects subsequent performance when naming in the other language (i.e., language B), for stimuli that have not been previously used in language A. Presumably, the control exerted during language production in language A, would subsequently affect the availability of any representations belonging to language B, regardless of whether these representations have been recalled or activated during the previous task.

Following some models of bilingual language processing, both control systems might be at play during bilingual language production (see De Groot & Christoffels, 2006). Our aim is to explore how the language control network is recruited when applying these two sorts of control. In order to test *local control* effects we assess changes of brain activity in the core areas proposed in the model by Abutalebi and Green (2007, 2008) (such as bilaterally the PFC, the LIPL, the RIPL, the LC and the dACC/pre-SMA complex) elicited when processing the same stimuli after and before a linguistic task change. We assess this effect by measuring "priming disruption" in the brain[21]. Instead, to test *global control* effects we assess changes of brain activity in the same brain areas elicited when processing new stimuli after and before a linguistic task change.

Importantly, for both questions addressed in this study we will consider the direction of the linguistic task change (from L1 to L2 vs. from L2 to L1). This is because the after-effects of naming in one language on the successive language may be different depending on the direction of language change (e.g., Misra et al., 2012; Branzi et al., 2014). In accordance to previous findings (e.g.,

---

[21] Note that in other studies (e.g., Dobbins et al., 2004), priming disruption effects have been measured differently than in the present study. In fact priming disruption was measured by comparing new vs. old items before and after the change of a task (see Dobbins et al., 2004).

Guo et al., 2011), we expect to observe such switch direction to have an effect in the brain areas involved in language control. Likewise, we expect to observe increased activity when passing from L2 to L1 than the reverse pattern. This is supposedly because language production in L2 might require a greater involvement of controlled processing, as compared to L1 production, when associating each stimulus to its corresponding lexical candidate for the first time. This extra-reinforcement of S-LR bindings in L2 likely will determine a greater effort in terms of control, when disengaging from the L2 S-LR bindings to establish new S-LR bindings for successive L1 production. Moreover, this L2 strengthening may be extended to the whole language set through a top-down controlled processing that would bias activation towards the correct language (see Runnqvist et al., 2012). Hence, if the whole L2 system is boosted the above mentioned effects may be observed also for *global control*. In the case of the reverse order, i.e., when going from L1 to L2, the outcome might be different, since L1 production as compared to L2 production might require less involvement of cognitive control areas when associating each stimulus to the lexical response and less control of interference from L2.

In summary, the purpose of the present fMRI study is twofold: to investigate whether the activity of the brain areas included in language control network (e.g., Abutalebi & Green, 2007; Green & Abutalebi 2013) is 1) modulated by the type of S-R bindings; and is 2) differentially engaged for *local* and *global control* in bilingual language production.

2. Material and Methods

2.1. Participants

Eighteen high-proficient German/Italian bilingual volunteers took part in the experiment. Bilingual participants came from South Tyrol, a region in Italy in which both German and Italian are spoken. For all the participants German was the first and dominant language (L1), whereas Italian was the second language, acquired early in life (L2; mean age of L2 acquisition= 4 years ± 3). Each participant received monetary remuneration for the participation in the study on behalf of the Pompeu Fabra University (Barcelona, Spain). Two participants were excluded from further analysis due to movement artifacts during fMRI recording or to anatomical irregularities in the brain, resulting in 16 participants (all females; mean age= 29 years ± 4).

The study protocol was approved by the Ethical Committee of the San-Raffaele University and was carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki) for experiments involving humans. All healthy subjects provided written consent and were asked to fill out a language proficiency\use self-evaluative questionnaire prior to their inclusion in the study. Participants also filled out a language proficiency test (Transparent Language Proficiency Test" (http://www.transparent.com/). In Table 1 are reported the scores for all participants relative to language use and language proficiency (self-assessed and tested with the Transparent Language Proficiency Test). In Table 2 are reported the scores relative to the frequency of language switching. We assessed these measures by administering both the BSWQ test (Rodriguez-Fornells et al., 2012) and another test including other questions on the frequency of language switching. All participants were right-handed and had normal or corrected-to-normal vision. No participant had a history of major medical, neurological disorders or treatment for a psychiatric disorder that were felt by the investigators to influence fMRI results.

	L1	**L2**
	Language Use	***Language Use***
Preschool	0.9 (0.1)	0.2 (0.1)
Primary Education	0.9 (0.1)	0.2 (0.1)
Secondary Education and High school	0.8 (0.1)	0.2 (0.1)
Adulthood	0.8 (0.2)	0.3 (0.2)
	L1	**L2**
	Language Proficiency	***Language Proficiency***
Reading	7 (0.5)	6 (0.7)
Writing	6 (1.3)	5 (1.1)
Speaking	7 (0.3)	5 (1.1)
Comprehension	7 (0.0)	6 (1.5)
	L1	**L2**
	Language Proficiency Test	***Language Proficiency Test***
Total score (% of correct responses)	99% (0.02)	96% (0.06)

Table 1. Language use and language proficiency. *Language use* scores represent a mean proportion (max. score=1, min=0) of languages' use in different periods of life: Preschool (from 0 to 5/6 years), Primary Education (from 5/6 to 12 years), Secondary Education and High school (from 12 to 18 years) and Adulthood (from 18 to the actual age). *Language proficiency* scores were on a 7 point scale, in which 7 represents a very high-level and 1 a very low level of proficiency. The self-assessed index is the average of participants' responses for each domain (reading, writing, speaking and comprehension). The *Language proficiency Test* used to assess L1 and L2 proficiency is the “Transparent Language Proficiency Test” (http://www.transparent.com/). The total score reported in the table was obtained by averaging results in different sections of the test (grammar, vocabulary and comprehension) across participants. In parentheses are reported Standard Deviations (SD).

	BSWQ	
Scale	***Mean***	***SD***
L1S	**7**	**1**
L2S	**8**	**1**
CS	**7**	**3**
US	**5**	**2**
OS	**28**	**5**
	SWITCH QUESTIONS	
Scale	***Mean***	***SD***
Switch in a bilingual group	**4**	**1**
Switch in a group with whom you always use your L1	**2**	**1**
Switch in a group with whom you always use your L2	**3**	**1**
Switch in a dialogue (just one other person besides you)	**2**	**1**
Switch in a sentence	**3**	**1**

Table 2. Language switching: BSWQ and Switch Questions. *BSWQ* (see Rodriguez-Fornells et al., 2012) scores for L1S (i.e., switch to German), for L2S (i.e., switch to Italian; CS (i.e., contextual switch); US (i.e., unintended switch); OS (i.e., overall switch). *Switch Questions* scores were on a 5 point scale, in which 5 represents "many switches" and 1 "very few switches/ no switches". The self-assessed index is the average of participants' responses for each scale.

2.2. Stimuli

Four-hundred and thirty-two line-drawings of common objects, belonging to a wide range of semantic categories (e.g., animals, body parts, buildings, furniture), were selected for the study (International Picture Naming Project, see Szekely et al., 2004). Items were selected so that 53.2 % were bigger than a shoebox and 42.4 % were smaller than a shoe-box[22]. Participants were told to consider the dimension of the object in the picture and then to classify the picture as bigger or smaller than a shoebox by

---

[22] Note that there were other pictures, the remaining 4.4 % that were not classifiable as bigger as or smaller than a shoebox. These pictures were included in two subsets of pictures that were used only for the naming tasks (17 % of the pictures). Note also that there were other two subsets of pictures that were used only for the semantic classification task (17 % of the pictures).

considering whether or not the object could be inserted in a shoebox.

Pictures were assigned to 12 different subsets of 36 pictures each. The 12 subsets were matched for visual complexity [F (11, 385) = .740, p = .7, ηp^2 = .21], name agreement (reported in the IPNP database) [F (11, 385) = .091, p = .999, ηp^2 = .03], and lexical frequency in Italian and German [F (11, 385) = .301, p = .986, ηp^2 = .009]. Furthermore, half of the pictures in each set were high frequency (mean frequency = 3.3, SD = .3) and the other half low frequency (mean frequency = .9, SD = .2) lexical items.

Each subset was assigned to each of the experimental sessions across participants (see below).

2.3. Experimental design

Participants were presented with three different blocked switching tasks, each one of them including a “Study” and two “Tests” blocks. During the Study blocks, participants saw pictures of common objects (pictures) and were asked either 1) to name pictures in either their L1 (German) or L2 (Italian) or 2) to classify the objects according to whether they were “bigger than a shoebox” or “smaller than a shoebox” in real life. During subsequent Test blocks, half of the pictures presented in the Study blocks were repeated along with new pictures. Thus, the picture stimuli at Test blocks had either been seen as pictures at Study (the “old” condition), or were experimentally novel (the “new” condition).

“Study” blocks

In each *Study* block, two sets of 36 pictures (i.e., a total of 72 pictures) were each presented three times, for a total of 216 trials. Participants underwent three Study blocks: 1) naming pictures in L1 (German), 2) naming pictures in L2 (Italian), 3) semantic classification task. In the Study block for the semantic classification task one half of the participants started with the task asking “to classify pictures as bigger than a shoebox” and the other half with the task asking “to classify pictures as smaller than a shoebox”.

“Test” blocks

Two Test blocks followed each one of the three Study blocks. In each Test block 72 pictures were presented only once, for a total of 144 trials across two blocks.

During each Test block, one half of the stimuli from the Study block (i.e., 36 stimuli) were intermixed with 36 novel stimuli. In one Test block, participants underwent the same task to that of the Study (i.e., naming/semantic classification task) but with the opposite decision (opposite language/opposite classification decision). In the other Test block, participants underwent the different task to that of Study (i.e., if the naming task was administered at Study, the semantic classification task was performed at test and vice versa). The order of the two test conditions (tasks) was counterbalanced across participants.

The stimulus manipulation was such that participants viewed both old and new pictures within each Test block (72 pictures of objects in total). Old pictures were never repeated within the Test blocks and each picture at Study was employed only once as an old stimulus in one or the other Test block (i.e., if an old picture was used in one Test block, it was not used in the other Test block).

Importantly, all Study-Tests combinations in terms of task/decision manipulation and stimulus lists (i.e., Study: naming pictures in L1 (German), 2) naming pictures in L2 (Italian), 3) bigger or smaller classification; Test: naming pictures in L1 (German), 2) naming pictures in L2 (Italian), 3) bigger or smaller classification) were systematically ordered, counterbalanced and randomized between participants, to minimize any potential confounds. Participants completed three sets of the Study-Tests combinations.

In Figure 1 we report a schematic overview of the experimental design. For example, in set 1 a participant was first presented with naming pictures in L1 in the Study block, then to name pictures in L2 in the Test1 block, and finally to classify the pictures according to their size (i.e., bigger or smaller classification) in the Test2 block. After a 5-min pause, set 2 would start in which the Study-Test combination would change and following another 5-min pause each participant would finally undergo set 3 (see Figure 1, for the details). Importantly, the set order (i.e., set 1, 2, and 3) was counterbalanced across participants.

Crucially, and important to our purposes, the two Test blocks (Test1 or Test2) implied a change in terms of “decision” or “task” as compared to the Study block. For instance, if the Study block required to name pictures in L1, Test1 would require to name pictures in L2 (i.e., opposite decision: picture naming but using a different language) and Test2 to classify pictures as bigger or smaller than a shoebox (i.e., different task: classify the object in the picture rather than naming it) or vice versa.

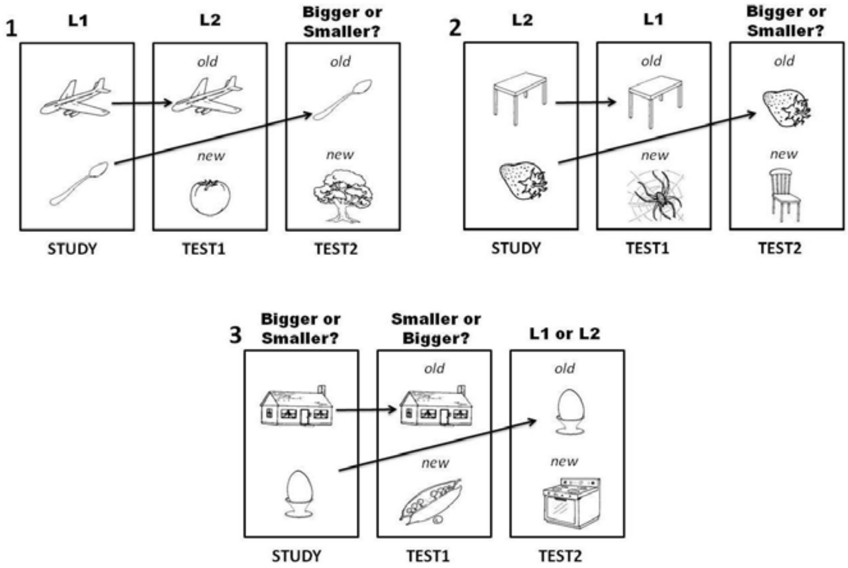


Figure 1. Experimental design. The figure illustrates an example of the experimental design. Participants underwent to three Study-Tests sets (1, 2, 3) composed by three blocks each (Study, Test1 and Test2). See main text for details.

2.4. Experimental Procedures

Before entering the MRI scanner, participants underwent to a practice session in which they performed the three Study-Tests sets on a reduced number of trials (i.e., 12 trials for each Study session and four trials for each Test block[23]). Importantly, the pictures presented in this practice session were all different from the set of 432 pictures used in the three experimental sets. Stimuli characteristics and task instructions and experimental timing were similar to those occurring during the real fMRI experiment.

Instructions were to name pictures aloud in either German or Italian (i.e., for the naming task) or classify them as bigger or smaller than a shoebox (i.e., for the semantic classification task), as fast as possible but without sacrificing accuracy. Participants were also informed that each Study or Test block would begin with a sentence indicating the task to be performed (i.e., "*Nomina queste immagini in Italiano*" or "*Benenne den Namen des Bildes auf Deutsch*" – name these pictures in Italian or German respectively; "*Questi oggetti sono piu piccoli di una scatola da scarpe?" or "Sind diese Objekte kleiner als ein Schuhkarton?"* – Are these objects smaller than a shoebox?*;"Questi oggetti sono piu GRANDI di una scatola da scarpe?" or "Sind diese Objekte größer als ein Schuhkarton?"* – Are these objects bigger than a shoebox?). Importantly, we opted for vocal responses (i.e., yes or no) also in response to the semantic classification task, in order to control for differences in terms of articulatory processes between the naming task and semantic classification task.

---

[23] Also for the practice session, two sets of pictures were presented and repeated three times in the Study block. These sets contained 2 pictures each. After the Study block, in the Test1, one of the two sets (i.e., in total two repeated pictures) previously presented in the Study, was represented along with other two new pictures. After the Test1 block, the remaining set of pictures presented in the Study was presented in the Test2 block, along with a set of new pictures. Importantly, "new" pictures in Test 1 and Test 2 were different.

Participants were also told that the tasks would appear in sets made of three blocks each and they would have been administered a total of three experimental sets. Subjects were not informed about the specific sequence of the Study-Tests combinations in each set. When the Study block in the first Study-Tests set entailed the naming task, participants always received the instructions in the language in which the first naming block was administered. If the Study block in the first Study-Tests set implied the semantic classification task, the language (i.e., German or Italian) in which instructions appeared was counterbalanced across participants.

At the beginning of each block (Study, Test1 and Test2) the cue sentence indicating the task to be performed along with the block name (e.g., "*Sessione A - Nomina queste immagini in Italiano*") was presented on a black background for 7500 ms. Following the cue sentence, each trial sequence began with a centrally placed white fixation cross ("+") on a black background presented for 1500 ms, followed by the first picture for 1500 ms, followed by a fixation cross jittered at a inter-stimulus interval (ISI) rate of one every 2030, 2196 or 2362 ms, in turn followed by another picture presented for 1500 msec.

Stimulus events were presented and jittered in counterbalanced orders optimized for efficient detection of contrasts between conditions of interest using a genetic algorithm (Wager and Nichols, 2003), including an additional 47 "null events" (fixation crosses) for the Study blocks and 16 for each Test block presented for 1500 ms with the same jitter range to maximize statistical efficiency and facilitate deconvolution of the hemodynamic response.

Finally, at the end of each block a blank screen was presented for 2000 ms followed by an “end message” (for 10884 ms and 10700 ms for Study and Test blocks, respectively). Stimuli were presented by means of Presentation software (Neurobehavioral systems: http://www.neurobs.com/).

Participants were also instructed to minimize jaw-tongue movements while producing overt vocal responses to pictures, while an experimenter outside the magnet room listened to vocal responses to each picture through an amplifier in order to classify correct responses, incorrect responses and omissions (non responses) for accuracy evaluation. Due to technical constrains, vocal onset times (VOTs) of responses were not recorded.

2.5. Scanning, image processing and preprocessing

The fMRI-event-related technique was used (3T Intera Philips body scanner, Philips Medical Systems, Best, NL, eight channels-sense head coil, sense reduction factor = 2, TE = 30 ms, TR = 2000 ms, FOV = 192 × 192, matrix size = 64 × 64, 3 mm ×3 mm in-plane resolution).

Slices were acquired axially, allowing whole brain coverage, and were tilted parallel to the anterior commissure–posterior commissure plane (36 slices; 3-mm slice thickness). Each run was preceded by 5 dummy scans that were discarded prior to data analysis.

