Bilingual language control: Evidence from Parkinson's disease

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“...anche lo studio è un mestiere, e molto faticoso, con un suo speciale tirocinio, oltre che intellettuale, anche muscolare-nervoso: è un processo di adattamento, è un abito acquisito con lo sforzo, la noia e anche la sofferenza.”

“Istruitevi, perché avremo bisogno di tutta la nostra intelligenza. Agitatevi, perché avremo bisogno di tutto il nostro entusiasmo. Organizzatevi, perché avremo bisogno di tutta la nostra forza”.

Antonio Gramsci

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Abstract

How can bilinguals easily and flexibly switch between languages without errors?

The aim of this thesis is to advance our knowledge about the control mechanisms involved in bilingual language production. I investigated this issue in two ways. Firstly, by exploring similarities between bilingual language control (bLC) and domain-general executive control (EC). Secondly, by investigating the specificity of bLC mechanisms within the linguistic domain. To do so, I measured behavioural responses of Catalan/Spanish bilinguals affected by Parkinson's disease and healthy controls in tasks tapping bLC, EC and language control, when only one language was involved.

I explored Parkinson's disease individuals because this neurodegenerative disorder affects brain areas involved in both domain-general EC and the bLC.

The findings of this dissertation suggest that some bLC mechanisms are highly specific and are not involved in other linguistic or non-linguistic control contexts.

However, some other mechanisms of bLC are shared across different domains of control and implemented by EC mechanisms.

These results extend previous knowledge about the nature of mechanisms involved in bLC and are useful for future models of bilingual language production.

Resum

Com ho fan els bilingües per passar d’una llengua a una altra amb facilitat, flexibilitat i sense cometre errors?

L’objectiu d’aquesta tesi és avançar el nostre coneixement sobre els mecanismes de control involucrats en la producció de llenguatge en bilingües.

He investigat aquest tema de dues maneres:

Primer: he explorat les similituds entre el control bilingüe del llenguatge i el control executiu de domini general. Segon: he investigat l’especificitat dels mecanismes de control bilingüe dins del domini lingüístic.

Per aquest supòsit, he avaluat les respostes conductuals de bilingües Català/Castellà afectats per la malaltia del Parkinson i controls bilingües (no malalts) en tasques de control de llenguatge bilingüe, control executiu i control de llenguatge quan una sola llengua hi està involucrada.

He estudiat aquesta malaltia degenerativa perquè afecta zones del cervell involucrades tant en control executiu de domini general, com en control bilingüe del llenguatge.

Els descobriments d’aquesta dissertació suggereixen que alguns dels mecanismes de control bilingüe del llenguatge són altament específics, i no estan involucrats en altres contextos de control lingüístic o no lingüístic.

D’altra banda, altres mecanismes de control estan compartits a través de diferents dominis i estan implementats per mecanismes de control executiu.

Aquests resultats amplien els coneixements previs sobre la naturalesa dels mecanismes involucrats en el control bilingüe del llenguatge i són útils per futurs models de producció bilingüe del llenguatge.

Preface

Imagine this daily situation. Jordi and Albert are two guys living in Barcelona and they meet up for a beer. They both really love football and the last match of the season is today. Jordi and Albert are bilinguals, grew up in Barcelona, and they usually talk to each other in Catalan. They are waiting for a friend from Madrid, Carlos, who will join them to watch the match. At some point Carlos shows up and starts to speak with them, but in Spanish. Therefore, in this conversation, Jordi and Albert need to switch to Spanish, in order to align with their interlocutor, Carlos.

The question is: which mechanisms allow them to rapidly and flexibly switch into another language without making errors? This doctoral thesis aims to explore the nature of these mechanisms, usually named as bilingual language control (bLC).

One of the most debated questions is whether these bLC mechanisms are domain-specific or whether they shared with other types of control in the linguistic domain or the domain-general executive control (EC). This PhD thesis investigates the overlap of the underlying mechanisms between bLC, EC and other language control conditions, when only one language is used.

The research has been conducted in healthy bilingual speakers and people affected by Parkinson's disease (PD). Essentially, there are two reasons to study this neurodegenerative disease. First, the brain areas affected by this pathology (fronto-striatal) have been identified as being part of both domain-general EC and the bLC network (Abutalebi & Green, 2007). Second, it has been suggested that the language impairments found in PD patients may be a consequence of the EC deficits that characterize this pathology (Colman & Bastiaanse, 2011 for review). Therefore, this gives us the opportunity to explore the overlap of the mechanisms across control types from a cognitive deficit perspective.

In the first chapter I will contextualize the issues explored in this thesis.

In the second chapter, I will present the experimental studies I conducted. The first study investigated the overlap between bLC and the domain-general EC (Section 2.1) and the second one investigating whether the same bLC mechanisms are also involved in other language control contexts (section 2.2).

Finally, I will discuss the findings from these two studies and how they can contribute to solve some of the issues under debate in the context of the bilingual language production research.

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1. GENERAL INTRODUCTION

The issue of how bilinguals control their languages and achieve successful communication is one of the central points in bilingual literature. In more than 20 years of research various views of how bilingual language control function have been proposed.

In order to contextualize the issues explored in this thesis, I will first focus on a brief overview of the most relevant cognitive and neural models of bilingual language production (section 1.1 and 1.2). Then, I will describe the relationship between EC and language production in the context of Parkinson's disease (section 1.3). Finally, in sections 1.4 and 1.5 I will detail the two approaches used to explore the nature of language control mechanisms in bilinguals.

1.1 Cognitive models of bilingual language production

Two main groups of models have been proposed for lexical retrieval in bilinguals: One suggests the involvement of language-specific mechanisms whereas the other suggests that the mechanisms are language non-specific.

According to the first group, lexical access is not a competitive process between languages, but rather that it is implemented by language-specific selection mechanisms similarly to lexical selection in monolinguals (Costa, Miozzo, & Caramazza, 1999;

Finkbeiner, Gollan, & Caramazza, 2006; La Heij, 2005). That is, the intention to speak in one language would activate language-specific mechanisms that drive the lexical selection process to items in the correct language, without considering potential competitors in the other.

Conversely, language non-specific models assume that during lexical selection words in both languages compete for selection (Green, 1986; Poulisse & Bongaerts, 1994). Among the most known of these models, there is the Inhibitory Control Model (ICM) proposed by Green (1986). The main assumption of this model is that the mechanism that allows bilinguals to resolve competition between languages is inhibition. According this proposal, once the goal to speak in one language is established, a "Supervisory attentional system" mediates the "task schema", which in turns inhibits lexical items in the other language. Moreover, the nature of such inhibitory control mechanism is domain-general, meaning that it is shared with the non-linguistic domain. Other assumptions of this model are that this inhibitory control is reactive and proportional to the strength of the languages. Therefore, the stronger the activation of a lexical node, the stronger the inhibition applied to it.

Some of the concepts related to control in bilingual language production have been studied, for instance, using language switching tasks but also picture-word interference and blocked naming. However, I will focus more on the findings from language switching given that it is the paradigm that I mainly employed to explore the nature of bLC mechanisms.

In the classical version of this task participants are asked to name a series of stimuli and a cue indicating the naming language. Specifically, there are two kinds of trials: switch trials (when the preceding stimulus is named in a different language) and repeat trials (when the preceding stimulus is named in the same language). Participants are slower and less accurate on switch trials than repeat trials, and this difference in reaction times (RTs) is known as the switch cost (for reviews see Declerck & Philipp, 2015; for task switcing see Kiesel et al., 2010).

According to the ICM, the switch cost is interpreted as the extra time needed to overcome the "reactive" inhibition previously applied to the language not in use and to retrieve the lexical item in the current language. Moreover, the amount of inhibition is claimed to be proportional to the relative strength of the languages and is modulated by the language dominance. That is, switching from the dominant language (L1) to the less dominant one (L2) should be less costly than switching in the opposite direction (asymmetrical switch cost). This prediction has consistently received experimental support (Costa, Santesteban, & Ivanova, 2006; Costa & Santesteban, 2004; Jackson, Swainson, Cunnington, & Jackson, 2001; Jin, Zhang, & Li, 2014; Macizo, Bajo, & Paolieri, 2012; Meuter & Allport, 1999; Peeters, Runnqvist, Bertrand, & Grainger, 2014; Philipp, Gade, & Koch, 2007; for a review see Bobb & Wodniecka, 2013).

However, it has been demonstrated that the asymmetries of switch costs are also modulated by other factors apart from the strength of the languages (Christoffels, Firk, & Schiller, 2007; Costa & Santesteban, 2004; Finkbeiner et al., 2006; Gollan & Ferreira, 2009; Verhoef, Roelofs, & Chwilla, 2009). In a series of experiments, Costa and Santesteban (2004) found a symmetrical switch cost pattern when high proficient bilinguals switched between two languages of different strengths (L1 and L3; see also Calabria, Hernandez, Branzi, & Costa, 2011; Costa et al., 2006). This brings into question the role of inhibition in controlling the two languages in this type of bilinguals.