A high resolution structural MRI (Magnetic Resonance Imaging) was acquired for each participant (MPRAGE, 150 slice T1-weighted image, TR = 8.03 ms, TE = 4.1 ms; flip angle = 8°, TA = 4.8 min, resolution = 1 × 1 × 1 mm) in the axial plane.

Nine fMRI sessions were acquired, equating to the three Study – Test sets. Five hundred thirty-two volumes were acquired during each study session, 182 were acquired during each test session.

SPM8 (Statistical Parametric Mapping) running on Matlab 7.4 (R2007a) was used for all preprocessing steps and statistical analysis.

Prior to analysis, all images for nine sessions underwent a series of preprocessing steps. Time series diagnostics using tsdiffana (Matthew Brett, MRC CBU:http://imaging.mricbu.cam.ac.uk/imaging/DataDiagnostics) were run for the nine fMRI session to verify the quality of the functional data in terms of variance of corresponding voxels between slices and between volumes relative to mean intensity values calculated respectively for each image or the entire time series. ArtRepair was used to remove noise spikes and to repair bad slices within a particular scan and bad slices were repaired by interpolation between adjacent slices (‘‘Noise Filtering’’, http://cibsr.stanford.edu/tools/ArtRepair/ArtRepair.htm).

Slice-timing correction was carried out by interpolating the voxel time series using sinc interpolation and re-sampling with the middle (fifteenth) slice in time as a reference point.

For each Study-Test set, all slice-time corrected EPI images were realigned to the first volume in each time series and successively to the mean. The unified normalization-segmentation procedure was used to normalize EPI images to the MNI space with resulting voxels size of 3 × 3 × 3 mm. This procedure implies 1) co-registering the anatomical T1 image to the mean EPI image generated during the realignment step, 2) apply the unified segmentation to the coregistered anatomical image using the default parameters in SPM5 to estimate the normalization parameters that encode the transformation from the native to MNI space, 3) apply the normalization parameters obtained from the segmentation step to write out all normalized realigned EPI images.

The normalized EPI images were then smoothed using a 6-mm full-width at half-maximum (FWHM) Gaussian kernel to ensure that the data were normally distributed and to account for any between-subject residual variations prior entering statistical analysis.

2.6. Statistical analysis

2.6.1. Behavioral analysis: Error Analysis

Failures to respond to a given stimulus or erroneous responses were considered errors and were eliminated from the analyses. In the naming tasks, responses were considered correct whenever the expected name was given, but also when participants used an appropriate category label for the item (e.g., naming a “coat” as “clothes”). Similarly to previous studies (e.g., Guo et al., 2011), we used this somewhat lax criterion given that we did not train participants with the experimental pictures in advance.

2.6.2. fMRI data analysis

2.6.2.1. *First-level Design*

The statistical analysis was performed in a two-stage approximation to a mixed effects model. At the first level, neural activity was modeled by a delta function at picture onset. The BOLD response was modeled by a convolution of these delta functions by a canonical hemodynamic response function to form regressors in a general linear model (GLM). Each Study-Test set was analyzed in a separate GLM model. For each Study block, six regressors were modeled coding the first presentation, the first and the second repetition of the two sets of 36 pictures, which were presented each three times. For each Test block, two regressors were included in the model, one for the set of “old” pictures from the Study session (i.e., 36 stimuli) and one for the “novel” pictures. Voxel-wise parameter estimates for these regressors were obtained by restricted maximum-likelihood (ReML) estimation, using a temporal high-pass filter (cutoff at 128 sec) to remove low-frequency drifts, and modeling temporal autocorrelation across scans with an AR (1) process.

2.6.2.2. *Second-level Designs*

2.6.2.2.1. *Stimulus-Response bindings in different tasks: Linguistic vs. Non-linguistic tasks*

Images belonged to three repetition contrasts:

(1) L1 local control contrast: old pictures in an L1-Test block “OLD-T-L1” vs. second repetition of the same pictures in the Study block “2REP-S-L2”, when the Study block involved the opposite language (i.e., L2 naming);

(2) L2 local control contrast: old pictures in an L2-Test block “OLD-T-L2” vs. second repetition of the same pictures in the Study block “2REP-S-L1”, when the Study block involved the opposite language (i.e., L1 naming);

(3) Semantic classification local control contrast: old pictures in a Bigger/Smaller semantic classification Test block “OLD-T-B or OLD-T-S” vs. second repetition of the same pictures in the Study block “2REP-S-S or 2REP-S-B”, when the Study block involved the opposite decision (i.e., bigger than a shoebox or smaller than a shoebox).

The images from these three repetition contrasts from our whole brain analysis were collapsed across the three Study-Test sets and comprised the data for the SPM8 one-way ANOVA, within subjects, which treated participants as a random effect. In addition to the 16 participants effects, this model had three *local* control condition effects, corresponding to a 1 × 3 (group × local control) repeated measures ANOVA. Within this model, SPMs (i.e., Statistical Parametric Maps) were created of the F statistic for the differences between the *local* control conditions when an opposite language is used for the same picture (i.e., L1 vs. L2 naming conditions) or when a different task is carried out (i.e., L1 or L2 naming vs. semantic classification task) (p < .005 uncorrected at the voxel level) and effects of interest were plotted to investigate the direction of any potential difference. Given our specific aim to test for differential *local* control effects in the brain areas involved in language control as identified in the neurocognitive model of bilingual language processing (i.e., Abutalebi & Green 2007, 2008) we used a more liberal threshold of p<.005, uncorrected at the voxel level, in order to trace very subtle potential changes in brain activity related to the same stimulus, which however entails the opposite language or semantic task. Post-hoc directional whole brain voxel-wise T-tests between conditions were then carried out in order to assess the significance of the differential effect in each area of interest.

Brain activation was localized by the Anatomy toolbox (Eickhoff et al., 2005). Significant peak activations are reported as Montreal Neurological Institute (MNI) coordinates.

2.6.2.2.2. *Language Control: Local vs Global Control*

A separate flexible 2x2 ANOVA factorial model in SPM8 was designed for the “global x local” control conditions (i.e., new vs old pictures) and the “L1 x L2” naming conditions to explore specific effects related to bilingual language control, namely related to the potential differences between the control mechanisms involved at the level of specific lexical items or at the level of language sets, in the same aforementioned areas included in the Abutalebi and Green model (e.g., 2007, 2008; Green & Abutalebi, 2013).

The factor matrix included contrast images relative to:

(1) L1 local control contrast: old pictures in an L1-Test block “OLD-T-L1” vs. second repetition of the same pictures in the Study block “2REP-S-L2”, when the Study block involved the opposite language (i.e., L2 naming);

(2) L2 local control contrast: old pictures in an L2-Test block “OLD-T-L2” vs. second repetition of the same pictures in the Study block “2REP-S-L1”, when the Study block involved the opposite language (i.e., L1 naming);

(3) L1 global control contrast: new pictures in an L1-Test block “NEW-T-L1” vs. first presentation of pictures in the Study block “1PRES-S-L2”, when the Study block involved the opposite language (i.e., L2 naming);

(4) L2 global control contrast: new pictures in an L2-Test block “NEW-T-L2” vs. first presentation of pictures in the Study block “1PRES-S-L1”, when the Study block involved the opposite language (i.e., L1 naming).

The factor ‘subject’ was additionally included in the factor matrix to control for the repeated measures.

In this model, a single F-test was performed testing for significant differences among the 4 Control x Language conditions (at $p< 0.005$ uncorrected at the voxel level). Effects of interest were plotted to investigate the direction of any potential difference between L1 and L2 1) at the language set level (i.e., *global control*) or 2) at the specific lexical level (i.e., S-R binding level or *local* control). Furthermore, we also explored possible interaction effects between control (i.e., *local* and *global*) and language (i.e., L1 and L2) conditions and whether an interaction effect could be detected between control and language conditions. Post-hoc directional whole-brain voxel-wise T-tests between conditions were then carried out in order to assess the significance of any differential effect in each area of interest. Brain activation was localized by the Anatomy toolbox (Eickhoff et al., 2005). Significant peak activations are reported as Montreal Neurological Institute (MNI) coordinates.

3. RESULTS

3.1. Stimulus-Response bindings in different tasks: Linguistic vs. Non-linguistic tasks

The F contrast testing for S-R binding differences between the *local control* conditions when an opposite language is used for the same picture (i.e., L1 vs L2 naming condition) or when a different task is carried out (i.e., L1 or L2 naming vs semantic classification task) in the areas included in the bilingual language production model (Abutalebi & Green, 2007; Green & Abutalebi, 2013), namely the PFC, the ACC\Pre-SMA, LIPL, RIPL and RPFC was computed. The critical threshold (i.e., considered at p < .005 uncorrected at the voxel level) was set at p<.0027 corrected for a total of 18 *local control* condition x Area of Interest post-hoc tests (i.e., 0.05/18 - maximum number of post-hoc comparisons). Effects of interest were plotted to investigate the direction of any potential difference between *local control* conditions.

The One-Way ANOVA revealed significant differences in the LPFC (x=-45, y=47, z=10; k = 35), the LIPL (x=-51, y=-46, z=46, k = 39), the RIPL (x=60, y=-52, z=34, k = 10), the ACC\Pre-SMA (x=12, y=11, z=49; k = 13) and two clusters in the RPFC (x=39, y=32, z=-5, k = 11; x=39, y=35, z=10, k = 6).

Post-hoc directional T-Tests revealed that 1) the differences observed in LPFC, LIPL, RIPL and the RPFC cluster located in the right inferior frontal gyrus (RIFG; pars triangularis) (x=39, y=35, z=10) were related to significant BOLD increases for OLD-T-L1 with respect to a significant decrease in OLD-T-L2 between the opposite language decision *local control* conditions; 2) the effects highlighted in the RIFG (pars orbitalis) (x=39, y=32, z=-5) were driven by an incremental difference from a significant BOLD decrease in the OLD-T-L2 condition, to a negligible effect in OLD-T-L1 opposite language decision condition to a significant increase in the OLD-T-B\S “opposite task” local control condition; 3) a significant difference emerged in the ACC\Pre-SMA (x=12, y=11, z=49; k = 13) due to a significant increase in BOLD signal for the OLD-T-L2 “opposite decision” condition with respect to other two *local control* conditions (see Figure 2).

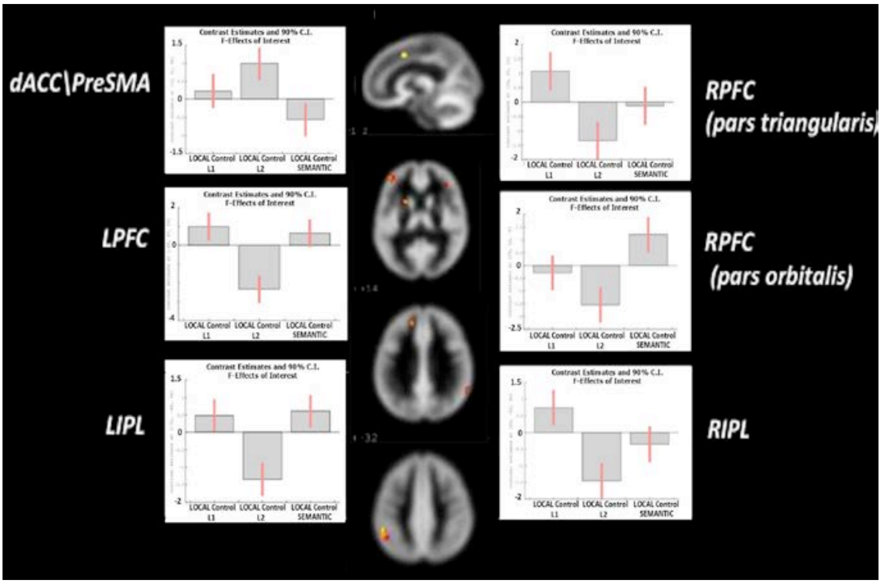
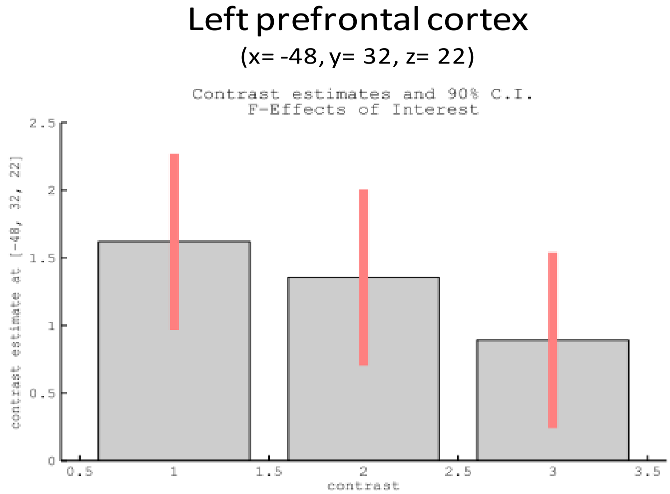


Figure 2. Stimulus-Response bindings in different tasks: Linguistic vs. Non-linguistic tasks. Columns 1 to 3 refer to the *local control* conditions for L1 naming, L2 naming and semantic classification, namely to the parameter estimates for: 1) *Local* control – L1, 2) *Local* control – L2, 3) *Local* control – semantic classification. The F- contrast showing differences between the three conditions in areas of interest is superimposed on the default SPM grey matter tissue prior map in MNI space.

In order to test the hypothesis that activation in areas sensitive to S-R binding strength for the two language conditions (i.e., between L1 and L2) will overlap with activation elicited by a condition entailing no language decision (i.e., semantic classification task), we conducted a conjunction analysis for conjoint activation between the three *local control* conditions (i.e., OLD-T-L1, OLD-T-L2, OLD-T-B\S) assessed at a threshold of $p < .005$ (uncorrected). The conjunction analysis revealed that exclusively LPFC (x=-48, y=32, z=19) was commonly engaged by *local control* in both opposite decision and opposite semantic task conditions (see Figure 3).



Left prefrontal cortex

(x= -48, y= 32, z= 22)

Figure 3. Stimulus-Response bindings in different tasks: Conjunction analysis. Conjoint activity in LPFC for the three *local control* conditions relative to L1 naming, L2 naming and semantic classification with the relative parameter estimates.

3.2. Language Control: Local vs Global Control

The F-contrast testing for significant differences among the 4 Control x Language conditions (at p< .005 uncorrected at the voxel level) revealed significant differences in the areas included in the language control network (Abutalebi & Green, 2007, 2008; Green & Abutalebi, 2013): Namely in the LPFC (x=-42, y=47, z=10, k=123), LIPL (x=-48, y=-52, z=49, k=84), RIPL (x=60, y=-55, z=31, k=69) and RPFC (x=57, y=20, z=13, k=34). The critical threshold (i.e., considered at p < .005 uncorrected at the voxel level) was set at $p < .002$ corrected for a total of 24 “Control x Language” condition x Area of Interest post-hoc tests (i.e., .05/24 - maximum number of post-hoc comparisons).

Plots of parameter estimates for each condition in each area of interest revealed that 1) differences in LPFC, LIPL, RPFC and RIPL were related to a main effect of language - L1 in terms of an increase of BOLD signal for the both L1 *local* and *global control* conditions and a significant decrease for the respective L2 conditions.

Additionally, post-hoc directional T-Tests revealed that 1) a difference in BOLD signal elicited in the head of the LC (x=-15, y=23, z=4, k=13) emerged between L1 and L2 conditions (i.e., higher for L1); 2) a large cluster peaking in the dACC (x=0, y=23, z=49, k=193) and extending to pre-SMA was highlighted for the difference between *local* and *global control* conditions exclusively for L2 (see Figure 4).

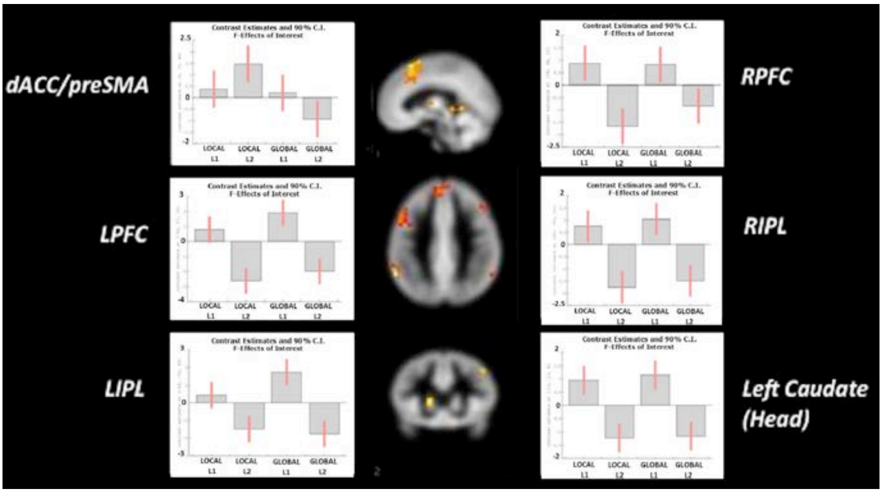


Figure 4. Language Control: *Local* vs *Global* Control. Columns 1 to 4 refer to the *local* and *global* language control conditions and namely to the parameter estimates for: 1) *Local* control – L1, 2) *Local* Control – L2, 3) *Global* Control - L1, 4) *Global* Control – L2. The F- contrast showing differences between the four conditions in areas of interest is superimposed on the default SPM grey matter tissue prior map in MNI space.