Moreover, alternative interpretations of these asymmetries in switch costs have been proposed. For instance, some refer to it as an effect of the differential repetition benefits of the two languages. Verhoef et al. (2009) proposed that repeat trials in L1 would be faster than those in L2 because they would suffer less or no interference from L2 (L1-repetition benefit). Therefore, the asymmetrical switch costs would result from the difference in the repetition benefits between L1 and L2. Others have proposed that asymmetries of switch costs can be explained in terms of activation instead of inhibition (e.g., Philipp et al., 2007). When people switch to L1 the persisting activation of L2 increases the competition between languages, but this should not be the case for the opposite situation. Therefore, the differential degree of activation of the two languages generates an asymmetrical switch cost. Similarly, switch costs can be explained in terms of persisting activation instead of persisting inhibition (Altmann & Gray, 2008; MacLeod, 2003). Switch costs may result from the inertia of the cognitive system to sustained naming in a given language; therefore it would be the cost needed to overcome this persistent activation when required to switch. In this view, the extra time needed to change languages is generated by the carry-over effect of the activation of the previously used language (see Koch, Gade, Schuch, & Philipp, 2010 for a review about alternative interpretations of the switch cost).

All these proposals interpret the switch cost as one of the underlying mechanisms of bLC but in different and sometimes opposing ways, which leaves open the debate about the nature of the mechanisms. Moreover, some models including the ICM make claims about inhibitory control and its reactive nature as the key mechanisms of bLC.

However it has recently been proposed that proactive mechanisms of control are also engaged during bilingual word production (Christoffels et al., 2007; Green & Abutalebi, 2013; Grosjean, 2013; Hilchey & Klein, 2011; La Heij, 2005; Misra, Guo, Bobb, & Kroll, 2012).

Indeed the distinction between proactive and reactive control comes from a theory proposed in the context of non-linguistic control and task switching by Braver (2013), named “Dual Mechanisms of Control model” (DCM). According to DCM, proactive control is defined as a sustained type of control that maintains a task goal active, promotes cognitive flexibility and facilitates the processing of possible upcoming conflicts. Reactive control, in contrast, is a more transient type of control that resolves interference when it is detected (e.g., trial by trial). In the context of language these two mechanisms may be translated in the following terms. Proactive control would manage the levels of activation of the two languages, prior to the activation of specific lexical items. Reactive control instead would be in charge of resolving transient interference between languages, for instance, as in the case of switch trials (Christoffels et al., 2007; Green & Abutalebi, 2013; Grosjean, 2013; Hilchey & Klein, 2011; La Heij, 2005; Ma, Li, & Guo, 2016; Misra et al., 2012; Poulisse & Bongaerts, 1994; Wang, Kuhl, Chen, & Dong, 2009).

In the language switching paradigm, switch costs are considered the index of reactive control, whereas mixing costs index proactive control. To be able to measure mixing costs it is necessary to require participants to do the task also in a blocked condition in addition to the mixing one. Therefore, the difference between the reaction times of the repeat trials (mixing condition) and those of the blocked condition (single trials) generates this cost.

This distinction is particularly relevant in the context of this thesis because both types of mechanisms (and their indices) have been studied as a way to investigate their overlap across different domains of control, including linguistic and non-linguistic ones.

1.2 Neural basis of bilingual language control

A further perspective about the organization of the bLC comes from the research that has explored the underlying brain network.

In this regard, some researchers have specifically explored the neural network used to control the two languages.

This neuroimaging research of bLC resulted in a general model that describes a network of a cortical-subcortical circuitry (Abutalebi & Green, 2008, 2016; Moritz-Gasser & Duffau, 2009).

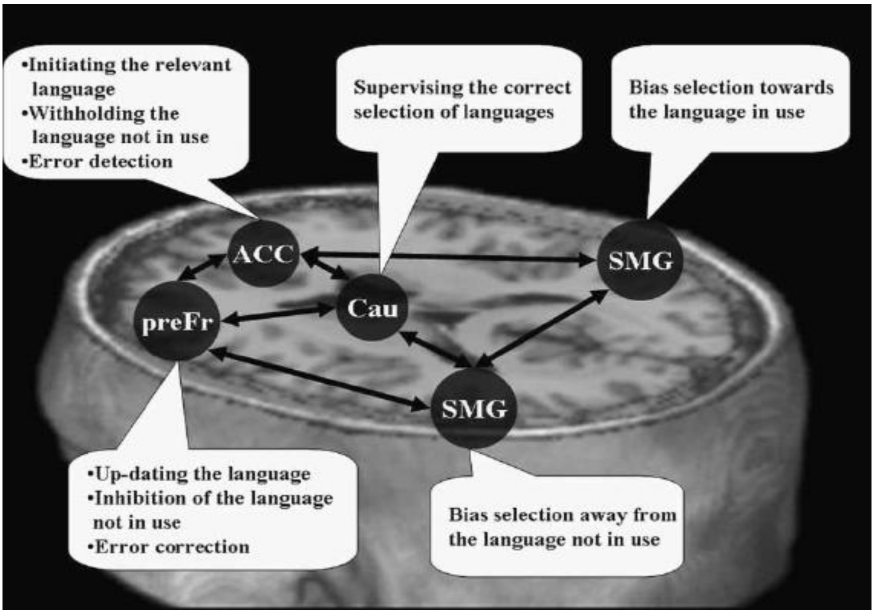

Figure 1. Schematic illustration of the brain system underlying language switching (taken from Abutalebi & Green, 2008)

This model, schematically represented in Figure 1, includes these areas: the left dorsolateral prefrontal cortex, anterior cingulate cortex, left caudate nucleus, and supramarginal gyri. The prefrontal cortex and anterior cingulate cortex and caudate nucleus are related to working memory and response inhibition, whereas the anterior cingulate cortex and prefrontal cortex would be involved in error detection. Finally, the supramarginal gyri would be engaged in language selection, whereas the left caudate would also be engaged in language planning and selection.

Recently this model was updated, following the "adaptive control model", by including other cortical and subcortical structures and their role at the cognitive level (Fig.2, Abutalebi & Green, 2016).

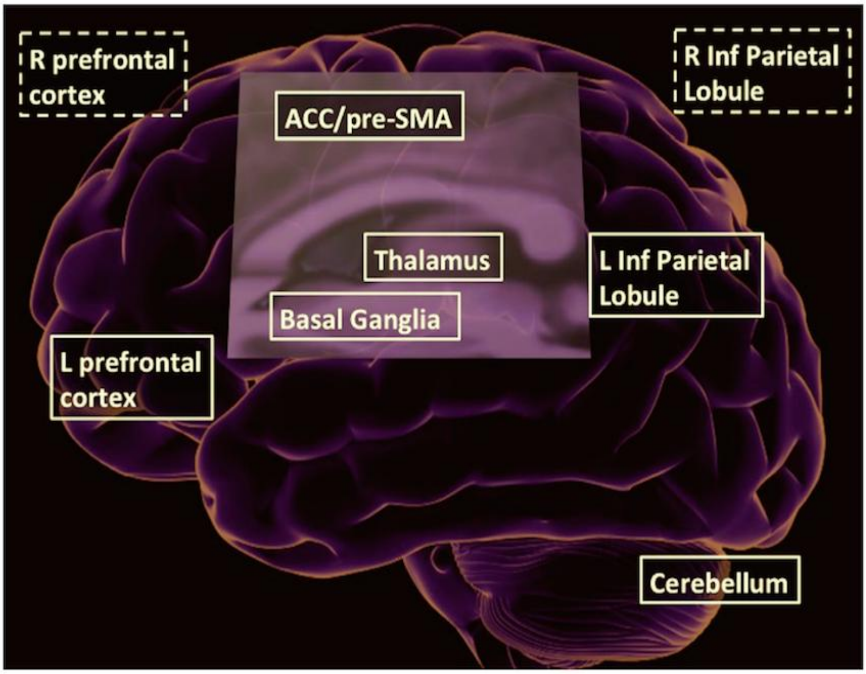

Figure 2. Brain regions related to language control as outlined by the adaptive control model (Green & Abutalebi, 2013) (taken from Abutalebi and Green, 2016)

First, the complex including the anterior cingulate cortex and pre-supplementary motor area would be responsible for conflict and error monitoring and for initiating speech during language switching. Second, the left prefrontal cortex, left inferior cortex, and basal ganglia would manage cross-language interference and resolve conflicts whereas parietal cortices (left and right parietal lobules) would maintain task representation. Third, the cerebellum would regulate the activation of the frontal cortex and exert a supervising role on morphosyntaxis. Finally, the right prefrontal cortex and the thalamus would be involved in external cue detection (Abutalebi & Green, 2016; Green & Abutalebi, 2013; Luk, Green, Abutalebi, & Grady, 2011).