4. Discussion

In this fMRI study we employed linguistic and non-linguistic blocked switching tasks in order to widen our knowledge of the neural basis of language control in bilinguals. We focused on brain areas known to be involved in bilingual language control as outlined in a neurocognitive model (Abutalebi & Green, 2007, 2008; Green & Abutalebi, 2013). This model identifies a network of specific brain areas subtending cognitive control processes, which are involved in language control in bilinguals at different stages and at different levels of processing.

In the present study, participants were asked to perform two linguistics tasks (naming in L1 and naming in L2) and two semantic classification tasks (classify picture as bigger as and smaller than a shoe box). Two main issues were explored. First, we assessed the effects of establishing new S-R bindings as a consequence of changing the task, for the two different tasks (linguistic and non-linguistic task). This exploration would help to better understand the extent to which the bilingual language control network is modulated similarly when controlling non-linguistic representations. Second, we assessed the effects of switching languages for items that were repeated across the languages and for items that were not repeated. The first effect would inform us about the so-called *local* control and the second one about the so-called *global control*.

For the sake of clarity, in this investigation the main focus was not put on the neural overlap between the bilingual language control network and the domain-general control network. Instead, we aimed at exploring how the bilingual language control network responds when controlling other types of representations that are not linguistic in nature.

Stimulus-Response bindings in different tasks: Linguistic vs. Non-linguistic tasks

The first question of the present study was addressed by comparing brain activity elicited by changing the S-R bindings for repeated stimuli across different tasks (L1 naming, L2 naming and semantic classification task), i.e., whether the type of S-R bindings modulates the activity in the control network. A crucial finding was that two brain areas, namely, the LPFC and the LIPL, were similarly involved (qualitatively and quantitatively) in the engagement of S-R bindings for L1 naming and in those for the semantic classification task. This may indicate that there are some common mechanisms between the control of the linguistic and the non-linguistic S-R representations. Both are characterized by a decision that implies general attention processes and to target attention not specifically bound to the nature of the elements considered for the decision. However the nature of the stimulus and response will drive more or less activity in other areas on the basis of the specific nature of the stimuli, the strength of task sets and according to specific task goals, which convey the response. For both tasks, increased LPFC activity may reflect the neural tuning for reestablishing new S-R bindings as a function of efficacious selection of the target, in contexts in which interference from the previous task is still present (Szameitat et al., 2002; Collette et al., 2005). Instead, increased LIPL activity may reflect processes to configure and adjust the current task-set parameters by biasing selection away from the task-set recently abandoned, and in turn, by signaling to the LPFC attention shifts induced by stimuli information (Sigman & Dehaene, 2006; Rowe et al., 2008).

However, we also observed some differences between the linguistic and the semantic classification task regarding *local control*. That is, an increased "priming disruption effect" was evident in the RIFG (pars orbitalis) (see Figure 2), which appeared to significantly respond (increased BOLD signal) in the semantic classification context with respect to the two linguistic tasks (i.e., naming in L1 and naming in L2). Interestingly, the RIFG has been previously related to domain-general inhibitory control (Jahfari et al., 2011; Forstmann, 2008; Aron et al., 2004; 2014). Hence, the fact that we found activity in this region as being significantly disrupted in the semantic classification task as compared to the two linguistic tasks, might suggest that semantic classification task entails a greater cognitive effort to detect salient cues in a task where individuals are asked to classify items on the basis of perceptual saliencies. On the other hand, we observed decreased activity within the dACC/pre-SMA complex for the semantic classification task possibly indicating that binding of non-linguistic S-R representations (at least for the task here employed) is in lesser need of monitoring resources than linguistic ones.

Taken together, our results for the S-R bindings in different tasks show that there are important commonalities between linguistic and non-linguistic *local control,* chief among them the BOLD responses in the LPFC and LIPL. However, we also report some crucial qualitative differences such as in the RIFG (pars orbitalis) and in the dACC/pre-SMA complex.

As to the differences between the two linguistics tasks, we report that brain areas involved in engaging S-R bindings in the L1 naming context (naming L1 after having named L2) were associated to significantly increased priming disruption effects in the LPFC, the LIPL, the RIPL and in a RPFC cluster located in the RIFG (pars triangularis). Importantly, these areas showed an opposite pattern of activity (i.e., significant deactivation) in the L2 context (naming L2 after having named L1). This may suggest that establishing new L2 S-R bindings after switching required less control than establishing L1 S-R bindings after switching.

At a first view, this may seem a paradox and contrary to our own and other findings in studies using trial-by-trial language switches between languages (e.g., Abutalebi et al., 2013; Wang et al., 2007). In those studies, usually switching into L2 (or in the less dominant language) was paralleled by increased activity in language control areas considered as inhibition-related activity necessary to overcome the prepotent language (L1) used in the preceding trial. The paradigm used in the present study does not allow us to infer over such fast control processes (i.e., transient control). Rather the present investigation was designed to investigate “priming disruption effects” and different response selection bindings in bilinguals. Interestingly, with the possible exception of the dACC/pre-SMA, we report a reverse pattern as those usually associated in trial-by-trial language-switching studies. Indeed, *local control* in L1 (i.e., naming in L1 after the same pictures were presented several times in L2 in a timely distinct previous run) was associated to more extensive engagement of language control areas.

Interestingly, the neural pattern of results is consistent with previous behavioral studies. Within language repetition trials usually lead to repetition priming, that is, to faster reaction times for the second repetition of the very same item. However, such priming is affected in an illustrative way when changing the language. That is, priming effects are absent when naming in L1 after having named the pictures in L2; but they are present in the opposite direction. We have also observed an interesting asymmetry regarding the pattern of brain activity according to the direction of the language change. Our suggestion is that naming in L1 after having named the same items in L2 might lead to an increased in the engagement of brain regions involved in language control as compared to the opposite direction. Presumably, this is because of the necessity to override the inhibition of the prepotent L1 during the previous L2 block. On the other hand, this extra-activity is not necessary while naming first in L1 and, hence, during subsequent L2 naming reduced language control related activity might be observed with the exception of the dACC. Importantly, dACC activity might specifically indicate that L2 production prominently drives monitoring and error detection processes. Indeed, ACC/Pre-SMA activity has been related to conflict monitoring (Botvinick et al., 1999). Recently, it has been shown that the ACC/Pre-SMA plays a major role in tasks involving conflict resolution subserving selection of the targeted response in both linguistic and non-linguistic contexts (Abutalebi et al., 2012). Related to our study, we suggest that in the L2 naming context, the priming disruption effect is grounded within the necessity to actively monitor S-R binding configuration in L2 to allow successful production. This activity in the ACC/Pre-SMA may reflect monitoring while updating response selection processes when establishing new S-R bindings in L2 (after L1 production), in order to hinder the production of unwanted, but still prepotent targets in L1 (Collette & Van der Linden, 2002).

Our findings may have important implications for neurocognitive models of bilingual language control, allowing us to postulate a possible functional dissociation between control mechanisms within brain areas responsible for cognitive control. The LPFC, RPFC, LIPL and RIPL were all found to be more engaged for *local control* in L1, while the dACC/pre-SMA complex was more active for *local control* in L2. We suggest that language control in bilinguals is hierarchically organized. On one hand, the language control mechanism lays upon a *supervisory attentional system* neurally identified in the dACC/pre-SMA complex and an *effector system*, comprising inferior parietal and prefrontal areas. The engagement of the latter is tailored to convey attentional resources for response selection purposes and is regulated by the amount of inhibition necessary to overcome L1 co-activation during L2 naming. The dACC/pre-SMA is recruited instead for increased attentional and monitoring demands as in the case of L2 naming after L1 naming, notwithstanding any facilitatory priming effects driven by L1.

The findings for *local control* in L1 and L2 reported in our study are very similar to what Guo et al. (2011) highlighted for their *global control* conditions. Indeed, Guo et al. (2011) found that naming in L1 after L2 (on the same stimuli) as compared to L1 in a first block elicited the activation of a network of frontal and parietal brain areas, whereas instead naming in L2 after L1 (on the same stimuli) as compared to L2 in a first block activated posterior brain areas, such as the cuneus and the precuneus, notoriously not involved in language and cognitive control. However, Guo et al. (2011) improperly refer to this condition as a *global control* condition since by definition the control on a subset of lexical items that were previously presented in the other language is usually referred to as *local control*. De Groot and Christoffels (2006) provided a clear distinction between *global control,* where control involves the activation and/or inhibition of complete language systems, and *local control*, where control is exerted a restricted set of lexical representations that were previously used. Taken together, the asymmetries observed in our study may be explained by assuming that disengaging from L2 lexicon to access the L1 lexicon is more demanding than the reverse as indicated by the engagement of the *effector* areas of the language control network. In other words, at least in bilinguals with two languages not equally balanced in terms of dominance and use[24], the language control brain network is involved to a different extent depending on whether the language to be produced is L1 or rather L2.

The Prefrontal Cortex and Response Selection

Finally, one of our main aims was to better characterize linguistic and non-linguistic *local control* functions and identify areas of conjoint activity for engagement of S-R bindings across opposite language or semantic task demands. For this purpose, a conjunction analysis between the three *local control* conditions was carried out (i.e., L1 *local* control, L2 *local* control, *local* control of the semantic classification task) and, strikingly, we found that the

---

[24] Recall that the bilinguals that participated to this study had similar proficiency in both the languages but they were not balanced in the use of the two languages (see Table 1 and Table 2).

LPFC was conjointly recruited, across all the *local* control conditions (see Figure 3).

This result underlines that the LPFC has a general key role in the implementation of S-R bindings during response selection (e.g., Miller & Cohen, 2001; Ridderinkhof et al., 2004), notwithstanding the nature of the representations involved. In more general terms, it has been suggested that the lateral PFC is tuned for adaptation of response-sets as a function of efficient selection of the target stimulus in contexts with interfering information (Szameitat et al., 2002; Ridderinkhof et al., 2004; Collette et al., 2005). Furthermore, on the basis of the present findings we suggest that the extent to which this area is involved in response selection seems to be bound to the strength of the previous S-R bindings (formed during the Study block), which should then be overcome during the subsequent task in the Test block. This conclusion is supported by the observation that in order to overcome L2 S-R bindings to set new L1 S-R bindings, increased LPFC activity is required than in the opposite situation (i.e., when naming first in L1 and then in L2). Assuming that the strength of the binding is inversely related to the strength of the language (i.e., overcoming L2-S-R bindings is harder than overcoming L1-S-R bindings), it is reasonable to conclude that the involvement of LPFC is related to the degree of cognitive effort imposed by control demands for the engagement/disengagement of response sets with different S-R strengths. Regarding the control of semantic S-R bindings we found them to recruit the LPFC to the same extent as for the control of L1-S-R bindings. As explained above, this result suggests that the LPFC has a domain-general role for the selection of target responses in contexts in which high interference is present.

Language Control: Local vs Global Control

The second question of this study concerned the representational level at which bilingual language control (i.e., specific lexicon subset or whole language set) is goal-directed (see De Groot & Christoffels, 2006), in terms of the same brain areas recruited to different degrees when controlling or engaging\disengaging a specific language response binding (S-LR) (i.e., *local control* for translation equivalents of repeated items) or when engaging and maintaining the whole language set (S-LS) (i.e., *global control* for new items in a given language seen for the first time).

The ability to control two languages is thought to be mirrored in the brain by the same task-control brain areas, although the processes beneath each *local* and *global control* may presumably lay upon functionally diverse regions. This aspect leaves open important questions about the nature, the context and extent to which such areas are engaged for bilingual language control, when two alternatives are constantly available for output, but only one needs to be produced.

We report a main effect of language dominance (i.e., L1 vs. L2) on the activity related to both types of control (i.e., *local* and *global*). This effect was observable in the LPFC, LIPL, RPFC and RIPL in terms of both an increased priming disruption effect (i.e., *local control*) and greater activity for the engagement of new S-R bindings for items seen for the first time (i.e., *global control*) in the L1 conditions and a significant deactivation in the corresponding L2 conditions. Globally seen, these findings underline that *local control* and *global control* are processed in a similar fashion in the *effector* component (i.e., LPFC, LIPL, RPFC and RIPL) of the language control network. Indeed, only L1 *local* and *global control* were paralleled by increasing activity of the LPFC, LIPL, RPFC and RIPL (and the head of the LC, see below for discussion) which presumes that, naming in L1 (independently of encountering a new or an old stimulus) after L2 naming is enacted by the activity in these areas ruled by demands to override previous inhibition of L1 during a preceding L2 block.

Additionally, our post-hoc directional T-Tests revealed a difference in BOLD signal elicited in the head of the LC between L1 and L2 conditions being higher for L1, while a large cluster in the dACC/pre-SMA complex for the difference between *local* and *global control* conditions appeared exclusively for L2. Again as aforementioned, these effects confirm a sort of dissociation between languages for activity in the brain areas of the neurocognitive model proposed by Abutalebi and Green (2007, 2008). At a first view, these findings seem to be in contradiction with the findings of Guo et al. (2011) who report a neural dissociation between *local* and *global control*. Indeed, the authors report the dACC/pre-SMA involved in *local* inhibition, while the left frontal gyrus and parietal cortex played an important role for *global* inhibition. However, we underline that Guo et al. (2011) indeed investigated two different kinds of control in bilinguals but, following the definition of De Groot and Christoffels (2006) and the one here employed, Guo et al. (2011) did not properly investigate *global control*. The authors compared language control in a trial-by-trial switching paradigm to language control in a similar paradigm as the one used here for *local control* (i.e., naming the same picture seen before in a different language block). Both these processes may be referred to as *local control*, since only repeated pictures were used throughout the tasks with the switching paradigm relying on fast transient trial-by-trial control processes and the blocked naming paradigm relying more on sustained control processes. The notion of *global control* refers to when a bilingual encounters a word or a stimulus not previously seen, and presumably this would activate the whole language system (as opposed to the activation of a subset of lexical items when previously encountering its translation equivalent). This was not specifically addressed in the study of Guo et al. (2011). Interestingly, we here report that both *local* and *global* processes are carried out in a similar fashion, but with an effect of language dominance. Indeed, we have shown a specific "L1" increased effect for both types of control mirrored by a significant "L2" activity decrease. This effect was also present in the in the head of the LC. The LC has been specifically linked to language control in bilinguals (Abutalebi et al., 2013; Crinion et al., 2006) and in the neurocognitive model of Abutalebi and Green (2007, 2008) it is thought to be a relais station in the network since it conveys communication between the dACC/pre-SMA and the prefrontal cortices for response inhibition and selection (Abutalebi & Green, 2008). Moreover, the fact that the LC activity affects similarly *local* and *global control* indicates that its control mechanisms are applied on the whole language-set.

Nevertheless, we found for *local* and *global control* an interesting functional dissociation, again, in the dorsal portion of ACC, including pre-SMA being more sensitive to *local* than *global control* demands for monitoring correct S-R bindings in the weaker language (i.e., L2). The role of the dACC/pre-SMA complex for bilingual language control has been well highlighted as the area responsible for monitoring and attentional control during bilingual language processing (Abutalebi et al., 2012) and it is more engaged when processing a weaker language (Abutalebi et al., 2008, Abutalebi et al., 2013). Thus, it appears that this specific area can be recruited differentially depending on the type of control demands imposed by the bilingual context. Namely, *local control* in L2, at least in the present context, seems to lay mainly upon control achieved through monitoring processes in terms of activity of dACC/pre-SMA, necessary when disengaging attention from previous S-LR bindings in L1 and when re-engaging attention to establish the now relevant S-LR in L2. The monitoring functions of the dACC/pre-SMA complex would hence work at the stimulus level and to a much lesser degree upon the entire language set.

5. Conclusion

Our present data allow us to functionally differentiate the language control network in bilinguals. On the one hand, we identify a cortical network of bilateral frontal and parietal areas such as the PFC and IPL, with the possible support of the head of the LC, defining the *effector* component of language control, responsible for both engagement and disengagement of inhibitory control during language production. Interestingly, some of the brain areas of this *effector* component, particularly the LPFC, seem to be similarly involved in the control of the semantic classification task. Particularly, we demonstrate that the LPFC has a general key role in the implementation of S-R bindings during response selection, irrespective of the nature of the representations involved. This network acts on both *local* and *global control* and its role is most prominent when it comes to L1 naming after L2 naming. We also identify a monitoring component of this network to which we refer as the *supervisory attentional component* of the language control network, residing in the dACC/pre-SMA complex. Its monitoring functions are most prominent for *local control*, when facing increased attentional and monitoring needs such as when naming in the weaker language.

References

Abutalebi J, Annoni JM, Zimine I, Pegna AJ, Seghier, ML, Lee-Jahnke H, et al. 2008. Language control and lexical competition in bilinguals: an event-related fMRI study. Cerebral Cortex. 18:1496-1505.

Abutalebi J, Della Rosa PA, Ding G, Weekes BS, Costa A, & Green DW. 2013. Language proficiency modulates the engagement of cognitive control areas in multilinguals. Cortex. 49:905-911.

Abutalebi J, Della Rosa PA, Green DW, Hernandez M, Scifo P, Keim R, Cappa SF, & Costa A. 2012. Bilingualism tunes the anterior cingulate cortex for conflict monitoring. Cerebral Cortex. 22:2076-2086.