More recently, the role of these areas in the control of the two languages have been supported by several neuroimaging studies (Baene, Duyck, Brass, & Carreiras, 2015; Branzi, Della Rosa, Canini, Costa, & Abutalebi, 2015; de Bruin, Roelofs, Dijkstra, & Fitzpatrick, 2014; Grant, Fang, & Li, 2015; Lei, Akama, & Murphy, 2014; Reverberi et al., 2015; Wattendorf et al., 2012; for a review see Luk et al., 2011).

Interestingly, some studies have highlighted that the activation of this cortico-striatal loop is modulated by the linguistic context in which bilinguals are required to name. For instance, Abutalebi et al. (2008) have shown that the left caudate is activated only when a language switch is required (dual-language context) but not when participants had to switch intra-language (single-language context). Similarly, Crinion et al. (2006) have shown that the activation of the left caudate occurs only in cross-language conditions of priming. In their study bilingual participants were presented with sequential word pairs and were instructed to judge their semantic relatedness. Crucially, the target word was in the same or a different language. Results revealed an increased activation of the left head of the caudate when prime and target were in different languages (dual-language context).

Finally, studies from brain-damaged individuals with pathological language mixing and switching support this language control network as well. Specifically, lesions over the left frontal and prefrontal cortices, basal ganglia and left caudate areas have been described in these patients, similarly to those areas activated during language control tasks (Abutalebi, Miozzo & Cappa, 2000; Aglioti, Beltramello, Girardi & Fabbro, 1996; Aglioti & Fabbro, 1993; Ansaldo, Saidi & Ruiz, 2010; Fabbro, Skrap & Aglioti, 2000; Kong, Abutalebi, Lam & Weekes, 2014; Leemann, Laganaro, Schwitter & Schnider, 2007; Mariën, Abutalebi, Engelborghs & De Deyn, 2005).

Interestingly, some of these studies also found that domain-general EC was impaired in these patients, suggesting a potential role of this non-linguistic control in determining pathological laguage switching (Adrover-Roig et al., 2011; Kong et al., 2014; Leemann et al., 2007). However, there are also exceptions, indicating that this overlap is not complete (Fabbro et al., 2000).

Recently, Calabria, Marne, Romero-Pinel, Juncadella, & Costa (2014) described the case of a Catalan/Spanish bilingual that presented pathological language switching. Besides the neuropsychological and linguistic assessments of spontaneous speech, these authors also evaluated switching abilities with a linguistic and a non-linguistic version of the switching task. The results revealed a parallel impairment in language control and domain-general EC. This suggests that the fronto-striatal circuitry is involved in both domains, in line with the proposal that at least some EC mechanims of control are involved in bLC (Abutalebi & Green, 2007; see Luk et al., 2011 for a review). Moreover the fact that the patients reported more switching from L1 to L2 than vice versa, similar to what has been found by other authors, is in line with the proposal of Adrover-Roig et al. (2011): that basal ganglia, and in particular the left caudate, is important in the lexicalization of L1.

To what extent bLC deficits parallel impairments in domain-general EC, and to what extent these two domains overlap, is still an important open issue that needs to be further investigated. In this PhD thesis I used a new approach, namely contrasting the deficits in the two domains by exploring specific mechanisms such as proactive and reactive control.

1.3 Linguistic and non-linguistic control deficits in Parkinson's disease

The experimental approach used in this thesis is the study of PD patients' performance in tasks of language control and EC. PD patients indeed show EC deficits, due to basal ganglia damage since the first stages of the disease. Hence, exploring how language and non-linguistic control are affected by the disease represents a strategy to investigate their relation in the context of bilingualism.

Specifically, PD is characterized by a decreased production of dopamine in the midbrain (substantia nigra pars compacta) affecting mesocortical and nigro-striatal connections to frontal cortex (Narayanan, Rodnitzky, & Uc, 2013). The principal clinical feature of this pathology is a loss of voluntary movement control, including resting tremor and bradykinesia (Helmich, Hallett, Deuschl, Toni, & Bloem, 2012). However, beyond motor symptoms, dopamine dysfunctions also impairs the efficiency of the EC system (Brück et al., 2001; Grahn, Parkinson, & Owen, 2008; Marié et al., 1999; Owen, Doyon, Dagher, Sadikot, & Evans, 1998; Polito et al., 2012).

Executive functions like set-shifting, planning, inhibitory control, conflict resolution, decision making and working memory are compromised since the first stages of disease (see Dirnberger & Jahanshahi, 2013; Kudlicka, Clare, & Hindle, 2011 for reviews). These deficits have been found with neuropsychological measures and experimental tasks such as the Eriksen flanker task (e.g., Wylie et al., 2009a, 2009b), Simon task (Praamstra & Plat, 2001; Wylie, Ridderinkhof, Bashore, Theodore & van den Wildenberg, 2010) and task switching (Cools, Barker, Sahakian, & Robbins, 2001; Hayes, Davidson, Keele, & Rafal, 1998; Rogers et al., 1998; Witt et al. 2006).

Beyond EC dysfunctions, linguistic impairments (in both comprehension and production) are also present in PD patients (see Altmann & Troche, 2011; Colman & Bastiaanse, 2011; Murray, 2008). However, some authors have considered that, at least to some extent, the EC deficits contribute to language impairment. Indeed Lieberman, Friedman, & Feldman (1990) proposed that these deficits would have a common origin in the dysfunction of the corticol-striatal network. Evidence supporting this claim comes from the role of EC in grammatical comprehension (Grossman, Lee, Morris, Stern & Hurtig; 2002). These authors administered a series of tasks involving sentence processing, word detection and executive functions (Trial Making Test, Stroop, Forward and Backward Digit Span) to a group of PD patients. The results of their study showed that comprehension deficits were related to executive dysfunctions. Similarly, Hochstadt, Nakano, Lieberman, & Friedman (2006) found that the errors made by PD patients in a sentence comprehension task correlated with their working memory deficits (for similar results see Murray, 2000).

Beyond sentence comprehension, linguistic deficits in language production have also been described in PD patients, especially for morphology. However, it is worth mentioning that the results are not so consistent across studies. For instance, Ullman et al. (1997) reported impaired rule-based generation of past tense in people affected by PD, but this finding has not been completely replicated (only partially for regular verbs compared to irregular verbs; Colman et al., 2009; Longworth, Keenan, Barker, Marslen-Wilson, & Tyler, 2005; Penke, Janssen, Indefrey, & Seitz, 2005; Terzi, Papapetropoulos, & Kouvelas, 2005; see also Colman & Bastiaanse, 2011 and Altmann & Troche, 2011 for reviews). Again, these deficits have been mainly related to EC, namely to impaired working memory and set switching abilities (Colman et al., 2009). Moreover, verb production deficits have also been reported (Bertella et al., 2002; Cotelli et al., 2007; Rodríguez-Ferreiro, Menéndez, Ribacoba, & Cuetos, 2009) in tasks such as naming, verbal fluency and verb generation (Péran et al., 2003; Piatt, Fields, Paolo, & Tröster, 1999; Piatt, Fields, Paolo, Koller, & Tröster, 1999; Signorini & Volpato, 2006). One explanation given for impairments in verb retrieval, which is greater than for nouns, is that their retrieval represents a less automatic and more controlled process that is more demanding in terms of executive functions (Péran et al., 2003; Piatt et al., 1999; Piatt et al., 1999). Finally, deficits in word production have also been found for object naming (Cotelli et al., 2007), semantic processing and in fluency specifically when the condition is demanding (alternating production of a word starting from a given letter with a word of a given category) (see Henry & Crawford, 2004 for a review).

In the context of bilingualism, only a few studies have investigated the impact of PD in language processing. In two studies Zanini et al. (2004) and Zanini, Tavano, and Fabbro (2010) showed that PD leads to difficulties in sentence and syntactic comprehension, and spontaneous speech production. In their first study, the authors tested Friulian/Italian bilinguals with PD and healthy controls in a sentence comprehension task, syntactic judgement tasks and an EC task (Wisconsin Card Sorting Test). The main result was that PD patients were impaired in syntactic processing, in particular in their first language (Friulian). Moreover, in line with what was found for monolinguals, performance in the EC task correlated with that of the sentence comprehension task, suggesting a link between grammatical processing and executive functions. Similar results were replicated recently by Johari et al. (2013) in Azari-Farsi bilinguals. Finally, Zanini et al. (2010) found that bilingual individuals with PD, compared to controls, produced more morphological, phonological and syntactic errors particularly in L1 speech production.

The authors have interpreted their results (2004, 2010) in line with the declarative procedural model. This proposal explains different linguistic impairments in terms of the dissociation between procedural and declarative memories underlying more or less explicit processing (Ullman, 2001; Ullman et al., 1997). In bilinguals the dominant and early-acquired language would be learned more implicitly and it would depend more on procedural memory, whereas a late-acquired second language would be acquired explicitly (e.g., at school) through declarative memory. Given that the fronto-basal ganglia network processes the procedural memory, this explains why bilingual PD patients have grater deficits in their dominant language (L1).

However, Zanini et al. (2004) also reported a positive correlation between performance in the linguistic and non-linguistic tasks, leaving open the possibility that EC deficits may contribute to language impairments in their bilinguals PD patients, (see also

Adrover-Roig et al., 2011 for a differential impairment of L1 and L2 due to EC deficits).

Therefore, the potential presence of a parallel impairment of language and EC motivate the study of the relation between bLC and EC in bilingual patients.

1.4 The overlap between mechanisms of bilingual language control and executive control

The first approach I used to explore the nature of mechanisms involved in bLC was to investigate to what extent they are implemented by domain-general EC. Previous studies that have examined this issue have compared and correlated the performances of the same bilingual participants in tasks of both bLC and EC.

The rationale is that if the same mechanisms are involved in the two domains, there should be similarities and correlations between performances in the tasks.

Linck, Schwieter, & Sunderman (2011) explored the relation between an index of non-linguistic control (Simon effect) and the switch costs in a trilingual language switching task. The correlation analysis between these two indexes of control was significant but only when people switched to their first language, suggesting a possible link between the two domains. However, using a Simon task, naming and verbal fluency tasks, Bialystok, Craik, & Luk (2008) failed to show correlations between these measures.

A more direct and promising approach is to test the same participants in similar versions of a task tapping the two domains of control. Some studies have employed two comparable versions of the switching paradigm, one linguistic and one non-linguistic (Branzi, Calabria, Boscarino, & Costa, 2016; Calabria, Branzi, Marne, Hernández, & Costa, 2013; Calabria, Hernandez, Branzi, & Costa, 2011; Prior & Gollan, 2013; Weissberger, Wierenga, Bondi, & Gollan, 2012).

Calabria et al. (2011) tested highly proficient Catalan-Spanish bilinguals in comparable versions of linguistic and non-linguistic switching tasks. The results showed different patterns in the asymmetries of switch costs between the two tasks and a lack of correlation between them. Specifically, in the linguistic task participants showed a similar symmetrical pattern of switch costs when they switched between their two proficient languages (Experiment 1) and when they switched between their L1 and the less proficient L3 (Experiment 2) (see Costa & Santesteban, 2004 for similar results). In the non-linguistic version, instead the pattern of switch costs was asymmetrical and these results were interpreted as suggesting that some mechanisms involved in bLC are domain-specific and unrelated to EC. These conclusions were supported by a follow-up study in which Calabria et al. (2013) tested bilinguals of different ages in similar linguistic and non-linguistic switching tasks. They found that whereas there was an age-related increase in the non-linguistic switch cost, the linguistic switch cost was similar across age groups. Moreover, also in this case there was a lack of correlation between the switch costs in the two tasks.

Similarly, Weissenberg et al. (2012) found that English dominant and Spanish dominant bilinguals showed different patterns of age-related impairments in similar versions of language and colour-shape switching tasks. In the Weissenberg et al. study, differently from Calabria et al. (2013), only the switch costs in the linguistic task showed an age-related increase. Despite the opposite direction of these results, possibly due to the difference in the language profile of bilinguals, the authors converged on the similar conclusion that mechanisms involved in non-linguistic and language control only partially overlap (for similar results see also Klecha, 2013; Prior & Gollan, 2013). A recent extension of these results to other indices of language switch abilities have been reported by Branzi et al. (2016). Specifically, they measured the "n-2 repetition cost", a more reliable index of inhibition (Koch et al., 2010), in bilinguals and still found no correlations between domains of control.

Taken together, these results suggest that at least reactive control mechanisms, indexed by switch costs, are not shared between bLC and domain-general EC.

Only a few studies also investigated mixing costs in order to better explore the overlap between these domains of control. For instance, Weissberger et al. (2012) explored the impact of aging on mixing costs and found that it was similarly impaired in both versions of the task in older adults. Similarly, Prior & Gollan (2013) in a test-retest experiment found a positive correlation between mixing costs in linguistic and non-linguistic switching tasks performed one week apart, but this was not the case for switch costs.

Besides this series of behavioural findings, more and more effort has been made to find overlap in the relevant brain areas. By now, the available evidence suggests that some areas are equally activated during bLC and EC tasks but others suggest only a partial overlap between the two domains of control (Branzi et al., 2015; Coderre, Smith, Van Heuven, & Horwitz, 2015; Weissberger, Gollan, Bondi, Clark, & Wierenga, 2015; see Pliatsikas & Luk, 2016 for a review).

Indeed, across these studies, whereas left frontal, prefrontal and parietal cortices showed similar activations in linguistic and non-linguistic tasks, pre-SMA, ACC and subcortical structures were sometimes particularly activated for language control (Baene et al., 2015; Branzi et al., 2016; Weissberger et al., 2015).

Also, studies that measured electrical brain activity during similar versions of linguistic and non-linguistic tasks report evidences in favour of partially independent language control mechanisms (Khateb et al., 2007; Magezi, Khateb, Mouthon, Spierer, & Annoni, 2012). In their first study, Khateb et al. (2007) compared event-related potentials (ERPs) induced by language switching and switching intra-language in a noun-verb switching task. The most important result showed early differences in the waveform in left frontal areas between 200 and 300 ms after the cue, suggesting differences in the mechanisms involved in lexical selection in the two tasks. These findings have been criticized for the fact that the noun-verb task switching used has a strong linguistic component. This task indeed may be considered a task tapping language control in a single-language context, when only one language is required, instead that a task tapping exclusively domain-general EC (Magezi et al., 2012; see Christoffels et al. 2007 for an ERP study in single- and dual-language contexts). However, these results bring up the issue of possible further specificity of some bLC mechanisms within the linguistic domain that I will discuss in the next section.

In a further study, Magezi et al. (2012) compared behavioural and ERP measures in a language switching task and a categorization task. Behavioural results showed symmetrical switch costs in the linguistic task and asymmetrical ones in the non-linguistic task, similar to what Calabria et al. (2011) found. These results, together with the differences in the patterns of ERPs in the linguistic and non-linguistic tasks, were taken as evidence that language and task selection rely on different mechanisms.

In this section I reviewed the main findings about the overlap between bLC and domain-general EC to contextualize the background for the experimental study done for this PhD thesis. Indeed, the aim of the first study (Section 2.1) was to explore the overlap of reactive and proactive control mechanisms in the two domains, by comparing the performance of PD and healthy controls in the linguistic and non-linguistic switching tasks.

Moreover, in the second study (Section 2.2) I tested the contribution of two EC mechanisms (working memory and monitoring) in two different contexts of language control. In particular I investigated which of these mechanisms of EC are related to proactive and reactive language control. The reason to use working memory (and not other measures) is driven by the proposal that proactive control reflects the demand for maintaining the two task sets active in a dual task situation (Braver, Reynolds, & Donaldson, 2003; Kray & Lindenberger, 2000; Mayr, 2001; Pettigrew & Martin, 2015; Rogers & Monsell, 1995). For instance, Pettigrew and Martin (2015) showed that working memory abilities of the participants in their study strongly predicted the index of proactive control (mixing costs) in the switching task administered. However, other authors have instead found that working memory has no influence on stimulus-response mapping and they claim that proactive control is a matter of conflict monitoring (Philipp, Kalinich, Koch, & Schubotz, 2008; Prior & Gollan, 2013; Prior & Macwhinney, 2010; Rubin & Meiran, 2005;). Therefore, given this alternative explanation of proactive control, a conflict monitoring task was also included.

The studies reviewed in this section evaluated the nature of bLC mechanisms comparing linguistic and non-linguistic tasks. However, within the linguistic domain there may be a further specificity, as suggested by the study of Katheb et al. (2007). Indeed, not all bLC mechanisms may be at play when bilinguals use language control but not to switch between languages. Only a few studies explored this issue and I will review them in the next section.

1.5 Further specificity in the linguistic domain

The second approach I used to characterize the nature of mechanisms involved in bLC is to investigate their involvement in different linguistic contexts. That is, we explored if mechanisms involved in bLC are an instantiation of general mechanisms of language control used in other contexts that not requires the use of both languages.