Abutalebi J, & Green DW. 2007. Bilingual language production: The neurocognition of language representation and control. Journal of Neurolinguistics. 20:242-275.

Abutalebi J, & Green DW. 2008. Control mechanisms in bilingual language production: Neural evidence from language switching studies. Language and Cognitive Processes. 23:557-582.

Ali N, Green DW, Kherif F, Devlin JT, & Price CJ. 2010. The role of the left head of caudate in suppressing irrelevant words. Journal of Cognitive Neuroscience. 22:2369-2386.

Aron AR, Robbins TW, & Poldrack RA. 2004. Inhibition and the right inferior frontal cortex. Trends in Cognitive Sciences. 8:170-177.

Aron AR, Robbins TW, & Poldrack RA. 2014. Inhibition and the right inferior frontal cortex: one decade on. Trends in Cognitive Sciences. 18:177-185.

Botvinick M, Nystrom LE, Fissell K, Carter CS, & Cohen JD. 1999. Conflict monitoring versus selection-for-action in anterior cingulate cortex. Nature. 402:179-181.

Christoffels IK, Firk C, & Schiller NO. 2007. Bilingual language control: An event-related brain potential study. Brain research. 1147:192-208.

Collette F, Olivier L, Van der Linden M, Laureys S, Delfiore G, Luxen A, & Salmon E. 2005. Involvement of both prefrontal and inferior parietal cortex in dual-task performance. Cognitive Brain Research. 24:237-251.

Collette F, & Van der Linden M. 2002. Brain imaging of the central executive component of working memory. Neuroscience & Biobehavioral Reviews. 26:105-125.

Costa A, Miozzo M, & Caramazza A. 1999. Lexical selection in bilinguals: Do words in the bilingual's two lexicons compete for selection?. Journal of Memory and Language. 41:365-397.

Crinion J, Turner R, Grogan A, Hanakawa T, Noppeney U, Devlin JT, et al. 2006. Language control in the bilingual brain. Science. 312:1537-1540.

De Groot, AMB, & Christoffels IK. 2006. Language control in bilinguals: Monolingual tasks and simultaneous interpreting. Bilingualism: Language and Cognition. 9:189-201.

Dobbins IG, Schnyer DM, Verfaellie M, & Schacter DL. 2004. Cortical activity reductions during repetition priming can result from rapid response learning. Nature. 428:316-319.

Dosenbach NU, Visscher KM, Palmer ED, Miezin FM, Wenger KK, Kang HC, et al. 2006. A core system for the implementation of task sets. Neuron. 50:799-812.

Eickhoff SB, Stephan KE, Mohlberg H, Grefkes C, Fink GR, Amunts K, & Zilles K. 2005. A new SPM toolbox for combining probabilistic cytoarchitectonic maps and functional imaging data. Neuroimage. 25:1325-1335.

Fleck MS, Daselaar SM, Dobbins IG, & Cabeza R. 2006. Role of prefrontal and anterior cingulate regions in decision-making processes shared by memory and nonmemory tasks. Cerebral Cortex. 16:1623-1630.

Forstmann BU, Dutilh G, Brown S, Neumann J, Von Cramon DY, Ridderinkhof KR, & Wagenmakers EJ. 2008. Striatum and pre-SMA facilitate decision-making under time pressure. Proceedings of the National Academy of Sciences. 105:17538-17542.

Garbin G, Costa A, Sanjuan A, Forn C, Rodriguez-Pujadas A, Ventura N, et al. 2011. Neural bases of language switching in high and early proficient bilinguals. Brain and language. 119:129-135.

Guo T, Liu H, Misra M, & Kroll JF. 2011. Local and global inhibition in bilingual word production: fMRI evidence from Chinese–English bilinguals. NeuroImage. 56:2300-2309.

Green DW. 1986. Control, activation, and resource: A framework and a model for the control of speech in bilinguals. Brain and Language. 27:210-223.

Green DW. 1998. Mental control of the bilingual lexico-semantic system. Bilingualism: Language and Cognition.1:67-81.

Green DW, & Abutalebi J. 2013. Language control in bilinguals: The adaptive control hypothesis. Journal of Cognitive Psychology. 25:515-530.

Henson RN, Eckstein D, Waszak F, Frings C, & Horner AJ. 2014. Stimulus–response bindings in priming. Trends in cognitive sciences. 18:376-384.

Henson RNA, & Rugg MD. 2003. Neural response suppression, haemodynamic repetition effects, and behavioural priming. Neuropsychologia. 41:263-270.

Kroll JF, Bobb SC, & Wodniecka Z. 2006. Language selectivity is the exception, not the rule: Arguments against a fixed locus of language selection in bilingual speech. Bilingualism: Language and Cognition. 9:119-135.

MacDonald AW, Cohen JD, Stenger VA, & Carter CS. 2000. Dissociating the role of the dorsolateral prefrontal and anterior cingulate cortex in cognitive control. Science. 288:1835-1838.

Meuter RF, & Allport A. 1999. Bilingual language switching in naming: Asymmetrical costs of language selection. Journal of Memory and Language. 40:25-40.

Miller EK, & Cohen JD. 2001. An integrative theory of prefrontal cortex function. Annual Review of Neuroscience. 24:167-202.

Misra M, Guo T, Bobb SC, & Kroll JF. 2012. When bilinguals choose a single word to speak: Electrophysiological evidence for inhibition of the native language. Journal of Memory and Language. 67:224-237.

Race EA, Shanker S, & Wagner AD. 2009. Neural priming in human frontal cortex: multiple forms of learning reduce demands on the prefrontal executive system. Journal of Cognitive Neuroscience. 21:1766-1781.

Ridderinkhof KR, Ullsperger M, Crone EA, & Nieuwenhuis S. 2004. The role of the medial frontal cortex in cognitive control. Science. 306:443-447.

Ridderinkhof KR, van den Wildenberg WP, Segalowitz SJ, & Carter CS. 2004. Neurocognitive mechanisms of cognitive control: the role of prefrontal cortex in action selection, response inhibition, performance monitoring, and reward-based learning. Brain and Cognition. 56:129-140.

Rodriguez-Fornells A, Krämer UM, Lorenzo-Seva U, Festman J, & Münte TF. 2012. Self-assessment of individual differences in language switching. Frontiers in Psychology, 2.

Rowe J, Hughes L, Eckstein D, & Owen AM. 2008. Rule-selection and action-selection have a shared neuroanatomical basis in the human prefrontal and parietal cortex. Cerebral Cortex. 18:2275-2285.

Runnqvist E, Strijkers K, Alario F, & Costa A. 2012. Cumulative semantic interference is blind to language: Implications for models of bilingual speech production. Journal of Memory and Language. 66:850-869.

Sigman M, & Dehaene S. 2006. Dynamics of the central bottleneck: Dual-task and task uncertainty. PLoS Biology. 4, e220.

Szameitat AJ, Schubert T, Müller K, & Von Cramon DY. 2002. Localization of executive functions in dual-task performance with fMRI. Journal of Cognitive Neuroscience. 14:1184-1199.

Szekely A, Jacobsen T, D’Amico S, Devescovi A, Andonova E, Herron D, et al. 2004. A new on-line resource for psycholinguistic studies. Journal of Memory and Language. 51:247-250.

Wager TD, & Nichols TE. 2003. Optimization of experimental design in fMRI: a general framework using a genetic algorithm. NeuroImage.18:293-309.

Wang Y, Xue G, Chen C, Xue F, & Dong Q. 2007. Neural bases of asymmetric language switching in second-language learners: An ER-fMRI study. NeuroImage. 35:862-870.

Waszak F, Hommel B, & Allport A. 2003. Task-switching and long-term priming: Role of episodic stimulus–task bindings in task-shift costs. Cognitive Psychology. 46:361-413.

Wig GS, Buckner RL, & Schacter DL. 2009. Repetition priming influences distinct brain systems: evidence from task-evoked data and resting-state correlations. Journal of Neurophysiology. 101:2632-2648.

3. GENERAL DISCUSSION: summary of the findings

The general aim of this dissertation was to advance the knowledge on bilingual language control. We assessed this general question by investigating two main issues: (1) the nature of the mechanisms of bilingual language control and (2) their representational scope.

Precisely, we assessed whether language control is implemented through domain-general inhibitory control, as proposed by Green (1986, 1998) and whether language control mechanisms are applied on the lexical representations recently used in the other language, or rather on the whole language (*local* and *global control,* respectively; see De Groot & Christoffels, 2006).

To do this, we conducted five experimental studies by assessing behavioral, electrophysiological, and neuroimaging measures.

In experimental studies presented in Sections 2.4 and 2.8, we investigated the mechanisms and the representational scope of bilingual language control in blocked language switching tasks. In Section 2.4 we measured behavioral and ERP responses elicited by “switch” of languages, for repeated and unrepeated items (*local* and *global control*, respectively). In Section 2.8 we employed the fMRI technique to assess whether specific brain areas (those included in the Neurocognitive model of bilingual language processing, see Abutalebi & Green, 2007, 2008; Green & Abutalebi, 2013) were similarly involved in the control of the two languages, for *local* and *global control*.

Four experimental studies presented in this dissertation (Sections 2.5, 2.6, 2.7 and 2.8) explored the extent to which the control mechanisms involved in bilingual language control were domain-general. We assessed this “overlap” by measuring behavioral and neural responses in linguistic and non-linguistic switching tasks.

In three behavioral studies (see Sections 2.5, 2.6 and 2.7) we employed trial-by-trial linguistic and non-linguistic switching tasks and we measured the behavioral performance of bilinguals (young, middle aged and elderly) in relation to different types of “switch costs”. In order to reveal to which extent bilingual language control mechanisms were domain-general, we assessed the patterns of switch costs related to the presence of inhibitory control in the task and we correlated switch costs across linguistic and non-linguistic tasks.

Finally, in an fMRI study (see Section 2.8) we examined whether the brain areas involved in bilingual language control (see the Neurocognitive model of bilingual language processing in Abutalebi & Green 2007, 2008; Green & Abutalebi, 2013) were similarly engaged in linguistic and non-linguistic blocked switching tasks. We assessed these effects by measuring in the same group of bilinguals *neural priming disruption effects* (see Dobbins et al., 2004), elicited by “switches” of (linguistic and non-linguistic) tasks.

The findings presented in this dissertation provide a complex pattern of results that may appear in somehow conflicting. The results may be summarized as follows:

(1) Bilingual language control is implemented through mechanisms different from inhibitory control, as revealed by electrophysiological (Section 2.4) and behavioral measures (Sections 2.5, 2.6, 2.7). However, neural switch cost patterns suggest that inhibitory control may be involved in bilingual language control (Section 2.8).

(2) The overlap between bilingual language control and domain-general executive control is partial. Particularly, inhibitory control is differently involved in bilingual language control and in domain-general executive control tasks, as revealed by a consistent set of behavioral findings (Sections 2.5, 2.6, 2.7). However, brain areas generally associated with inhibitory control processes appear to be similarly involved in linguistic and non-linguistic tasks (Section 2.8).

(3) Bilingual language control mechanisms are applied *globally* on the dominant language when speaking in the non-dominant language. This was suggested by behavioral, ERP and fMRI evidence (Section 2.4 and Section 2.8). Besides, language production in the non-dominant language recruits also monitoring control brain areas *locally*.

In the following two sections we discuss more in detail the above-mentioned findings.

3.1 On the mechanisms of bilingual language control: the after-effects of bilingual language production

In Section 2.3 we concluded that the available evidence in support to the inhibitory account in bilingual language control seems to be rather shaky. The main problem is that we have not sufficiently advanced our understanding of what asymmetrical/symmetrical switch costs mean, respect to inhibitory control processes.

There could be different strategies to improve our understanding of such asymmetries in relation to the inhibitory account. One of them is to constrain the experimental design in such a way that the asymmetries of switch costs can be interpreted clearly. Another strategy is to measure the patterns of switch costs along with other indices that are thought to reflect inhibitory control processes too.

In the experimental studies presented in this dissertation we tried to follow these strategies.

The most consistent observation in the literature of language switching is that only L1 production is affected by previous use of the other language. However, most of these studies (see Guo et al., 2011; Misra et al., 2012) compared adjacent blocks (or trials) of naming to measure linguistic switch costs, hence leaving out the possibility that switch cost asymmetries were caused by L2 over activation, rather than L1 inhibition[25] (see Sections 1.1.2.1 and 2.1). In other words, to explain such asymmetries there is no need to advocate for inhibitory mechanisms[26].

The studies presented in Section 2.4 and 2.8 went a step forward in respect to the above mentioned ones, since the patterns of switch costs were measured in experimental contexts that allowed disambiguating between inhibitory control and other alternatives.

In Section 2.4, we employed a blocked language switching task with three blocks of picture naming. This design allowed measuring the after-effects of naming in one language on the other language, without comparing adjacent blocks of picture naming. Hence, we had two groups of Catalan/Spanish high-proficient bilinguals: one group was required to naming in the L1-L2-L1 sequence and the other group in the L2-L1-L2 sequence. The comparison between the third and the first block of picture naming was crucial to determine whether at the origin of switch costs there

---

[25] According to “proactive interference” accounts, switch costs (or n-1 shift costs) would primarily reflect the passive *after-effects* of previous active control processes (i.e., *task-set inertia*), which result in both positive and negative priming of task sets (e.g., Allport et al., 1994; Allport & Wylie, 1999; Wylie & Allport, 2000). Hence, regarding the origin of switch costs and related asymmetries there are at least two equally good explanations within the “proactive interference” accounts (Allport et al., 1994; Allport & Wylie, 1999; Wylie & Allport, 2000). One is that switch costs origin because previous task inhibition (e.g., Green, 1986, 1998; Meuter & Allport, 1999). The other possibility is that at the origin of switch costs and related effects there is a carryover effect of the activation of the previous task on the successive one (Yeung & Monsell, 2003).

[26] This issue is problematic for all the instantiations of the language switching paradigm that measured switch costs by comparing adjacent blocks or trials of naming.

was language inhibition or previous language activation. This is because the inhibition account predicts that recovering a previously inhibited language should hamper the performance, due to the need of overcoming a ‘residual inhibition’ (e.g., Gade & Koch, 2007; Mayr & Keele, 2000). Conversely, the activation account (e.g., Yeung & Monsell, 2003), predicts facilitation or no changes[27] in performance.

Hence, when comparing the third with the first block of picture naming we focused on a specific ERP component, that is, the N200. In fact, this ERP component is particularly relevant to test the ICM (Green 1986, 1998), since it has been related specifically to domain-general inhibitory control processes (see Misra et al., 2012). In accord with the ICM (Green 1986, 1998; Misra et al., 2012), we should have observed slower RTs and more negative-going N200 deflections for L1 “recovery”[28] (i.e., when comparing the third with the first block of L1 naming; cf. Section 2.4). Conversely, according to the activation account we should have observed facilitatory effects (i.e., reduced negativity and faster response times) or at least no variation in RTs and in the ERPs for L2 “recovery” (i.e., when comparing the third with the first block of L2 naming).

---

[27] We hypothesized to observe no changes in RTs when comparing the third with the first block since the simple activity of switching between blocks requires some executive control.

[28] We hypothesized to observe also more positive-going P200 deflections if L1 “recovery” implied to overcoming inhibition. However, we considered the N200 modulation to be mandatory to conclude for the involvement of inhibition in the task.

Behavioral results revealed that naming in L1 was hampered when preceded by naming in L2, whereas naming in L2 was not affected by previous naming in L1. Although this asymmetrical pattern fits in the inhibitory account, the ERP modulation according to the naming direction was present at the P200 and not at the N200. The P200 component has been related to variables that affect the time to retrieve words, such as cognate status, lexical frequency and language dominance (Strijkers, Costa, & Thierry, 2010; Strijkers, Holcomb, & Costa, 2011; Strijkers, Baus, Runnqvist, Fitzpatrick, & Costa, 2013), but it has not been associated to inhibitory control specifically. Hence, to the extent to which inhibitory processes should have been observed at the ERP N200 component, our findings indicated that behavioral asymmetries could occur without inhibition, at least in high-proficient bilinguals.

In this study, we interpreted the presence of P200 effects and the absence of inhibitory ones at the N200 as indicating that control mechanisms different from inhibitory control are at the origin of the asymmetries between languages. We proposed that the P200 modulation according to the naming direction reflected other type of control processes applied in a proactive manner, at the early stage of lexical access. We also proposed that these control processes might work by adjusting the relative activation of the languages when the linguistic system is settled according to a bilingual mode context (e.g., Grosjean, 2001). In other words, when the languages have been activated and used once, these control processes would raise the lexical selection threshold of the L1 to allowing successful L2 production. This explanation is in accord with previous studies (trial-by-trial switching tasks[29]), suggesting that switching between languages might set out such processes in high-proficient bilinguals (see Costa & Santesteban 2004; Costa et al., 2006).

All in all, results from Section 2.4 suggest that inhibitory control is not necessarily involved in the processes that allow high-proficient bilinguals to control their two languages. Nevertheless, other studies reported such inhibitory effects. Misra et al. (2012) reported behavioral results in line with ours, that is, only the L1 production was affected by previous naming in the other language. However, the ERP modulation according to the naming direction was present at the N200 component. Conversely, we found it at the P200 component. Our findings and those reported by Misra et al. (2012) are in accord with the proposal that high- and low-proficient bilinguals would employ different mechanisms to control their languages: the first group would employ "language-specific selection mechanisms" and the second group inhibitory control (see Costa & Santesteban 2004; Costa et al., 2006).

In Section 2.8 we sought evidence regarding the patterns of switch costs and inhibitory control by following this logic: if we would have found those areas known to be involved in inhibitory control (see Abutalebi & Green, 2007, 2008 Green & Abutalebi, 2013) to be sensitive to the naming order, hence, we would have concluded that inhibitory control was involved in bilingual language production.

---

[29] Costa and Santesteban (2004) and Costa et al. (2006) to explain the paradoxical speed disadvantage for L1 in "trial-by-trial language switching tasks" proposed that RTs for the L1 are slowed down because its selection threshold is heightened to favor L2 production.

Our results showed that naming a set of pictures in L1 after having named them in L2 induced an increase of the BOLD signal in the left prefrontal cortex (LPFC), in the left/right inferior parietal lobule (LIPL and RIPL) and in the right prefrontal cortex RPFC (a cluster located in the pars triangularis of the right inferior frontal gyrus-RIFG). A decrease of the BOLD signal in the same brain areas was observed for the opposite naming direction, that is, when naming in L2 after L1.

These results were interpreted as reflecting that naming in L1 after L2 was enacted by the activity in these areas, likely ruled by demands to override previous inhibition of L1, during a preceding L2 naming block. In fact, the above-mentioned areas and especially the LPFC have been found as involved in language selection, switching and inhibition (e.g., Abutalebi & Green, 2007, 2008; Guo et al., 2011; Hernandez, Dapretto, Mazziotta, & Bookheimer, 2001; Hernandez, Martinez, & Kohnert, 2000). Moreover, the RPFC has been related to domain-general inhibitory control (e.g., Aron, Robbins, & Poldrack, 2004, 2014; de Bruin et al., 2014).

Conversely, naming a set of pictures in L2 after having named them in L1 induced an increase of the BOLD signal in the dACC/pre-SMA complex, which has been related to monitoring processes (e.g., Abutalebi et al., 2012).

To the extent to which these asymmetries indicate that disengaging from L2 lexicon to access to the L1 lexicon is more demanding than the reverse, this evidence is in line with previous findings (e.g., Meuter & Allport, 1999; Costa & Santesteban, 2004; Costa et al., 2006; Guo et al., 2011; Misra et al., 2012). For example, Guo et al. (2011) observed that naming in L1 after L2 (second block) as compared to L1 in a first block elicited the activation of a network of frontal and parietal brain areas, whereas instead naming in L2 after L1 (second block) as compared to L2 in a first block activated just posterior brain areas, not involved in executive control (i.e., Cuneus and PreCuneus).

Regarding the specific interpretation of these neural asymmetries they may reflect that naming in L1 after L2 requires control processes necessary to recover from inhibition, that are implemented by an *effector neural system* (cf. in Section 2.8). Instead, naming in L2 after L1 requires rather monitoring demands and error-detection processes (Collette & Van der Linden, 2002) (cf. in Section 2.8 *supervisory attentional system*) that simply reduce the possibility that unwanted and still proponent targets in L1 interfere with L2 production.

Taken together, the evidence gathered from Section 2.4 and 2.8 leads to apparently contrasting conclusions in respect to the question of the mechanisms of bilingual language control. In fact, on one hand, we found the ERP P200 component behind the after-effects of bilingual language control, suggesting that the mechanisms employed by bilinguals to control the two languages might be different from inhibition. On the other hand, the neural asymmetries between the two languages may indicate that the L1 was inhibited during L2 production. These findings are difficult to be reconciled, especially when considering that the bilinguals tested in these two studies were high-proficient in the two languages[30] (see Section 2.4 and 2.8). Although differences in language proficiency cannot explain different outcomes in these two studies, other aspects of bilinguals' linguistic experience may help to reconcile these results. In the last section of this dissertation we will discuss them.

3.2 On the mechanisms of bilingual language control: the overlap between bilingual language control and domain-general executive control

In the present dissertation we investigated the question about the mechanisms of bilingual language control also by examining the overlap between bilingual language control and domain-general executive control (Sections 2.5, 2.6, 2.7 and 2.8). This approach enables to test one important assumption of the ICM (Green, 1986, 1998), stating that the mechanisms involved in bilingual language control are domain-general.

In three studies (see Section 2.5, 2.6 and 2.7), we explored the overlap between bilingual language control and domain-general executive control by employing linguistic and non-linguistic "trial-by-trial switching tasks". We tested high-proficient Catalan/Spanish

---

[30] In Appendix C are reported the scores relative to self-assessed language proficiency, across all the studies presented in this dissertation. When examining these scores, it seems that bilinguals in Section 2.4 were slightly more proficient in their L2 than bilinguals in Section 2.8. Nevertheless, bilinguals in Section 2.8 obtained very similar scores for the two languages in a language proficiency test ("Transparent Language Proficiency Test"). Hence, this objective measure ensures us to characterize bilinguals in Section 2.8 as high-proficient in both the two languages.

bilinguals and, as mentioned above, we revealed only a partial overlap between the two systems (see also Prior & Gollan, 2013).

In Section 2.5 and 2.6, we tested different hypotheses relative to the n-1 shift cost. First, we hypothesized that finding similar patterns of n-1 shift costs in the two tasks would have indicated a similar involvement of (inhibitory) control processes in bilingual language control and domain-general executive control. To recall, the patterns of n-1 shift costs for tasks of different difficulty generally show that the cost of switching to the stronger (or the more simple) of a pair of tasks is larger than the cost of switching to the weaker (or the less simple) of a pair of tasks (e.g., Martin et al., 2011). This asymmetry of switch costs finds a straightforward explanation in the ICM (Green, 1986, 1998) that predicts that more time and cognitive sources would be required to overcoming the inhibition of the stronger task, than to overcoming that of the weaker task. Hence, to the extent to which switch costs asymmetries indicate that inhibitory control is involved in the task, we were expecting to observe differences between the patterns of switch costs in linguistic and in non-linguistic switching tasks. This is because we tested high-proficient bilinguals, that in the linguistic version of these tasks have shown symmetrical (e.g., Costa & Santesteban, 2004; Costa et al., 2006), rather than asymmetrical (e.g., Meuter & Allport, 1999) patterns of switch costs.

Indeed, we observed different patterns of switch costs between linguistic and non-linguistic switching tasks. We took these results as suggesting that high-proficient bilinguals control their two languages through mechanisms different from domain-general inhibitory control (i.e., “language-specific selection mechanisms”, see Costa & Santesteban, 2004; Costa et al., 2006). In addition to this, results from Section 2.6 revealed that the magnitude of the n-1 shift cost was affected by aging only in the non-linguistic switching task. Indeed, the age of the participants was correlated with the magnitude of the non-linguistic n-1 shift cost only. These results become very relevant when considering that the overall speed of processing in the two tasks was similarly affected by aging.

These findings along with those relative to the patterns of switch costs in linguistic[31] and in non-linguistic switching tasks, may indicate that bilingual language control and domain-general executive control do not share the same inhibitory control processes.

We are aware that previous findings reporting inconsistent patterns of switch costs (e.g., Christoffels et al., 2007) and explanations alternative to inhibition to obtain the same patterns (see Yeung & Monsell, 2003), may compromise a straightforward interpretation of these results as a lack of inhibitory control in the linguistic switching task. However, results of Section 2.7 support the conclusion that inhibitory control is differently involved in bilingual language control and in domain-general executive control.

---

[31] Importantly, in Section 2.5 this symmetry was present not only when bilinguals were required to switch between the L1 and the L2, but also when they were required to switch between the L1 and a much weaker L3. This last experiment ensured that the (relative) difference between the “strength” of the two languages was indeed present. Hereby, according the ICM the amount of inhibition to be overcome would have been different when switching to L1 and to L3.

In Section 2.7 we explored the role of inhibitory processes in bilingual language control by assessing also the “n-2 repetition cost”, supposed to be an unequivocal index of inhibitory control in switching tasks (e.g., Mayr & Keele, 2000). Hence, bilinguals were tested in linguistic and in non-linguistic switching tasks in which we measured both n-1 shift and n-2 repetition costs. As previously hinted, calculating both types of costs allowed us to know to which extent inhibitory control was involved in linguistic and non-linguistic tasks.

To recall, differently from the n-2 repetition cost, the n-1 shift cost may capture the efficiency of other mechanisms besides inhibitory control (see Koch et al., 2010; Philipp & Koch, 2006; Kiesel et al., 2010). Hereby, we considered the n-2 repetition cost as an index of inhibitory control in the task. And, since the inhibition measured through the n-2 repetition cost contributes also to the size of the n-1 shift cost, we expected to observe a reduction of the n-2 repetition cost, as compared to the n-1 shift cost, only in the linguistic switching task. The results we observed were in line with our predictions.

Overall, the evidence on the patterns of switch costs across the studies presented in sections 2.5, 2.6 and 2.7 suggests a partial overlap between bilingual language control and domain-general executive control. Particularly, to the extent to which the patterns of switch costs we revealed inform on the involvement of inhibition in the task, our results suggest that inhibitory control is not similarly involved in bilingual language control and in domain-general executive control.

Secondly, we also hypothesized that if the same control processes were applied when bilinguals must switch between languages or between non-linguistic tasks, these processes should have varied similarly across tasks. In other words, we hypothesized to find a correlation between linguistic and non-linguistic switch costs. However, we could not observe any significant correlation between tasks in any of these three behavioral studies (Section 2.5, 2.6 and 2.7). Importantly, the lack of a significant correlation regarded not only the n-1 shift cost (that was tested in populations of different ages), but also the n-2 repetition cost, which, as explained, is thought to reflect specifically inhibitory control processes (see Koch et al., 2010; Kiesel et al., 2010).

Therefore, also the results of the correlation analyses do not support the ICM (Green 1986, 1998), according to which the mechanisms involved in bilingual language control are inhibitory and domain-general.

Besides the assessment of the patterns of switch costs and the correlation analyses, in Section 2.6 and 2.7 we employed also the ex-Gaussian distribution analysis[32] to explore dissociations and associations between linguistic and non-linguistic tasks that might not be detectable in the mean RTs.

---

[32] As we hinted in Section 2.2, this analysis decomposes the overall RT distribution in two distributions: the normal and the exponential one. Importantly, the former is characterized by two parameters, that is, mu (μ) which is the mean of the fitted normal distribution and sigma (σ), that is, the variance. The exponential distribution corresponds to the tail of the RT distribution and is characterized as the tau parameter (τ) (e.g., Spieler et al., 1996; McAuley et al., 2006).

Interestingly, in Section 2.6 we revealed that the n-1 shift cost was not affected by age in the linguistic switching task, in neither the exponential (τ) nor the normal (μ) component of the RT distribution. Instead, the n-1 shift cost was affected by age in the non-linguistic switching task, given that the elderly group had larger switch costs than the young group of bilinguals. Interestingly, this effect was driven by the values of the exponential component (τ) of the RT distribution in switch trials, rather than by those of the normal component (μ). In line with these findings, in Section 2.7 we observed that RTs and switch costs in the two tasks were captured by different components of the RT distribution. That is, we observed larger τ values in the non-linguistic switching task as compared to the linguistic switching task, across all experimental conditions. Moreover, the exponential component (τ) captured both the n-1 shift cost and the n-2 repetition cost in the non-linguistic switching task, whereas only the n-1 shift cost in the linguistic switching task. Since the exponential component (τ) has been related to domain-general executive control and to inhibitory control (e.g., McAuley et al., 2006; Penner-Wilger, Leth-Steensen, & LeFevre, 2002; Shao et al., 2012; Spieler et al., 1996) and since aging is also associated with a decline of the inhibitory control system (Greenwood, 2000; Rhodes, 2004; Verhaeghen & Cerella, 2002), the results from the Ex-Gaussian analyses (Sections 2.6 and 2.7) support the conclusion of different involvements of inhibitory control in the linguistic and in the non-linguistic switching tasks.

On one side, across these three behavioral studies (see Section 2.5, 2.6 and 2.7) we provided consistent evidences that are difficult to be reconciled with the ICM (Green, 1986, 1998). On the other side, these results leave open the question on the overlap between bilingual language control and domain-general executive control.

In respect to this point, some results from Section 2.7 might provide a tentative answer to this question, i.e., the correlation between the n-1 shift cost and the n-2 repetition cost, in both linguistic and non-linguistic switching tasks. In Section 2.7, we explored the possibility that the overlap between bilingual language control and domain-general executive control regarded a control ability that allows combining different executive control mechanisms required in a task ("cognitive control flexibility"). This hypothesis is motivated by recent observations in the bilingual advantage literature (e.g., Morales et al., 2013). As suggested by Hilchey and Klein (2011) and in accord with other studies (e.g., Costa, Hernández, Costa-Faidella, & Sebastián-Gallés, 2009; Costa, Hernandez, & Sebastian-Galles, 2008; Morales et al., 2013; Prior & MacWhinney, 2010; Prior, 2012) bilingual experience would make them more efficient in applying relevant executive control processes, according to task demands (e.g., Hilchey & Klein, 2011; Prior, 2012). Hence, we interpreted the negative correlation between the two costs (in both linguistic and the non-linguistic switching tasks) as reflecting that this control ability, to adjust the deployment of task activation and task inhibition (i.e., the processes required by the task), was shared between bilingual language control and domain-general executive control systems.

The idea that the overlap between bilingual language control and domain-general executive control regards this control ability is further corroborated by the lack of this correlation in monolinguals (Branzi, Calabria, Gade, Fuentes & Costa, under review). In fact, in another study we compared bilinguals and monolinguals in the same non-linguistic switching task and in bilinguals only we observed the negative correlation between the two costs, along with faster RTs across all conditions. The correlation between the two costs may reflect a control ability that is learned with the experience of juggling with two different languages. Once established in the linguistic domain, this ability might be then transferred also to the non-linguistic domain. This hypothesis needs further research to be confirmed. However, it is in accord with the idea that this control ability may come about because bilinguals need to continuously monitor which language needs to be activated or inhibited, according to the interlocutor (see Costa et al., 2009). We acknowledge that this explanation may not be applicable to all the bilingual cases. We will come back to this point in the last section of the dissertation (see Section 3.4).

The last study that explored the overlap between bilingual language control and domain-general executive control is the fMRI study presented in Section 2.8. In this study, we tested high-proficient German/Italian bilinguals in linguistic and non-linguistic blocked switching tasks. We did so to explore whether linguistic and non-linguistic tasks were entailing similarly the brain areas involved in the language control network (see Abutalebi & Green 2007, 2008). This study provided evidence of a limited overlap between bilingual language control and domain-general executive control systems. In fact, this overlap was restricted to the control of the dominant language (i.e., when the switches were from L2 to L1). Although limited, however, this neural overlap concerned brain areas involved in inhibitory control.

As discussed above, we proposed that naming in L1 after L2 recruited executive control brain areas likely because L1 was strongly inhibited during previous L2 production. According to the ICM (Green, 1986, 1998), these inhibitory mechanisms and their neural correlates should be domain-general, that is, observable also in experimental settings that require switching between non-linguistic tasks. In accord with this interpretation, we revealed that the control mechanisms applied when naming in L1 after L2 seem to be elicit brain responses similar to those applied for the control of the semantic classification task. Specifically, we revealed a similar shift of activity in the LPFC, previously associated to different executive control functions, including inhibitory control and interference suppression (e.g., Aron et al., 2004; Bunge, Hazeltine, Scanlon, Rosen, & Gabrieli, 2002; Bunge et al., 2002; Figner et al., 2010; Guo et al., 2011; Knoch & Fehr, 2007).

Hence, to the extent to which the involvement of the PFC reflects inhibitory control, our results suggest that this mechanism is similarly involved in the linguistic and in the non-linguistic task.

Despite this functional overlap, nevertheless our findings indicated some differences between linguistic and non-linguistic tasks. In fact, we observed that pars orbitalis of the RIFG was increasingly activated for the semantic classification task, whereas it showed a negligible effect for L1 control and a significant decrease for L2 control. Conversely, pars triangularis of the RIFG was increasingly activated for L1 control, whereas it showed a negligible effect for the control of the semantic classification task. Interestingly, the RIFG has been particularly related to domain-general inhibitory control (Forstmann et al., 2008; Jahfari et al., 2011). Aron et al. (2014) recently suggested that the RIFG would be specifically involved in various forms of inhibition, including inhibition of S-R bindings or task-sets, when the context or the task changes (see also Lenartowicz, Verbruggen, Logan, & Poldrack, 2011).

Therefore, according to these findings one could speculate that the inhibitory mechanisms involved in bilingual language control and in domain-general executive control are distinct. This is an interesting hypothesis that may be worth to be investigated in the future.

To summarize, the evidence provided in this section suggests only a partial overlap between bilingual language control and domain-general executive control. Regarding domain-general inhibitory control in particular, we do not provide strong evidences that support a similar involvement in bilingual language control and in domain-general executive control tasks. We acknowledge that the evidence presented in this section may lead to contrasting conclusions. On one hand, in the first three studies (Sections 2.5, 2.6 and 2.7) presented in this section, we do not reveal any evidence of an overlap between bilingual language control and domain-general inhibitory control. On the other hand, in the fMRI study (Section 2.8) we obtained some results that may lead to the opposite conclusion. In the last section of this dissertation we discuss possible ways to reconcile these results.