Indeed cognitive and neural models of bilingual language production have recently proposed that the linguistic context might differentially modulate the involvement of some control mechanisms and the engagement of some brain structures (Abutalebi & Green, 2016; Green & Abutalebi, 2013). The first and most important evidences supporting the engagement of different control mechanisms depending on the linguistic context come from neuroimaging and ERPs studies (Abutalebi et al., 2008; Crinion et al., 2006; Khateb et al., 2007). Khateb et al. (2007) compared ERPs induced by switching in two different linguistic contexts. In the dual-language context participants switched between languages while in the single-language context they switched between grammatical categories (nouns and verbs). Results showed different electrical responses in both early and late components of the waveform in the two tasks, suggesting differences in the mechanisms involved in the two linguistic contexts. The most relevant difference appeared particulary in left anterior areas between 220 and 300 ms after cue. This difference was interpreted as representing the neural correlates of the differences in the lexical selection processes involved in the two contexts. Also, neuroimaging studies have shown differences in the brain activation during naming in single- and dual-language contexts. For instance, Abutalebi et al. (2008) tested participants in an object naming task, a language switching task and a within language noun-verb switching task. The two switching tasks showed similar increased activation in the middle frontal gyrus and inferior frontal gyrus. This finding was interpreted as the selection processing between competing alternatives and working memory (Petrides, Alivisatos, Meyer, & Evans, 1993; Rodriguez-Fornells et al., 2005). However, the comparison between the two switching tasks also showed that the left anterior cingulate cortex and the left caudate were activated only in the dual-language context (for similar conclusions regarding the left caudate see also Crinion et al. 2006 for a cross-language priming task). Recently, a behavioural study by Boukadi, Davies and Wilson (2015) also showed that language specific or language non-specific mechanisms of lexical selection are engaged in relation to the linguistic context.

One theoretical framework that can account for these evidences is the "language mode hypothesis" (Grosjean, 2001). This proposal suggests that bilinguals are on a continuum between the two extremes (single-language mode and dual-language mode). In the single-language mode the target language is highly activated while the other is much less activated. In the dual-language mode, both languages are highly activated. This means that in the single-language context, the interference between languages is reduced to a minimum whereas in the dual-language context the cross-language interference is high. In this condition there may be the need to engage other control mechanisms to resolve this interference.

Recently, following the language mode hypothesis (Grosjean, 2001), other authors (Green & Abutalebi, 2013) have proposed the “adaptive control hypothesis”. This model considers that language control mechanisms are differently engaged by bilingual speakers depending on the interactional situation, that is, whether required to speak only one language or to switch back and forth between languages (Abutalebi & Green, 2016; Green & Abutalebi, 2013). In this proposal the authors distinguish between three bilingual interactional contexts. The first is a single-language context: each language is used according distinct environments, for instance at home or at work. In this case switching between languages is not so frequent. The second one is the dual-language context, in which different languages are used in the same context with different speakers, therefore with a high rate of language switching. The third context is a dense code-switching context in which people interweave languages in the same utterance of word.

Concerning control abilities, the authors suggest that in the single-language context speakers may only use goal maintenance, which allows them to reduce interference from the other language to a minimum (or eliminate). In their view, this stable state should be resistant to interference, but scarcely flexible, which would be at odds with a state that promotes flexibility in response to new inputs.

Conversely, in the dense code-switching context people freely switch and mix the two languages, therefore any form of control is hypothesised to be at play. Finally, the dual-language context represents a more complex and demanding situation because it requires changing the goal (to speak in the other language) in response to environmental cues. In this context the demand of the control processes such as goal maintenance, conflict monitoring, and interference resolution is highly increased. Moreover, a control process of cue detection is needed to trigger selective response inhibition, task engagement and disengagement for achieving a fluent language switch. Indeed in order to reduce interactional costs in a dual situation, speakers must sustain the current language goal, suppress interference from the other language, but also be in a position to switch languages upon detecting an addressee with whom they converse in their other language. In other words, the speakers have to balance the use of mechanisms in order to adapt to situational demands.

One way to characterize these processes in the dual-language context is to hypothesize the involvement of both proactive and reactive control. The first will maintain the dual-task setting active (languages), the second instead will be in charge of resolving interference when required to switch languages.

In the second study (Section 2.2) I directly tested the involvement of proactive and reactive control mechanisms of bLC in different language control contexts as a way to assess whether they are similarly involved.

2. EXPERIMENTAL SECTION

The aim of this dissertation is to advance our knowledge on the nature of mechanisms involved in bilingual language production.

In order to do this, I conducted two behavioral experiments carried out using two main approaches. Firstly, I explored the overlap between mechanisms of bLC and domain-general EC. Secondly, I investigated the relation between bLC and language control in general – that is, when it is not required to switch between languages.

This chapter is the recompilation of one published article in an internationally recognized, peer-reviewed and indexed scientific journal and one submitted article.

2.1 The role of executive control in bilingual language production: A study with Parkinson's disease individuals.

Cattaneo G, Calabria M, Marne P, Gironell A, Abutalebi J, Costa A. The role of executive control in bilingual language production: A study with Parkinson's disease individuals. Neuropsychologia. 2015 Jan;66:99–110. DOI: 10.1016/j.neuropsychologia.2014.11.006

2.3 Deconstructing bilingual language control processes

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Deconstructing bilingual language control processes

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Abstract

This study aims to investigate the nature of bilingual language control (bLC) mechanisms using two approaches. Firstly, by exploring the involvement of mechanisms of reactive and proactive control in bLC and language control when only one language is involved. Secondly, by investigating the contribution of two EC components such as working memory and conflict monitoring in the tasks of language control. In order to do so we explored performances of bilinguals affected by Parkinson's disease (PD) and healthy controls in two linguistic tasks (language switching and noun-verb switching language) and two non-linguistic tasks (n-back and spatial Stroop task).

The results showed that PD patients were impaired in reactive control (indexed by switch costs) only when they switched between languages, whereas they were impaired in proactive control (indexed by mixing costs) in both versions of the switching tasks. Moreover switch costs in the two linguistic tasks did not correlate whereas mixing costs did. Finally, mixing costs but not switch costs correlated with participants' abilities in working memory and conflict monitoring (albeit less so).

These results, together with other previous findings, suggest that the nature of proactive control is more domain-general, whereas reactive control seems specific to some contexts of language control. Moreover the results from correlations seem to indicate that proactive language control is more related to working memory abilities than conflict monitoring.

Keywords: Bilingualism, Parkinson’s disease, Bilingual language control, reactive control, proactive control, working memory.

1. Introduction

Understanding how bilinguals avoid cross-language interferences while speaking requires knowledge about the nature of the underlying control processes involved. In order to improve this understanding we need to know how these processes are related to those of general language control and domain-general executive control (EC). In other words, are the processes behind bilingual language control (bLC) just an instance of EC or general language control, or rather, do they have some sort of specificity? The current answer to this question is yes and no, and here we aim to advance in this knowledge.

By now, a substantial body of evidence suggests that only some mechanisms are shared between bLC and domain-general EC, suggesting therefore a certain degree of specificity (Blanco-Elorrieta & Pylkkänen, 2016; Branzi, Della Rosa, Canini, Costa, & Abutalebi, 2016; Calabria, Branzi, Marne, Hernández, & Costa, 2013; Ivanova, Murillo, Montoya, & Gollan, 2016; Magezi, Khateb, Mouthon, Spierer, & Annoni, 2012; Weissberger, Gollan, Bondi, Clark, & Wierenga, 2015; Weissberger, Wierenga, Bondi, & Gollan, 2012). However, given some evidence of a complete overlap between the underlying neural systems, the specificity of these control mechanisms is an open issue (Baene, Duyck, Brass, & Carreiras, 2015).

Here, we aim to further investigate the overlap of these processes by comparing the performance of Parkinson’s disease (PD) patients in tasks that require control, related to three domains: bLC, domain-general EC, and language control that does not involve the two languages. Crucially we pay special attention to reactive (transient) and proactive (sustained) control mechanisms, two of the mechanisms at play in both language and non-linguistic control. Proactive control is defined as a sustained mechanism that facilitates the processing of possible upcoming conflicts, while reactive control is defined as transient and in charge of resolving interference when it is detected.

For these two types of control we already have some evidence of a partial overlap, at least for bLC and domain-general EC. Indeed, in our previous study (Cattaneo et al., 2015) we explored whether these two mechanisms of control were equally impaired in PD patients for bLC and EC, as a way to investigate their overlap. The reason to study this issue in PD patients was because this pathology affects the fronto-striatal network involved both in bLC (Abutalebi & Green, 2007 for a review) and domain-general EC (Dirnberger & Jahanshahi, 2013 for a review). The results showed that PD patients, when compared to healthy controls, were differentially impaired when tested in language switching for bLC and task switching for EC. That is, they were impaired for both proactive and reactive control in language switching, but only for proactive control in task switching. Moreover, individuals' performance of proactive control correlated between the linguistic and non-linguistic tasks, while those of reactive control did not. Hence, we interpreted these results as evidence of the specificity of reactive control and a more domain-general nature of proactive control. That is, proactive control seems to be one of the common underlying mechanisms of bLC and domain-general EC, whereas reactive control would be specific of bLC.