3.3 On the scope of bilingual language control

The second main question investigated in this dissertation is relative to the representational scope of bilingual language control (e.g., De Groot & Christoffels, 2006). In Section 2.3 we pointed out that, at present, there are not conclusive findings on this issue. This is because previous studies did not provide a clear distinction between *local* and *global* aspects of bilingual language control (e.g., Guo et al., 2011; Misra et al., 2012; Van Assche et al., 2013), or they conflated control demands with representational issues[33] (e.g., Guo et al., 2011).

In the introduction of this dissertation we reviewed those few studies that we believe have addressed some aspects of this issue. The overall picture provided is rather mixed. In fact, some evidence indicates that naming in one language affects the other language, only when the same items are involved in the task (i.e.,

---

[33] In the literature, quite often the very same terms are used improperly to define different and relatively independent aspects of bilingual language control, such as those related to the representational aspects (*local* and *global control*) and those related to the timing and the demands of such control (i.e., transient and sustained control, see Christoffels et al., 2007). As explained in the introductive section, *global control* refers to the inhibition or activation of a complete language system, whereas *local control* involves specific lexical representations, such as those involved in the task (e.g., De Groot, & Christoffels, 2006). In other words, what distinguishes *local* from *global control* would be the type of lexical representations involved only.

local control; see Finkbeiner et al., 2006). Other findings instead are more compatible with a *global control* view (Vann Assche et al., 2013).

In the present dissertation we presented two experimental studies in which we investigated the representational scope of bilingual language control (see Sections 2.4 and 2.8).

In Section 2.4 we measured behavioral performance and ERPs to explore whether the after-effects of naming in one language on the other language affected similarly repeated and unrepeated items (i.e., *local* and *global control*). We found that the L1 was negatively affected by previous naming in L2, for both repeated and unrepeated pictures. Behaviorally, these effects were observable in a lack of repetition priming facilitation for repeated items (i.e., *local control*) and in a slowdown of RTs for unrepeated items (i.e., *global control*). Accordingly, we found for both repeated and unrepeated items larger P200 amplitudes when comparing naming in L1 after L2 with naming in L1 first.

Since both repeated and unrepeated items were similarly modulated in terms of behavioral and electrophysiological responses, we hereby concluded that bilingual language control was applied *globally* on the L1, that is, to the whole language.

In Section 2.8 we measured brain responses to repeated and unrepeated items across blocks of picture naming and we revealed differences between *local* and *global control* driven by language dominance. That is, we found that when the switch was from L2 to L1, *local* and *global control* were entailing similarly many of the brain areas of the language control network, such as the LPFC, the RPFC, the RIPL, and the LIPL (see Abutalebi & Green 2007, 2008; Green & Abutalebi, 2013). These areas showed increased brain responses for L1 and decreased brain responses for L2. We interpreted these findings as reflecting that L1 control entails the mechanisms for language control *globally*.

Nevertheless, we revealed differences between *local* and *global control* for L2 naming after L1. In fact, we found the dACC/pre-SMA was more activated for *local* than *global control,* suggesting that naming in L2 a set of items that were previously named in L1, requires extra demands for monitoring control. The role of the pre-SMA has been previously associated to some aspects of *local control* (Guo et al., 2011[34]; Abutalebi et al., 2013). This area has been particularly related to monitoring language context and it is considered to have a general role in task monitoring (Abutalebi et al., 2012; Rodríguez-Pujadas et al., 2014).

These results indicate some dissociation between languages regarding the scope of bilingual language control. On one hand, we revealed that bilingual language control is applied *globally,* when it is necessary to access to L1 representations after L2 production. This is in accord with results revealed in Section 2.4. On the other

---

[34] Note that Guo et al. (2011) refer to "*local control*" as the effects arising from the comparison between trials in the trial-by-trial switching task vs. trials in the blocked switching task. Instead, they refer to "*global control*" as to the effects originating from the comparison between blocks of language (second block vs. first block). However, since in both cases the pictures employed were repeated, in this study "*local*" and "*global*" *control* might be considered as two different measures of "*local control*"; the first driven by "transient" attentional processes and the second driven by "sustained" attentional processes (e.g., Braver, Reynolds, & Donaldson, 2003).

hand, only in this study we found that bilingual language control is also applied *locally*, when accessing to L2 representations after L1 production.

3.4 On how different socio-linguistic contexts may affect the mechanisms and the scope of bilingual language control

The idea that some aspects of language experience may affect the way in which bilinguals control the two languages is far from being new. For example, different behavioral patterns of linguistic switch costs have been observed when comparing high- and low-proficient bilinguals (see Costa & Santesteban, 2004; Costa et al., 2006). Language proficiency not only affects behavioral performance, but also the brain network of language control, given that high-proficient and low-proficient bilinguals engage different brain areas when switching between languages (see Wang et al., 2007; Garbin et al., 2011). Accordingly, other evidence indicates that language proficiency modulates the neural responses and structural changes in the language control network (Abutalebi et al., 2014; Abutalebi, Della Rosa, Ding, et al., 2013; Abutalebi, Della Rosa, Gonzaga, et al., 2013).

All these observations are in line with the current view on language processing, according to which structural and functional components of the language control network are not fixed, but rather dynamically organized as a function of linguistic experience (e.g., Abutalebi, Della Rosa, Ding, et al., 2013; Abutalebi, Della

Rosa, Gonzaga, et al., 2013; Blumstein & Amso, 2013; Green & Abutalebi, 2013; Jones et al., 2012; Zou et al., 2012).

Regarding the case of bilingualism in particular, linguistic experience concerns other factors besides language proficiency, such as language use and rate of language switching on daily basis (e.g., Christoffels et al., 2007; Prior & Gollan, 2011; Rodriguez-Fornells, Krämer, Lorenzo-Seva, Festman, & Münte, 2012). This idea is at the core of the "adaptive control hypothesis" proposed by Green and Abutalebi (2013). This hypothesis suggests that bilingual language control mechanisms are adapted by demands placed on them. That is, according to the interactional context that refers to the recurrent pattern of conversational exchanges within a community of (bilingual) speakers.

Hence, if the interactional context affects brain plasticity and behavioral performance, there should be consistent difference between those bilinguals that make similar use of the two languages or/and that switch frequently between them and those bilinguals that do not do that.

In the present dissertation, we report some results that are in accord with this hypothesis.

We tested two different samples of bilinguals, i.e., Catalan/Spanish and German/Italian bilinguals. Although these two groups may be considered "dual language context"[35] speakers (see

---

[35] According to Green and Abutalebi (2013) "dual-language" speakers refer to those bilinguals that every day use both the two languages, but for which switching between languages occur within a conversation and not within an utterance.

Green & Abutalebi 2013), nevertheless they are different for some aspects. For example, the use of the two languages is less balanced in the case of German/Italian bilinguals than in the case of Catalan/Spanish bilinguals (see Appendix C, Appendix A and Appendix B). Moreover, also the frequency of language switching on daily basis of German/Italian bilinguals seems not to be exactly the same as that of Catalan/Spanish bilinguals (see Appendix A and Appendix B; see also Appendix C). This is not surprising since Catalan/Spanish bilinguals live in a particular socio-linguistic context in which the use of the two languages is very balanced and frequent switches between languages are natural aspects of bilingual conversations (see Appendix A).

These considerations may help to reconcile some of the results presented in this dissertation. To recall, in Catalan/Spanish bilinguals we found behavioral switch costs asymmetries accompanied with ERP effects, suggesting that mechanisms for bilingual language control do not necessarily resort to inhibitory control (Section 2.4). We provided an alternative account to the application of inhibition for this asymmetry. Importantly, this account is in accord with previous evidence (Costa & Santesteban, 2004; Costa et al., 2006) and also with the findings provided in three studies of this dissertation (Sections 2.5, 2.6 and 2.7). In Sections 2.5 and 2.6 we reported symmetrical patterns of linguistic switch costs in Catalan/Spanish bilinguals, that have been taken to reflect that high-proficient and balanced bilinguals may resort to “language-specific selection mechanisms”, rather than to inhibitory processes, to control their two languages (see Costa & Santesteban

2004; Costa et al., 2006). Support for this hypothesis comes also from results in Section 2.7, in which the reduction of the linguistic n-2 repetition cost as compared to the n-1 shift cost suggests a negligible role of inhibitory control in bilingual language control, at least for high-proficient and balanced bilinguals.

Indeed, these “language-specific selection mechanisms” might be relevant in the linguistic context in which Catalan/Spanish bilinguals are immersed (see Appendix A). In fact, in this socio-linguistic context in which the two languages are equally used and frequently alternated in conversational settings (see Appendix A), strong inhibition on the non-intended language may not be advantageous.

Conversely, German/Italian bilinguals (Section 2.8) reported a rather unbalanced use of the two languages (see Appendix C). This may have influenced the mechanisms of bilingual language control in such a way that the use of inhibition is advantageous. Indeed, a context in which the L1 is used much more than the L2, would likely determine greater cross-language interference when speaking in L2 than when speaking in L1. Hence, for these bilinguals the use of inhibitory control may be particularly useful to allow the production of the non-dominant language (i.e., L2).

The difference between bilinguals with different socio-linguistic experiences has been observed not only in tasks that require language control, but also in those tasks that require domain-general executive control (Luk, De Sa, & Bialystok, 2011; Prior & Gollan, 2011; Singh & Mishra, 2012; Soveri, Rodriguez-

Fornells, & Laine, 2011; Tao, Marzecová, Taft, Asanowicz, & Wodniecka, 2011).

For example, Prior and Gollan (2011) found that only one of the two groups of bilinguals (Spanish-English) tested in their study showed reduced switch costs in the non-linguistic switching task, as compared to monolinguals. Interestingly, this group was the one that reported to switch frequently between the two languages.

In addition, it has been also demonstrated a relationship between intrusion errors in a single-language conversational context and cognitive measures of executive functioning (Festman, 2012; Gollan et al., 2011) and between measures of language switching and the control of nonverbal interference (Linck et al., 2012).

According to the "adaptive control hypothesis" (Green & Abutalebi, 2013), those control processes that are contingent during interactional contexts will be correlated between tasks, only if the two tasks tap the same processes.

In the present dissertation, we presented results that are in accord with this hypothesis.

We found a negative correlation between the n-1 shift cost and the n-2 repetition cost, in both linguistic and non-linguistic switching tasks. We interpreted this correlation as reflecting control processes to adjust the deployment of task activation and task inhibition processes, in a task context that required both of them. This interpretation is in accord with the idea that the linguistic context of Catalan/Spanish bilinguals may have required to developing this (control) ability to detect salient cues to switch smoothly between languages. Indeed, this hypothesis is in line with various evidences on bilingual advantage in domain-general executive control (e.g., Costa et al., 2008; Costa et al., 2009; Branzi, Calabria, Gade, Fuentes, & Costa, under review).

Importantly, this correlation might be present in Catalan/Spanish bilinguals because they need to coordinate optimally the mechanisms to activating one language and, at the same time, to inhibit the other language, to allow language switching. Instead, this correlation might not be present in those bilinguals that do not switch very frequently between languages. This is an interesting hypothesis that needs to be investigated in the future.

As the results on the mechanisms of bilingual language control, also those related to the representational scope may be explained according to differences in language use and language switching rate.

In Sections 2.4 and 2.8, we revealed that language control was applied *globally* on the L1 to allow L2 production. However, only in German/Italian bilinguals we found the involvement of monitoring processes applied *locally* during L2 production.

These evidences may indicate that differences in language use could affect, besides the mechanisms, also the extent to which they are applied.

Hence, one interesting possibility would be that, when bilinguals are balanced in the use of the two languages (i.e., Catalan/Spanish bilinguals), “language-specific selection mechanisms” are applied *globally* on the L1, to allow L2 production (see Section 3.1). However, when bilinguals are less balanced cross-language interference may be disproportionately due to L1. Hence, the bilingual language control system might need to apply (inhibitory) control mechanisms *globally* on the L1 and, at the same time, to apply also (monitoring) control *locally* on the L2. This last operation would ensure that L1 inhibition has been applied successfully.

Future research needs to reveal how language control mechanisms and its neural correlates are recruited as function of the above-mentioned socio-linguistic factors (i.e., language proficiency, language use and rate of language switching on daily basis). In any event, we believe it is necessary to take into account such factors in order to reduce variability in the data and to better characterize the phenomena related to bilingualism (see Green & Abutalebi, 2013; Green, 2011; Luk & Bialystok, 2013; Rodriguez-Fornells et al., 2012).

3.5 Final Remarks

The work realized for this dissertation aimed to advance our knowledge on how language production and control is achieved in bilingual speakers. In particular, we sought new evidence on two related aspects: on the mechanisms and the representational scope. The most consistent set of results presented in this dissertation suggests that the mechanisms of bilingual language control are different from domain-general inhibitory control. We acknowledge this conclusion is not completely supported by the observation that inhibitory control brain areas were similarly involved in linguistic and non-linguistic tasks. However, some small difference in the activation pattern of some brain regions would indicate that more fine-grained analyses are needed to better understand the issue of the underlying control mechanisms in the linguistic and non linguistic domain.

The second main conclusion of this dissertation is that the mechanisms of bilingual language control are applied *globally* on the dominant language and likely also *locally* on the non-dominant language.

The present dissertation contributes in two important ways to the research field of bilingual language control. It advanced the knowledge on the mechanisms and the representational scope and it suggested some experimental strategies to clarify the role of inhibitory processes in switching tasks.

As a final consideration, we believe that determining the weights of the socio-linguistic factors in sculpting the language control system will be a relevant question for future research in the context of bilingualism.

References

Abutalebi, J., Canini, M., Della Rosa, P. a, Sheung, L. P., Green, D. W., & Weekes, B. S. (2014). Bilingualism protects anterior temporal lobe integrity in aging. *Neurobiology of Aging*, *35*(9), 2126–33.

Abutalebi, J., Della Rosa, P. A., Ding, G., Weekes, B., Costa, A., & Green, D. W. (2013). Language proficiency modulates the engagement of cognitive control areas in multilinguals. *Cortex*, *49*(3), 905–911.

Abutalebi, J., Della Rosa, P. A., Gonzaga, A. K. C., Keim, R., Costa, A., & Perani, D. (2013). The role of the left putamen in multilingual language production. *Brain and Language*, *125*(3), 307–315.

Abutalebi, J., Della Rosa, P. A., Green, D. W., Hernandez, M., Scifo, P., Keim, R., … Costa, A. (2012). Bilingualism tunes the anterior cingulate cortex for conflict monitoring. *Cerebral Cortex*, *22*, 2076–2086.

Abutalebi, J., & Green, D. W. (2007). Bilingual language production: The neurocognition of language representation and control. *Journal of Neurolinguistics*, *20*(3), 242–275.

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

Allport, A., Styles, E. A., & Hsieh, S. (1994). Shifting intentional set: Exploring the dynamic control of tasks. In C. Umilta & M. Moscovitch (Eds.), *Attention and performance XV: Concious and nonconcious information processing* (Vol. 15, pp. 421–452). Hillsdale, NJ: Elrbaum.

Allport, A., & Wylie, G. (1999). Task switching: Positive and negative priming of task-set. In G. W. Humphreys, J. Duncan, & A. M. Treisman (Eds.), *Attention, space and action: Studies in cognitive neuroscience.* pp. 273-296). Oxford, England: Oxford University Press.

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

Aron, A. R., Robbins, T. W., & Poldrack, R. A. (2014). Inhibition and the right inferior frontal cortex: one decade on. *Trends in cognitive sciences, 18*(4), 177-185.

Baldo, J. V, Shimamura, A. P., Delis, D. C., Kramer, J., & Kaplan, E. (2001). Verbal and design fluency in patients with frontal lobe lesions. *Journal of the International Neuropsychological Society* : JINS, *7*(5), 586–596.

Baus, C., Branzi F. M., & Costa A. (In press). On the mechanism and scope of language control in bilingual speech production. *The Cambridge Handbook of bilingual processing.*

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

Blumstein, S. E., & Amso, D. (2013). Dynamic Functional Organization of Language: Insights From Functional Neuroimaging. *Perspectives on Psychological Science*, *8*(1), 44–48.

Branzi, F. M., Calabria M., Boscarino M. L., & Costa A. (Under review). Inhibitory control and cognitive control flexibility: the overlap between bilingual language control and domain-general executive control. *Journal of Experimental Psychology: Learning, Memory, and Cognition.*

Branzi, F. M., Calabria M., Gade M., Fuentes L., & Costa A. (Under review). Beyond the switch cost: flexible strategies in bilingual minds. *Journal of Memory and Language.*

Branzi, F. M., Della Rosa P. A., Canini M., Costa A., & Abutalebi J. (Under review). Language control in bilinguals: monitoring and response selection. *Cerebral Cortex.*

Branzi, F. M., Martin, C. D., Abutalebi, J., & Costa, A. (2014). The after-effects of bilingual language production. *Neuropsychologia*, *52*, 102–116.

Braver, T. S., Reynolds, J. R., & Donaldson, D. I. (2003). Neural Mechanisms of Transient and Sustained Cognitive Control during Task Switching. *Neuron*, *39*(4), 713–726.