This interpretation is in line with the results of other studies that explored the relationship between bLC and EC. Indeed these studies failed to find an overlap between these two domains for reactive control mechanisms (Branzi, Calabria, Boscarino, & Costa, 2016; Calabria et al., 2013; Calabria, Hernandez, Branzi, & Costa, 2011; Prior & Gollan, 2013; Weissberger et al., 2012) and evidence of an overlap for proactive control (Prior & Gollan, 2013; Weissberger et al., 2012).

Here we aim to extend these observations to language control tasks that do not involve bilingual control and also to specific domain-general EC processes. Indeed, much less attention has been devoted to the relationship between bLC and language control processes in general. For instance, we know that partially different mechanisms and brain areas are engaged when bilinguals perform control tasks that involve either languages or only one (Abutalebi et al., 2008; Khateb et al., 2007). Here, we specifically explored the overlap of proactive and reactive mechanisms for these two types of linguistic control contexts.

Moreover, we aim to extend the study of the relationship between language control and EC by investigating two subcomponents: working memory and conflict monitoring. We focus on these two EC processes because they have been suggested as being behind non-linguistic proactive control (Braver, Reynolds, & Donaldson, 2003; Rubin & Meiran, 2005).

1.1. Proactive and reactive control in bilinguals

Recent proposals of how bLC works identify at least two possible mechanisms, namely proactive and reactive control, similarly to what has been proposed for non-linguistic EC (for bLC see Christoffels, Firk, & Schiller, 2007; Green & Abutalebi, 2013; Ma et al., 2016; for domain-general EC see Dual Mechanisms of Control model by Braver, 2013). In the context of bilingualism, reactive control is defined as a transient process that resolves interference between languages. It is to some extent similar to what Green (1986, 1998) proposed as inhibitory control, which is the mechanism that allows task schema to inhibit the words in the non-target language in order to reduce their activation. Proactive control instead would modulate the balance of the activation between the two languages, by for instance deactivating the non-target language to make the intended language more available or vice versa (Ma et al., 2016).

The classical measures of these two types of control studied with switching paradigms are switch and mixing costs, respectively (Braver et al., 2003; Jimura & Braver, 2009; Ma et al., 2016). These two costs are generated by the differences between reaction times in naming pictures in different trial conditions. Specifically, switch cost is calculated as the difference in naming latencies between switch and repeat trials in a mixed language condition. Switch trials are those in which the preceding picture was to be named in a different language, and repeat trials are those in which the preceding picture was to be named in the same language. Mixing costs instead are calculated as the difference between repeat trials (in the mixed condition) and trials in a blocked language naming condition.

Few studies have investigated the involvement of proactive and reactive control in bilingual language production (Cattaneo et al., 2015; Ma et al., 2016; Prior & Gollan, 2013; Weissberger et al., 2012), and, crucially, even fewer have explored their overlap with mechanisms of language control in general – that is, the set of control mechanisms involved in those situations in which two languages are not mixed. Indeed, in situations in which only one language is used, as for monolinguals, control mechanisms are engaged to manage the level of activation of lexical items and prevent interferences from other competitors (e.g., semantics; Levelt, Roelofs, & Meyer, 1999; Roelofs, 2003; Thompson-Shill & Botvinik, 2006). Therefore, the question is also whether the same proactive and reactive mechanisms of bLC are at play in this situation.

In other words we want to explore the overlap between bLC and language control in general. To do so, we will compare the performance of PD patients in two switching tasks, namely language switching and noun-verb switching. In the language switching task participants will be asked to name pictures and the naming language will be cued in every trial. In the noun-verb switching task participants will name pictures only in one language and a cue will indicate whether the picture will be named as an object or action. In both versions of the tasks we will measure both switch and mixing costs, as measures of reactive and proactive control respectively. Therefore, similar deficits of PD patients in both tasks and a significant correlation between costs would suggest the presence of an overlap between these two domains of language control.

Given our previous study, in which we found partial overlap between bLC and EC, we predict the same here for this comparison within the linguistic domain. That is, we predict impaired reactive control for PD patients when they need to control the two languages but not in the noun-verb switching task. Moreover, similar to what we found in our previous study, proactive control should be impaired in patients in both tasks, given its domain-general nature.

This prediction is also supported by neural evidence that basal ganglia structures, damaged by PD, are in charge of controlling the two languages but not for control mechanisms used when only one language is used (Abutalebi et al., 2008; see also Crinion et al., 2006 for similar results on the sensitivity of left caudate for control the language in use). Similarly, lesions over basal ganglia structures result in pathological language switching and mixing, supporting their crucial role in regulating the control of the two languages (Abutalebi, Miozzo, & Cappa, 2000; Aglioti, Beltramello, Girardi, & Fabbro, 1996; Aglioti & Fabbro, 1993; Ansaldo, Saidi, & Ruiz, 2010; Mariën, Abutalebi, Engelborghs, & De Deyn, 2005).

1.2 Working memory, monitoring and language production

A further aim of this study is to investigate the relationship between language control and EC by examine working memory and conflict monitoring. Specifically, we aim to explore whether these two EC components overlap with language proactive and reactive control. The reason to focus on working memory and conflict monitoring is because they have been suggested as being behind proactive control (Braver et al., 2003; Rubin & Meiran, 2005).

Specifically, two main hypotheses have been proposed to explain the EC processes related to proactive control. For some authors it would reflect the demand on working memory to maintain active and update relevant information in demanding situations (e.g., mixed blocks in task switching; Braver et al., 2003; Kray & Lindenberger, 2000; Mayr, 2001; Pettigrew & Martin, 2015; Rogers & Monsell, 1995). For instance, Pettigrew and Martin (2015) provided evidence for such a functional link showing that participants' working memory abilities predicted the index of proactive control (mixing costs) in a switching task.

Alternatively it has been suggested that proactive control would reflect the abilities of monitoring and resolving interferences, without any involvement of working memory (Rubin & Meiran, 2005; Philipp, Kalinich, Koch, & Schubotz, 2008; Prior & Gollan, 2013; Prior & Macwhinney, 2010). For instance Rubin et al. (2005) manipulated the working memory load in task switching (increasing the stimulus-response mapping) and found that working memory did not modulate the magnitude of the mixing costs. These authors argued that mixing costs reflect a set of mechanisms in charge of monitoring and resolve the conflict between potentially relevant stimulus dimensions.

In this study we will make use of two tasks (n-back task and spatial Stroop) tapping these EC components to see their relation to proactive language control. Hence, whether proactive control is related to working memory and/or conflict monitoring will be determined by the correlation of the performance in these two tasks with the linguistic control tasks. Given that reactive control does not seem to depend on these EC components, we do not expect significant correlations between working memory and conflict monitoring for this type of control.

In summary, in the present study we will compare the performance of bilingual individuals with PD to those of age-matched healthy controls in order to investigate:

a) The overlap of reactive and proactive control mechanisms involved bLC and language control in general;

b) The involvement of working memory and/or conflict monitoring in language control mechanisms;

2. Methods

2.1. Participants

24 bilingual individuals with a diagnosis of Parkinson's disease (12 female, mean age=71.3 ± 6.8, mean education= 10.7 ± 4.5) and 17 healthy controls matched for age and education (12 female, mean age=71.5 ± 7.5, p=0.95; mean education=9.9 ± 3.7, p=0.59) took part in the study. All participants were early and high proficient Catalan-Spanish bilinguals. The language proficiency level was tested with a questionnaire in which participants self-rated their abilities of comprehension, reading, writing, fluency and pronunciation in a four-point scale (4=perfect, 3=good, 2=sufficient, 1=poor). As reported in Table 1, participants self-rated as high proficient in both languages. The mean age of L2 acquisition was 3.2 (± 2.4) for patients and 3.3 (± 2.6) for healthy controls indicating early acquisition. Moreover, they were also regularly exposed to both languages since they lived in the metropolitan area of Barcelona, a high bilingual context.

All individuals with PD were recruited at the Movement Disorders Unit of the Sant Pau Hospital in Barcelona. A senior neurologist (AG) specialized in movement disorders performed the clinical diagnosis according to the clinical criteria of UK Parkinson's disease Brain Bank (Hughes, Daniel, Kilford, & Lees, 1992). All PD were in the mild stage of disease according to UPDRS scale (mean= 12.8 ±4.4 out of 159, range=8-21; Fahn et al. 1987) and Hoehn and Yahr score (all rating from I to IIa; Hoehn & Yahr, 1967), and without dementia according to the MMSE score

(Folstein, Folstein, & McHugh, 1975; mean 28.7 ±1.1, range=26-30). All patients were stable, without motor fluctuations and on anti-parkinsonian pharmacological treatment. Patients with psychiatric and neurological disorders other than PD, clinically known hearing or vision impairment, a past history of alcohol abuse, were excluded from the study.

Table 1. *Socio-demographic characteristics of the participants and clinical data of the PD patients.*

	PD patients	**Controls**	**p values**
	Mean (SD)	***Mean (SD)***	
Age (years)	71.3 (6.8)	71.5 (7.5)	0.95
Education (years)	10.7 (4.5)	9.9 (3.7)	0.59
UPDRS (0-159)	12.7 (4.3)	-	-
Age of L2 aqcuisition	3.2 (2.4)	3.3 (2.6)	0.81
Self rating questionnaire (1-4)			
L1			
Comprehension	4.0 (0.0)	4.0 (0.0)	-
Fluency	4.0 (0.2)	3.9 (0.3)	0.10
Pronounciation	3.9 (0.2)	3.9 (0.3)	0.37
Writing	2.0 (1.4)	3.1 (1.1)	0.01
Reading	3.8 (0.4)	3.9 (0.2)	0.11
L2			
Comprehension	4.0 (0.0)	3.9 (0.2)	0.24
Fluency	3.9 (0.4)	3.8 (0.4)	0.46
Pronounciation	3.8 (0.4)	3.8 (0.4)	0.93
Writing	3.0 (1.1)	3.3 (1.0)	0.46
Reading	3.9 (0.3)	3.8 (0.6)	0.26

Healthy adults were relatives of the patients, recruited in the Hospital Sant Pau, or people recruited in a recreational association for elderly people (Casal d'avis del Congrés) in the metropolitan area of Barcelona. They were without cognitive impairment according to the MMSE score (mean 28.5 ±1.0, range=26-30).

The study procedures were approved by the local ethical committee of the University Pompeu Fabra. Informed consent was obtained from all individuals and caregivers prior to testing, after a full explanation of the study.

2.2. Neuropsychological assessment

All the participants performed a neuropsychological assessment (see Table 2) which included: Mini Mental State Examination assessing the global cognitive status (Folstein et al., 1975); CERAD Word List Memory test (Morris et al., 1989) for verbal long-term memory assessment; Digit Span Test forward and Backward for short-term memory and working memory (from Test Barcelona, Peña-Casanova, 2005); Parts A and B of the Trial Making Test for an assessment of visuo-perceptual and shifting abilities (Reitan & Wolfson, 1985); semantic and the letter fluencies in Spanish and Catalan.

Table 2. *Neuropsychological assessment of participants. Means and standard deviations (in parenthesis) of raw and adjusted scores for age and educations.*

	PD patients		Controls		p values
	Raw	*Adjusted scores**	*Raw*	*Adjusted scores**	
MMSE	28.7 (1.1)	-	28.5 (1.0)	-	0.43
Long-term Memory					
CERAD immediate	16.7 (4.2)	-	16.3 (3.0)	-	0.77
CERAD delayed recall	4.1 (0.4)	-	4.7 (0.4)	-	0.28
CERAD recognition	18.2 (1.8)	-	18.3 (1.3)	-	0.88
Short-Term Memory					
Forward digit span	5.2 (1.2)	9.7 (3.0)	5.4 (0.7)	10.9 (1.8)	0.56
Executive Functions					
Backward digit span	3.6 (1.0)	10.29 (1.7)	4.1 (0.6)	12.6 (1.2)	0.07
TMT A	48.7 (2.8)	10.39 (1.8)	39.7 (3.4)	12.1 (2.3)	0.05
TMT B	133.7	9.1 (1.3)	111.5	10.2 (1.5)	0.06
Language production					
Semantic fluency L1	10.14 (2.4)	10.1 (2.4)	10.24 (1.6)	10.2 (1.6)	0.89
Semantic fluency L2	9.77 (1.8)	9.8 (1.8)	9.9 (1.8)	9.9 (1.8)	0.78
Phonemic fluency L1	8.9 (1.6)	8.9 (1.6)	10.2 (1.1)	10.2 (1.1)	<0.01
Phonemic fluency L2	9.9 (1.8)	9.9 (1.8)	10.5 (1.5)	10.5 (1.5)	0.30

***** *Mean scores adjusted for age and education on the basis of the "Spanish multicenter Normative studies (NEURONORMA PROJECT)" (Peña- Casanova et al.,2009).*

2.3. Materials and procedures

All participants were tested in four tasks: noun-verb switching task (in L1 and L2), language switching task, n-back task, and the spatial Stroop task. Data from 13 PD patients and 8 healthy controls for language switching come from the previous study (Cattaneo et al., 2015).

The tasks were administered in two different experimental sessions a week apart, with a linguistic and a non-linguistic task per session in a counterbalanced order.

All of the experimental tasks were administered through a laptop (screen 15.6" and resolution of 1280x800) and were controlled by the DMDX software (Forster & Forster, 2003) recording for vocal and manual responses. Responses were analyzed off-line, and naming latencies for the linguistic task were measured through Checkvocal software (Protopapas, 2007).

2.3.1. Linguistic control tasks

Noun-verb switching task. Eight pictures of objects were selected from Snodgrass & Vanderwart (1980). Participants were required to name the pictures or produce the verb related as fast as possible. All the pictures were selecting considering that the noun and the verb that had to be produced were not phonologically overlapping within the same language [Catalan and Spanish: ‘Got/Beure’ and ‘Vaso/Beber’ (Glass/to Drink); ‘Ocell/Volar’ and ‘Pájaro/Volar’ (Bird/to Fly); ‘Paella/Fregir’ and ‘Sartén/Freir’ (Pan/to Fry); 'Piano/Tocar' and 'Piano/Tocar' (Piano/to Play Piano); 'Tren/Viatjar' and 'Tren/Viajar' (Train/to Travel); 'Cigarreta/Fumar' and 'Cigarro/Fumar' (Cigarette/to Smoke); 'Plat/Menjar' and 'Plato/Comer' (Dish/toEat); 'Ganivet/Tallar' and 'Cuchillo/Cortar' (Knife/to Cut).

There were two types of blocks: single blocks and mixed blocks. In the single blocks the grammatical category to be produced (name or verb) was always the same, whereas in the mixed blocks participants had to name the pictures or produce the related verb according to a cue appearing on the screen. Therefore, in the mixed blocks there were two types of trials: repeat trials in which participants had to name according to the same grammatical category used in the previous trial, and switch trials in which participants were required to name according to the grammatical category different from that one used in the previous trial. The order of blocks was in a sandwich design such that participants completed two single blocks and three mixed blocks, followed by two more single blocks (similar to Cattaneo et al., 2015). There were a total of 96 trials (48 for nouns and 48 for verbs) in the single block condition and 96 trials in the mixed block condition (33 “noun” repeat trials, 33 “verb” repeat trials, 15 “noun” switch trials and 15 “verb” switch trials). The proportion of switch and repeat trials was of 31% and 69% respectively.

Every trial started with a fixation point (a white cross) in the centre of the screen displayed for 500 ms, followed by a cue of 500 ms (‘NOM’/’NOMBRE’ for nouns, ‘VERB’/’VERBO’ for verbs) and then by the picture for a maximum of 2500 ms. At the beginning of each block a word cue presented on the screen for 1000 ms indicated with which grammatical category participants had to start.

Language switching task. Eight pictures of objects were selected from Snodgrass & Vanderwart (1980). All of them were non-cognate words [Spanish/Catalan names: ‘Manzana/Poma’ (Apple); Calcetín/Mitjó (Sock); ‘Queso/Formatge’ (Cheese); ‘Silla/Cadira’ (Chair); ‘Zanahoria/Pastanaga’ (Carrot); ‘Cepillo/Raspall’ (Brush); ‘Tenedor/Forquilla’ (Fork); ‘Mariposa/Papallona’ (Butterfly)]. Participants were required to name the pictures in Catalan or in Spanish as fast as possible according to a cue (flag).

The task was the same used in Cattaneo et al., (2015), and type and number of blocks, type of trials and number of trials were the same as for the noun-verb switching task.

2.3.2. Non-linguistic tasks

N-Back task. Letters (consonants) were serially presented and participants were required to do a matching in three different memory load conditions. In the 0-back condition, the target was any letter that matched a pre-specified letter (e.g., “X”); in the n-1 and n-2 back conditions, the target had to match to the letter that was presented one or two trials before respectively (for a similar version of the task see Braver, Cohen, Nystrom, Jonides, Smith & Noll, 1997; Cohen, Perlstein, Braver, Nystrom, Noll, Jonides, 1997). Participants responded by pressing one key if the presented stimuli matched the target or another one if the stimuli didn’t match.