Bunge, S. A., Dudukovic, N. M., Thomason, M. E., Vaidya, C. J., & Gabrieli, J. D. E. (2002). Immature frontal lobe contributions to cognitive control in children: evidence from fMRI. *Neuron*, *33*(2), 301–11.

Bunge, S. A., Hazeltine, E., Scanlon, M. D., Rosen, A. C., & Gabrieli, J. D. E. (2002). Dissociable contributions of prefrontal and parietal cortices to response selection. *NeuroImage*, *17*(3), 1562–1571.

Calabria, M., Branzi, F. M., Marne, P., Hernández, M., & Costa, A. (2013). Age-related effects over bilingual language control and executive control. *Bilingualism: Language and Cognition*, 1-14.

Calabria, M., Hernández, M., Branzi, F. M., & Costa, A. (2012). Qualitative differences between bilingual language control and executive control: evidence from task-switching. *Frontiers in Psychology*, *2*.

Caramazza, A. (1997). How many levels of processing are there in lexical access? *Cognitive Neuropsychology*, *14*(1), 177–208.

Chialant, D., & Caramazza, A. (1997). Identity and similarity factors in repetition blindness: implications for lexical processing. *Cognition*, *63*(1), 79–119.

Christoffels, I. K., Firk, C., & Schiller, N. O. (2007). Bilingual language control: an event-related brain potential study. *Brain Research*, *1147*, 192–208.

Collette, F., & Van der Linden, M. (2002). Brain imaging of the central executive component of working memory. *Neuroscience & Biobehavioral Reviews*, *26*(2), 105–125.

Colomé, A. (2001). Lexical Activation in Bilinguals' Speech Production: Language-Specific or Language-Independent? *Journal of Memory and Language*, *45*(4), 721–736.

Costa, A., Alario, F. X., & Caramazza, A. (2005). On the categorical nature of the semantic interference effect in the picture-word interference paradigm. *Psychonomic Bulletin & Review*, *12*(1), 125–131.

Costa, A., & Caramazza, A. (1999). Is lexical selection in bilingual speech production language-specific? Further evidence from Spanish–English and English–Spanish bilinguals. *Bilingualism: Language and Cognition*, *2*(03), 231–244.

Costa, A., Caramazza, A., & Sebastian-Galles, N. (2000). The cognate facilitation effect: implications for models of lexical access. *Journal of Experimental psychology: Learning, Memory, and Cognition*, *26*(5), 1283–1296.

Costa, A., Hernández, M., Costa-Faidella, J., & Sebastián-Gallés, N. (2009). On the bilingual advantage in conflict processing: Now you see it, now you don’t. *Cognition*, *113*(2), 135–149.

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

Costa, A., La Heij, W., & Navarrete, E. (2006). The dynamics of bilingual lexical access. *Bilingualism: Language and Cognition*, *9*(02), 137–151.

Costa, A., Miozzo, M., & Caramazza, A. (1999). Lexical selection in bilinguals: Do words in the bilingual’s two lexicons compete for selection? *Journal of Memory and Language*, *41*(3), 365–397.

Costa, A., & Santesteban, M. (2004). Lexical access in bilingual speech production: evidence from language switching in highly proficient bilinguals and L2 learners. *Journal of Memory and Language*, *50*(4), 491–511.

Costa, A., Santesteban, M., & Ivanova, I. (2006). How do highly proficient bilinguals control their lexicalization process? Inhibitory and language-specific selection mechanisms are both functional. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *32*(5), 1057–1074.

De Bot, K. (1992). A bilingual production model: Levelt’s speaking model adapted. *Applied Linguistics*, *13*(1), 1–24.

De Bruin, A., Roelofs, A., Dijkstra, T., & Fitzpatrick, I. (2014). Domain-general inhibition areas of the brain are involved in language switching: FMRI evidence from trilingual speakers. *NeuroImage, 90*, 348–59.

De Groot, A. M. B., & Christoffels, I. K. (2006). Language control in bilinguals: Monolingual tasks and simultaneous interpreting. *Bilingualism: Language and Cognition*, *9*(02), 189–201.

Dell, G. S. (1986). A spreading-activation theory of retrieval in sentence production. *Psychological Review, 93*(3), 283–321.

Dhooge, E., & Hartsuiker, R. J. (2010). The distractor frequency effect in picture-word interference: Evidence for response exclusion. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *36*(4), 878–891.

Dhooge, E., & Hartsuiker, R. J. (2011). The distractor frequency effect in a delayed picture-word interference task: further evidence for a late locus of distractor exclusion. *Psychonomic Bulletin & Review*, *18*(1), 116–122.

Dobbins, I. G., Schnyer, D. M., Verfaellie, M., & Schacter, D. L. (2004). Cortical activity reductions during repetition priming can result from rapid response learning. *Nature*, *428*(6980), 316–319.

Falkenstein, M., Hoormann, J., & Hohnsbein, J. (1999). ERP components in Go/Nogo tasks and their relation to inhibition. *Acta Psychologica*, *101*(2), 267–291.

Festman, J. (2012). Language control abilities of late bilinguals. *Bilingualism: Language and Cognition*, *15*(03), 580-593.

Figner, B., Knoch, D., Johnson, E. J., Krosch, A. R., Lisanby, S. H., Fehr, E., & Weber, E. U. (2010). Lateral prefrontal cortex and self-control in intertemporal choice. *Nature Neuroscience, 13*(5), 538–539.

Finkbeiner, M., Almeida, J., Janssen, N., & Caramazza, A. (2006). Lexical selection in bilingual speech production does not involve language suppression. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *32*(5), 1075–1089.

Finkbeiner, M., & Caramazza, A. (2006). Now you see it, now you don't: On turning semantic interference into facilitation in a Stroop-like task. *Cortex*, *42*(6), 790-796.

Finkbeiner, M., Gollan, T. H., & Caramazza, A. (2006). Lexical access in bilingual speakers: What's the (hard) problem? *Bilingualism: Language and Cognition*, *9*(02), 153-166.

Forstmann, B. U., Dutilh, G., Brown, S., Neumann, J., von Cramon, D. Y., Ridderinkhof, K. R., & Wagenmakers, E. J. (2008). Striatum and pre-SMA facilitate decision-making under time pressure. *Proceedings of the National Academy of Sciences of the United States of America*, *105*(45), 17538–17542.

Gade, M., & Koch, I. (2007). The influence of overlapping response sets on task inhibition. *Memory & Cognition*, *35*(4), 603–609.

Garavan, H., Ross, T. J., Murphy, K., Roche, R. A. P., & Stein, E. A. (2002). Dissociable executive functions in the dynamic control of behavior: inhibition, error detection, and correction. *NeuroImage*, *17*(4), 1820–1829.

Garavan, H., Ross, T. J., & Stein, E. A. (1999). Right hemispheric dominance of inhibitory control: an event-related functional MRI study. *Proceedings of the National Academy of Sciences of the United States of America*, *96*(14), 8301–8306.

Garbin, G., Costa, A., Sanjuan, A., Forn, C., Rodriguez-Pujadas, A., Ventura, N., … Avila, C. (2011). Neural bases of language switching in high and early proficient bilinguals. *Brain and Language, 119*(3), 129–135.

Glaser, W. R., & Dunglehoff, F. J. (1984). The time course of picture-word interference. *Journal of Experimental Psychology*, *10*(5), 640–654.

Gollan, T. H., & Acenas, L. A. (2004). What is a TOT? Cognate and translation effects on tip-of-the-tongue states in Spanish-English and tagalog-English bilinguals. *Journal of Experimental psychology: Learning, Memory, and Cognition, 30*(1), 246–269.

Gollan, T. H., Fennema-Notestine, C., Montoya, R. I., & Jernigan, T. L. (2007). The bilingual effect on Boston Naming Test performance. *Journal of the International Neuropsychological Society* : *JINS*, *13*(2), 197–208.

Gollan, T. H., & Ferreira, V. S. (2009). Should I stay or should I switch? A cost-benefit analysis of voluntary language switching in young and aging bilinguals. *Journal of*

Experimental Psychology: Learning, Memory, and Cognition, *35*(3), 640–665.

Gollan, T. H., Montoya, R. I., Cera, C., & Sandoval, T. C. (2008). More use almost always a means a smaller frequency effect: Aging, bilingualism, and the weaker links hypothesis. *Journal of Memory and Language*, *58*(3), 787–814.

Gollan, T. H., Montoya, R. I., Fennema-Notestine, C., & Morris, S. K. (2005). Bilingualism affects picture naming but not picture classification. *Memory and Cognition*, *33*(7), 1220–1234.

Gollan, T. H., Montoya, R. I., & Werner, G. A. (2002). Semantic and letter fluency in Spanish-English bilinguals. *Neuropsychology*, *16*(4), 562–576.

Gollan, T. H., Sandoval, T., & Salmon, D. P. (2011). Cross-language intrusion errors in aging bilinguals reveal the link between executive control and language selection. *Psychological Science*, *22*(9), 1155–1164.

Gollan, T. H., & Silverberg, N. B. (2001). Tip-of-the-tongue states in Hebrew–English bilinguals. *Bilingualism: Language and Cognition*, *4*(01), 63–83.

Green, D. W. (1986). Control, activation, and resource: a framework and a model for the control of speech in bilinguals. *Brain and Language*, *27*(2), 210–223.

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

Green, D. W. (2011). Language control in different contexts: the behavioral ecology of bilingual speakers. *Frontiers in Psychology*, 2, 103.

Green, D. W., & Abutalebi, J. (2013). Language control in bilinguals: The adaptive control hypothesis. *Journal of Cognitive Psychology*, *25*(5), 515-530.

Greenwood, P. M. (2000). The frontal aging hypothesis evaluated. *Journal of the International Neuropsychological Society : JINS*, *6*(6), 705–726.

Grosjean, F. (2001). The bilingual's language modes. In *One mind, two languages: Bilingual language processing* (Vol. Nicol, J., pp. 1–22). Oxford, U.K.: Blackwell.

Guo, T., Liu, F., Chen, B., & Li, S. (2013). Inhibition of non-target languages in multilingual word production: evidence from Uighur-Chinese-English trilinguals. *Acta Psychologica, 143*(3), 277–83.

Guo, T., Liu, H., Misra, M., & Kroll, J. F. (2011). Local and global inhibition in bilingual word production: fMRI evidence from Chinese-English bilinguals. *NeuroImage, 56*(4), 2300–9.

Guo, T., Ma, F., & Liu, F. (2013). An ERP study of inhibition of non-target languages in trilingual word production. *Brain and Language,* 127(1), 12–20.

Hermans, D. (2004). Between-language identity effects in picture-word interference tasks: A challenge for language-nonspecific or language-specific models of lexical access? *International Journal of Bilingualism, 8*(2), 115-125.

Hermans, D., Bongaerts, T., De Bot, K., & Schreuder, R. (1998). Producing words in a foreign language: Can speakers prevent interference from their first language? *Bilingualism: Language and Cognition*, *1*(03), 213–229.

Hernández, A. E., Dapretto, M., Mazziotta, J., & Bookheimer, S. (2001). Language switching and language representation in Spanish-English bilinguals: an fMRI study. *NeuroImage, 14*(2), 510–520.

Hernández, A. E., Martinez, A., & Kohnert, K. (2000). In Search of the Language Switch: An fMRI Study of Picture Naming in Spanish-English Bilinguals. *Brain and Language, 73*(3), 421–431.

Hilchey, M. D., & Klein, R. M. (2011). Are there bilingual advantages on nonlinguistic interference tasks? Implications for the plasticity of executive control processes. *Psychonomic Bulletin & Review*, *18*(4), 625–658.

Ivanova, I., & Costa, A. (2008). Does bilingualism hamper lexical access in speech production? *Acta Psychologica*, *127*(2), 277–288.

Jackson, G. M., Swainson, R., Cunnington, R., & Jackson, S. R. (2001). ERP correlates of executive control during repeated language switching. *Bilingualism: Language and Cognition*, *4*(02), 169–178.

Jahfari, S., Waldorp, L., van den Wildenberg, W. P., Scholte, H. S., Ridderinkhof, K. R., & Forstmann, B. U. (2011). Effective connectivity reveals important roles for both the hyperdirect (fronto-subthalamic) and the indirect (fronto-striatal-pallidal) fronto-basal ganglia pathways during response inhibition. *The Journal of Neuroscience*, *31*(18), 6891-6899.

Janssen, N., Schirm, W., Mahon, B. Z., & Caramazza, A. (2008). Semantic interference in a delayed naming task: evidence for the response exclusion hypothesis. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *34*(1), 249–256.

Jersild, A. T. (1927). Mental set and shift. *Archives of Psychology*.Vol, *14*(89), 81.

Jodo, E., & Kayama, Y. (1992). Relation of a negative ERP component to response inhibition in a Go/No-go task. *Electroencephalography and Clinical Neurophysiology*, *82*(6), 477–482.

Jones, O. P., Green, D. W., Grogan, A., Pliatsikas, C., Filippopolitis, K., Ali, N., … Price, C. J. (2012). Where, when and why brain activation differs for bilinguals and monolinguals during picture naming and reading aloud. *Cerebral Cortex*, *22*(4), 892–902.

Kiesel, A., Steinhauser, M., Wendt, M., Falkenstein, M., Jost, K., Philipp, A. M., & Koch, I. (2010). Control and interference in task switching-A review. *Psychological Bulletin*, *136*(5), 849–874.

Knoch, D., & Fehr, E. (2007). Resisting the power of temptations: The right prefrontal cortex and self-control. In *Annals of the New York Academy of Sciences* (Vol. 1104, pp. 123–134).

Koch, I., Gade, M., Schuch, S., & Philipp, A. M. (2010). The role of inhibition in task switching: a review. *Psychonomic Bulletin & Review*, *17*(1), 1–14.

Kohnert, K. J., Hernandez, A. E., & Bates, E. (1998). Bilingual performance on the Boston naming test: Preliminary norms in Spanish and English. *Brain and Language, 65*(3), 422–440.

Kroll, J. F., & Stewart, E. (1994). Category Interference in Translation and Picture Naming: Evidence for Asymmetric Connections Between Bilingual Memory Representations. *Journal of Memory and Language, 33*(2), 149–174.

La Heij, W. (2005). Selection processes in monolingual and bilingual lexical access. In J. F. Kroll. & A. M. B. de Groot. (Eds.), *Handbook of bilingualism: Psycholinguistic approaches* (pp. 289–307). New York: Oxford.

Lee, M. W., & Williams, J. N. (2001). Lexical access in spoken word production by bilinguals: Evidence from the semantic competitor priming paradigm. *Bilingualism: Language and Cognition*, *4*(03), 233–248.

Lenartowicz, A., Verbruggen, F., Logan, G. D., & Poldrack, R. A. (2011). Inhibition-related activation in the right inferior frontal gyrus in the absence of inhibitory cues. *Journal of Cognitive Neuroscience, 23*(11), 3388-3399.

Levelt, W. J. M., Roelofs, A., & Meyer, A. S. (1999). A theory of lexical access in speech production. *Behavioral and Brain Sciences*, *22*(01), 1–38.

Levelt, W. J., Schriefers, H., Vorberg, D., Meyer, A. S., Pechmann, T., & Havinga, J. (1991). The time course of lexical access in speech production: A study of picture naming. *Psychological review*, *98*(1), 122.

Levy, B. J., McVeigh, N. D., Marful, A., & Anderson, M. C. (2007). Inhibiting your native language: the role of retrieval-induced forgetting during second-language acquisition. *Psychological Science*, *18*(1), 29–34.

Linck, J. A., Kroll, J. F., & Sunderman, G. (2009). Losing access to the native language while immersed in a second language: Evidence from the role of inhibition in second language learning. *Psychological Science, 20*(12), 1507–1515.

Linck, J. A., Schwieter, J. W., & Sunderman, G. (2012). Inhibitory control predicts language switching performance in trilingual speech production. *Bilingualism: Language and Cognition, 15*(3), 651–662.

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

Luk, G., De Sa, E., & Bialystok, E. (2011). Is there a relation between onset age of bilingualism and enhancement of cognitive control? *Bilingualism: Language and Cognition, 14*(04), 588-595.

Luk, G., Green, D. W., Abutalebi, J., & Grady, C. (2012). Cognitive control for language switching in bilinguals: A quantitative meta-analysis of functional neuroimaging studies. *Language and Cognitive Processes, 27*(10), 1479–1488.

Macizo, P., Bajo, T., & Paolieri, D. (2012). Language switching and language competition. *Second Language Research*, *28*(2), 131–149.

Mägiste, E. (1984). Stroop tasks and dichotic translation: The development of interference patterns in bilinguals. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 10*(2), 304.

Mägiste, E. (1985). Development of intra- and interlingual interference in bilinguals. *Journal of Psycholinguistic Research*, *14*(2), 137–154.

Mahon, B. Z., Costa, A., Peterson, R., Vargas, K. A., & Caramazza, A. (2007). Lexical selection is not by competition: a reinterpretation of semantic interference and facilitation effects in the picture-word interference paradigm. *Journal of Experimental psychology: Learning, Memory, and Cognition*, *33*(3), 503–535.

Martin, C. D., Barcelo, F., Hernandez, M., & Costa, A. (2011). The time course of the asymmetrical “local” switch cost: evidence from event-related potentials. *Biological Psychology, 86*(3), 210–218.

Martin, C. D., Strijkers, K., Santesteban, M., Escera, C., Hartsuiker, R. J., & Costa, A. (2013). The impact of early bilingualism on controlling a language learned late: an ERP study. *Frontiers in Psychology*, 4.

Mayr, U., & Keele, S. W. (2000). Changing internal constraints on action: the role of backward inhibition. *Journal of Experimental Psychology: General*, *129*(1), 4–26.

McAuley, T., Yap, M., Christ, S. E., & White, D. A. (2006). Revisiting inhibitory control across the life span: insights from the ex-Gaussian distribution. Developmental Neuropsychology, *29*(3), 447–458.

Meiran, N. (1996). Reconfiguration of processing mode prior to task performance. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *22*(6), 1423.

Meuter, R. F. I., & Allport, A. (1999). Bilingual language switching in naming: asymmetrical costs of language selection. *Journal of Memory and Language*, *40*(1), 25–40.

Miozzo, M., & Caramazza, A. (2003). When more is less: a counterintuitive effect of distractor frequency in the picture-word interference paradigm. *Journal of Experimental Psychology: General*, *132*(2), 228–252.

Misra, M., Guo, T., Bobb, S. C., & Kroll, J. F. (2012). When bilinguals choose a single word to speak: Electrophysiological evidence for inhibition of the native language. *Journal of Memory and Language*, *67*(1), 224–237.

Monsell, S. (2003). Task switching. *Trends in Cognitive Sciences*, *7*(3), 134–140.

Morales, J., Gómez-Ariza, C. J., & Bajo, M. T. (2013). Dual mechanisms of cognitive control in bilinguals and monolinguals. *Journal of Cognitive Psychology*, *25*(5), 531–546.

Morsella, E., & Miozzo, M. (2002). Evidence for a cascade model of lexical access in speech production. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *28*(3), 555–563.

Navarrete, E., & Costa, A. (2005). Phonological activation of ignored pictures: Further evidence for a cascade model of lexical access. *Journal of Memory and Language*, *53*(3), 359–377.

Navarrete, E., Mahon, B. Z., & Caramazza, A. (2010). The cumulative semantic cost does not reflect lexical selection by competition. *Acta Psychologica*, *134*(3), 279–289.

Nieuwenhuis, S., Yeung, N., van den Wildenberg, W., & Ridderinkhof, K. R. (2003). Electrophysiological correlates of anterior cingulate function in a go/no-go task: Effects of response conflict and trial type frequency. *Cognitive, Affective, & Behavioral Neuroscience*, *3*(1), 17–26.

Penner-Wilger, M., Leth-Steensen, C., & LeFevre, J.-A. (2002). Decomposing the problem-size effect: a comparison of response time distributions across cultures. *Memory & Cognition*, *30*(7), 1160–1167.

Philipp, A. M., Gade, M., & Koch, I. (2007). Inhibitory processes in language switching: Evidence from switching language-defined response sets. *European Journal of Cognitive Psychology*, *19*(3), 395–416.

Philipp, A. M., & Koch, I. (2006). Task inhibition and task repetition in task switching. *European Journal of Cognitive Psychology*, *18*(4), 624–639.

Philipp, A. M., & Koch, I. (2009). Inhibition in language switching: what is inhibited when switching between languages in naming tasks? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *35*(5), 1187–95.

Poulisse, N. (1999). Slip of the tongue: Speech errors in first and second language production. *Amsterdam, Philadelphia*: John Benjamins.

Poulisse, N., & Bongaerts, T. (1994). First language use in second language production. *Applied Linguistics*, *15*(1), 36–57.

Prior, A. (2012). Too much of a good thing: Stronger bilingual inhibition leads to larger lag-2 task repetition costs. *Cognition*, *125*(1), 1–12.

Prior, A., & Gollan, T. H. (2011). Good Language-Switchers are Good Task-Switchers: Evidence from Spanish–English and Mandarin–English Bilinguals. *Journal of the International Neuropsychological Society*, *17*(04), 682-691.

Prior, A., & Gollan, T. H. (2013). The elusive link between language control and executive control: A case of limited transfer. *Journal of Cognitive Psychology, 25*(5), 622–645.

Prior, A., & MacWhinney, B. (2010). A bilingual advantage in task switching. *Bilingualism: Language and Cognition*, *13*(02), 253-262.

Rhodes, M. G. (2004). Age-related differences in performance on the Wisconsin card sorting test: a meta-analytic review. *Psychology and Aging*, *19*(3), 482–494.

Roberts, P. M., Garcia, L. J., Desrochers, A., & Hernandez, D. (2002). English performance of proficient bilingual adults on the Boston Naming Test. *Aphasiology*, *16*(4-6), 635–645.

Rodriguez-Fornells, A., Krämer, U. M., Lorenzo-Seva, U., Festman, J., & Münte, T. F. (2012). Self-assessment of individual differences in language switching. *Frontiers in Psychology,* 2, 388.

Rodríguez-Pujadas, A., Sanjuán, A., Fuentes, P., Ventura-Campos, N., Barrós-Loscertales, A., & Ávila, C. (2014). Differential neural control in early bilinguals and monolinguals during response inhibition. *Brain and Language*, *132*, 43–51.

Roelofs, A. (1992). A spreading-activation theory of lemma retrieval in speaking. *Cognition*, *42*(1-3), 107–142.

Runnqvist, E., Strijkers, K., Alario, F.-X., & Costa, A. (2012). Cumulative semantic interference is blind to language: Implications for models of bilingual speech production. *Journal of Memory and Language, 66*(4), 850–869.

Sadat, J., Martin, C. D., Alario, F. X., & Costa, A. (2012). Characterizing the bilingual disadvantage in noun phrase production. *Journal of Psycholinguistic Research, 41*(3), 159–79.

Sandoval, T. C., Gollan, T. H., Ferreira, V. S., & Salmon, D. P. (2010). What causes the bilingual disadvantage in verbal fluency? The dual-task analogy. *Bilingualism: Language and Cognition*, *13*(02), 231–252.

Schneider, D. W., & Anderson, J. R. (2010). Asymmetric switch costs as sequential difficulty effects. *The Quarterly Journal of Experimental Psychology, 63*(10), 1873–1894.

Schwieter, J. W., & Sunderman, G. (2008). Language switching in bilingual speech production: in search of the language-specific selection mechanism. *The Mental Lexicon, 3*(2), 214–238.

Shao, Z., Roelofs, A., & Meyer, A. S. (2012). Sources of individual differences in the speed of naming objects and actions: The contribution of executive control. *The Quarterly Journal of Experimental Psychology*, *65*(10), 1927-1944.

Singh, N., & Mishra, R. K. (2012). Does language proficiency modulate oculomotor control? Evidence from Hindi–English bilinguals. *Bilingualism: Language and Cognition, 15*(04), 771-781.

Soveri, A., Rodriguez-Fornells, A., & Laine, M. (2011). Is There a Relationship between Language Switching and Executive Functions in Bilingualism? Introducing a within group Analysis Approach. *Frontiers in Psychology*, *2*, 183.

Spieler, D. H., Balota, D. A., & Faust, M. E. (1996). Stroop performance in healthy younger and older adults and in individuals with dementia of the Alzheimer’s type. *Journal of Experimental psychology: Human Perception and Performance*, *22*(2), 461–479.

Strijkers, K., Baus, C., Runnqvist, E., Fitzpatrick, I., & Costa, A. (2013). The temporal dynamics of first versus second language production. *Brain and Language*, *127*(1), 6–11.

Strijkers, K., Costa, A., & Thierry, G. (2010). Tracking lexical access in speech production: electrophysiological correlates of word frequency and cognate effects. *Cerebral Cortex, 20*(4), 912–928.

Strijkers, K., Holcomb, P., & Costa, A. (2011). Conscious intention to speak proactively facilitates lexical access during overt object naming. *Journal of Memory and Language, 65*(4), 345–362.

Tao, L., Marzecová, A., Taft, M., Asanowicz, D., & Wodniecka, Z. (2011). The efficiency of attentional networks in early and late bilinguals: the role of age of acquisition. *Frontiers in Psychology, 2,* 123.

Thierry, G., & Wu, Y. J. (2007). Brain potentials reveal unconscious translation during foreign-language comprehension. *Proceedings of the National Academy of Sciences of the United States of America*, *104*(30), 12530–5.

Van Assche, E., Duyck, W., & Gollan, T. H. (2013). Whole-language and item-specific control in bilingual language production. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *39*(6), 1781.

Van Heuven, W. J. B., Schriefers, H., Dijkstra, T., & Hagoort, P. (2008). Language conflict in the bilingual brain. *Cerebral Cortex*, *18*(11), 2706–2716.

Verhaeghen, P., & Cerella, J. (2002). Aging, executive control, and attention: a review of meta-analyses. *Neuroscience and Biobehavioral Reviews*, *26*(7), 849–857.

Verhoef, K., Roelofs, A., & Chwilla, D. J. (2009). Role of inhibition in language switching: Evidence from event-related brain potentials in overt picture naming. *Cognition*, *110*(1), 84–99.

Wang, Y., Xue, G., Chen, C., Xue, F., & Dong, Q. (2007). Neural bases of asymmetric language switching in second-language learners: an ER-fMRI study. *NeuroImage, 35*(2), 862–70.

Wu, Y. J., & Thierry, G. (2010). Chinese-English bilinguals reading English hear Chinese. *The Journal of Neuroscience, 30*(22), 7646–51.

Wu, Y. J., & Thierry, G. (2012). Unconscious translation during incidental foreign language processing. *NeuroImage*, *59*(4), 3468–3473.

Wylie, G., & Allport, A. (2000). Task switching and the measurement of “switch costs”. Psychological Research, *63*(3-4), 212–233.

Yeung, N., & Monsell, S. (2003). Switching between tasks of unequal familiarity: the role of stimulus-attribute and response-set selection. *Journal of Experimental Psychology: Human Perception and Performance*, *29*(2), 455.

Zou, L., Abutalebi, J., Zinszer, B., Yan, X., Shu, H., Peng, D., & Ding, G. (2012). Second language experience modulates functional brain network for the native language production in bimodal bilinguals. *NeuroImage*, *62*(3), 1367–75.

Appendix A

Description of the Catalan/Spanish bilingual sample.

The Catalan/Spanish bilinguals employed in the experimental studies of this dissertation (see Section 2.4, 2.5, 2.6, 2.7) were recruited in Catalonia, specifically in Barcelona. Catalonia is a bilingual region in Spain, in which both Catalan and Spanish are official languages. In many families both the two languages are spoken and the current educational system is completely bilingual. At the end of the primary school (ages 4-5) children are able to read, write and speak and understand correctly both Catalan and Spanish. In primary school and in high-school, classes are thought in both the two languages, even though Catalan is more predominant. University classes and tests are taught in both Catalan and Spanish. Radio and television programs broadcast in Catalan and in Spanish, news papers contain articles written in Catalan and Spanish and the official bureaucracy can be done in either language. All the Catalan/Spanish bilinguals tested for this dissertation passed the Catalan/Spanish language proficiency exam that is required to have access to the university. This exam requires having a very high level of proficiency in the two languages regarding various aspects (grammar, vocabulary, etc.). In Barcelona, Catalan/Spanish conversations are very frequent, in both private and professional settings. This promotes a very balanced use of the two languages and situations in which, even if not needed, language switching in bilingual groups occurs naturally.

For example, it is common to observe that a given interlocutor speaks in Spanish to a particular interlocutor and in Catalan to another within the same conversation, even if all three speakers are high-proficient Catalan/Spanish bilinguals (even among members of the same family).

As a result of this particular environment, all the Catalan/Spanish bilinguals tested in the present dissertation were exposed before the age of 4 years to both the two languages in similar proportions, and they kept using them in this way until the time of testing.

Appendix B

Description of the German/Italian bilingual sample.

The German/Italian bilinguals employed in Section 2.8 were recruited in South Tyrol. South Tyrol is a bilingual region in Italy, in which both German and Italian are official languages. However, German is predominant as compared to Italian. In many families one or the other language is spoken, depending on the “linguistic group” (German or Italian). The current educational system is not bilingual: that is, school classes are thought in German or in Italian, but not in both the languages. The German/Italian bilinguals tested in Section 2.8 received their education in German, which for them was the dominant language (i.e., L1). Radio and television programs broadcast in German and in Italian and news papers are written in both the languages.

In South Tyrol, especially in urban areas as Brixen, where we recruited our participants, German/Italian conversations are observable. However, German is more used than Italian and in interactional contexts the switching between languages is not a natural phenomenon (see Appendix C). The socio-linguistic context of the German/Italian bilinguals tested in Section 2.8, might be considered a “dual language context” (*see* Green & Abutalebi, 2013), since both the languages are used in bilingual interactions. Nevertheless, the two linguistic systems are quite segregated (e.g., educational system).

As a result of this particular environment all the participants tested in Section 2.8 were exposed to both the two languages very early (4 years old). However, these bilinguals were more exposed to German (i.e., L1) than to Italian (i.e., L2) and importantly, they were using German more than Italian at the time of testing.

Appendix C

Description of the bilingual samples across the studies in respect to language use, proficiency and language switching rate.

Table 1. Self-assessed language use.

STUDY		L1	L2	L1 vs. L2
Section 2.4	**Preschool**	0.7 (0.2)	0.4 (0.2)	0.3
	Primary Education	0.7 (0.2)	0.4 (0.2)	0.3
	Secondary Education/High school	0.7 (0.2)	0.4 (0.2)	0.3
	Adulthood	0.6 (0.2)	0.4 (0.2)	0.2
Section 2.7	**Preschool**	0.7 (0.2)	0.3 (0.2)	0.4
	Primary Education	0.7 (0.2)	0.3 (0.2)	0.4
	Secondary Education/High school	0.6 (0.2)	0.3 (0.1)	0.3
	Adulthood	0.6 (0.2)	0.4 (0.2)	0.2
Section 2.8	**Preschool**	0.9 (0.1)	0.2 (0.1)	0.7
	Primary Education	0.9 (0.1)	0.2 (0.1)	0.7
	Secondary Education/High school	0.8 (0.1)	0.2 (0.1)	0.6
	Adulthood	0.8 (0.2)	0.3 (0.2)	0.5

Language use scores represent a mean proportion (max. score=1, min=0) of languages' use in different periods of life: Preschool (from 0 to 5/6 years), Primary Education (from 5/6 to 12 years), Secondary Education and High school (from 12 to 18 years) and Adulthood (from 18 to the actual age).

Table 2. Self-assessed language proficiency.

STUDY		L1	L2	L1 vs. L2
Section 2.4	**Reading**	5 (0.2)	5 (0.2)	0
	Writing	5 (0.4)	5 (0.4)	0
	Speaking	5 (0.3)	5 (0.3)	0
	Comprehension	5 (0.2)	5 (0.2)	0
Section 2.5	**Reading**	4 (0.0)	4 (0.0)	0
	Writing	4 (0.0)	4 (0.3)	0
	Speaking	4 (0.0)	4 (0.3)	0
	Comprehension	4 (0.0)	4 (0.0)	0
Section 2.6	**Reading**	4 (0.0)	4 (0.0)	0
young	**Writing**	4 (0.0)	4 (0.3)	0
	Speaking	4 (0.0)	4 (0.3)	0
	Comprehension	4 (0.0)	4 (0.0)	0
Section 2.6	**Reading**	4 (0.0)	4 (0.0)	0
middle aged	**Writing**	4 (0.5)	4 (0.4)	0
	Speaking	4 (0.0)	4 (0.0)	0
	Comprehension	4 (0.0)	4 (0.0)	0
Section 2.6	**Reading**	3 (1.1)	4 (0.0)	-1
elderly	**Writing**	2 (1.5)	4 (1.6)	-2
	Speaking	4 (0.0)	4 (0.4)	0
	Comprehension	4 (0.0)	4 (0.0)	0
Section 2.7	**Reading**	7 (0.3)	7 (0.4)	0
	Writing	6 (0.7)	6 (0.8)	0
	Speaking	7 (0.6)	6 (0.7)	1
	Comprehension	7 (0.3)	7 (0.3)	0
Section 2.8	**Reading**	7 (0.5)	6 (0.7)	1
	Writing	6 (1.3)	5 (1.1)	1
	Speaking	7 (0.3)	5 (1.1)	2
	Comprehension	7 (0.0)	6 (1.5)	1

The self-assessed index of language proficiency is the average of participants' responses for each domain (reading, writing, speaking and comprehension).

Note: The score scale was different across studies due to the fact that data were acquired in different periods in time, with slightly different questionnaires. In study 2.4 scores are on a 5 point scale, in which 5 represents a very high level and 1 a very low level of proficiency. In studies 2.5 and 2.6 scores are on a 4 point scale, in which 4 represents a very high level and 1 a very low level of proficiency. In studies 2.7 and 2.8 scores are on a 7 point scale, in which 7 represents a very high level and 1 a very low level of proficiency.

Table 3. Bilingual Switching Questionnaire.

STUDY		**BSWQ**	
Section 2.7	**Scale**	**Mean**	**SD**
	L1S	8	2
	L2S	9	2
	CS	8	2
	US	7	2
	OS	32	5
Section 2.8	**Scale**	**Mean**	**SD**
	L1S	7	1
	L2S	8	1
	CS	7	3
	US	5	2
	OS	28	5

The self-rating of individual differences in language switching is reported according to the following scales: L1S, switch to L1; L2S, switch to L2; CS, contextual switch; US, unintended switch; OS, overall switch.