At the beginning of every trial a fixation point appeared on the screen for 500 ms, followed by the stimuli that remained on the screen for 500 ms. The timeout to respond was 1500 ms. There were a practice block of 25 trials and three other blocks of 25 trials in which there were 7 target trials (28%) and 18 no target trials (72%) in each block.

Spatial Stroop task. Participants had to respond according to the left/right direction of the arrow appeared on the left or right half part of the screen. If the arrow pointed to the right they had to press with the right hand one key on the right part of the keyboard, whereas the arrow pointed to the left they had to respond with the left hand pressing one key in the left part of the keyboard (for a similar version of this task see Funes, Lupiáñez, & Milliken, 2007; Luo, Lupiáñez, Funes, & Fu, 2010; Lupiáñez & Jesús Funes, 2005). A fixation cross appeared in the centre of the screen for 500 ms and then the arrow was displayed until the participant response or for a maximum of 2500 ms.

In the congruent condition the direction of the arrow and its position of the screen was the same, while in the incongruent condition the direction of the arrow and its location was not same (for instance, arrow pointing to left presented in the right-side part of the screen). Moreover, the proportion of congruent/incongruent trials was manipulated in order to have one condition of high conflict and one of low conflict. In the mostly congruent condition, 75% of the trials were congruent and 25% were incongruent, while mostly incongruent condition consisted of 75% congruent and 25% incongruent. The total number of trials was 192, 96 for each conflict condition (two blocks of 48 per condition).

3. Results

The analysis we will be organized in the following way. First, to explore the similarities of the control mechanisms between the two language context conditions we will compare the performance of PD patients and older adults in the two linguistic tasks and we will correlate the costs (mixing and switch) between them. Second, to explore the integrity of EC mechanisms we will compare the performance of PD patients and older adults in the n-back task and the spatial Stroop task. Finally, to see whether the two EC mechanisms are related to language control we will correlate the performance of PD patients and older adults in linguistic and non-linguistic tasks.

Latencies exceeding 3 SDs above or below a given participant's mean and incorrect responses were excluded from the analyses.

3.1 Linguistic control tasks

Noun-verb switching task. The noun-verb task was performed both in L1 and L2 for all participants therefore the analysis also included the main effect of naming language. A repeated measures ANOVA on accuracy and RTs was run with the following variables: "Type of trial" (single, repeat, switch), "Language" (L1, L2) and "Category" (noun, verb) as within-subjects factors and "Group" (controls, PD patients) as a between-subjects factor.

RTs. Participants were slower in switch trials (1092 ms) compared to repeat trials (1045 ms, $p<0.01$), and repeat slower than single trials (959 ms, $p<0.01$) [Type of trial: $F(2, 78)=41.14$, $p<0.01$, $\eta p^2=0.51$] (see Fig.1). The main effect of Category was also significant [$F(1, 39)= 30.63$, $p<0.01$, $\eta p^2=0.44$], indicating that participants were faster producing nouns (1007 ms) than producing verbs (1057 ms). However, the language used in the task did not modulate the participants' naming latencies [Language: $F(1, 39)=0.89$, $p=0.35$, $\eta p^2=0.02$].

Finally, the main effect of Group was significant, that is, individuals with PD were overall slower (1106 ms) than controls (957 ms) [$F(1, 39)= 6.65$, $p<0.05$, $\eta p^2=0.15$]. Moreover, the interaction between Group and Type of trial was significant [$F(2, 78)=6.73$, $p<0.01$, $\eta p^2=0.15$], suggesting a difference in the magnitude of the costs (mixing and/or switch) between the two groups.

To further analyze this interaction, we calculated the magnitude of the costs and then performed a one-way ANOVA for each cost separately with Group as a between-subjects factor. In order to avoid bias due to different baseline RTs for the two groups we calculated the costs as proportions. Proportional switch costs were calculated as the difference between RTs in switch trials and repeat trials (mixed blocks) divided by RTs in repeated trials. Proportional mixing costs were calculated as a difference between RTs in repeat and single trials divided by RTs in single trials.

The results revealed that individuals with PD had increased mixing costs as compared to controls [13.4% and 4.0%; $F(1, 39)=10.58$, $p<0.01$, $\eta p^2=0.21$], but not switch costs [3.4% and 4.8% respectively; $F(1, 39)=1.00$, $p=0.33$, $\eta p^2=0.02$]. No other interaction resulted significant.

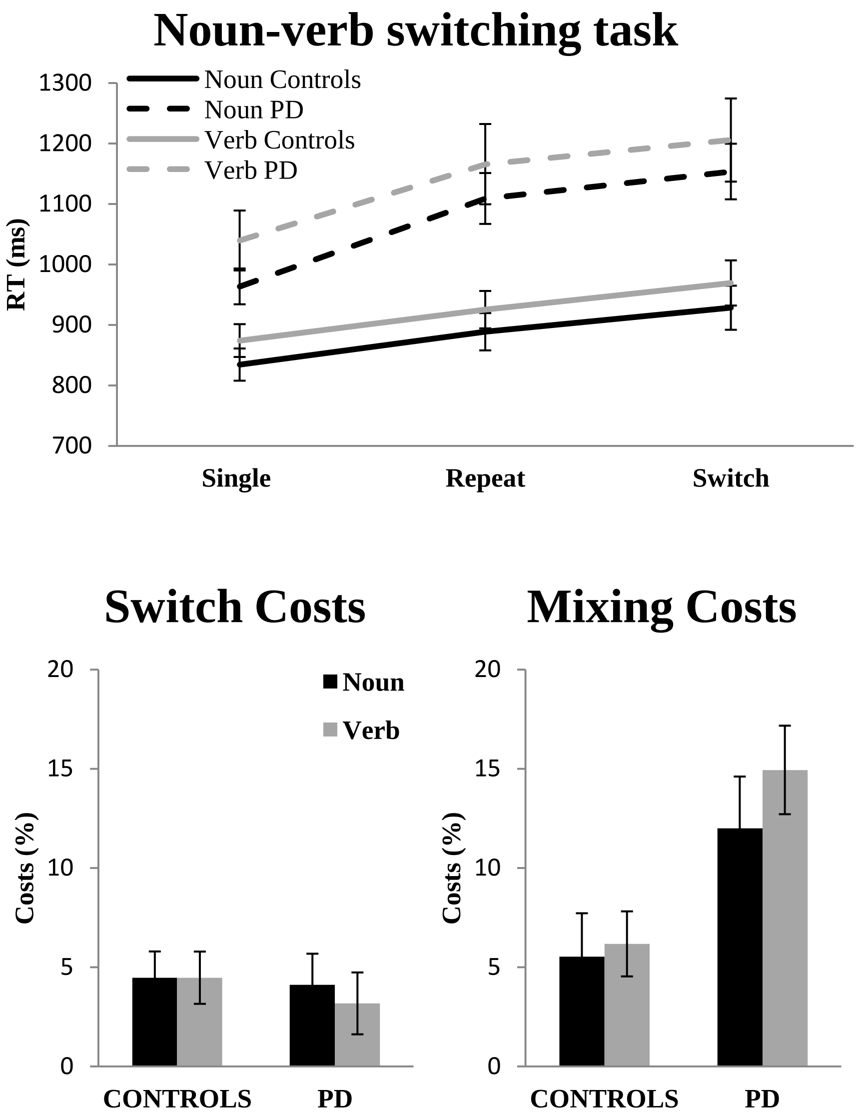

Figure 1. Reaction times and switch and mixing costs in the noun-verb switching task.

Accuracy. The main effect of Type of trial resulted significant [$F(2, 78)=9.59$, $p<0.01$, $\eta p^2=0.20$] and post-hoc analysis revealed that participants were less accurate in switch trials (95.6%) compared to repeat (97.3%, $p<0.01$) and single trials (97.5%, $p<0.01$), but they performed with the same accuracy in these two latter ($p=0.39$; see Table 3). There was no difference in accuracy between L1 (96.6%) and L2 (97.0%) [Language: $F(1,39)=0.58$, $p=0.45$, $\eta p^2=0.01$] and between nouns (97.2%) and verbs (96.5%) [$F(1, 39)=1.81$, $p=0.19$, $\eta p^2=0.04$]. No other main effect or interaction resulted significant.

Table 3. *Accuracy (%) of participants in the noun-verb switching task.*

Noun-verb switching task - Accuracy (%)	PD patients			Controls		
	Mean (SD)			*Mean (SD)*		
	Noun	**Verb**	**Total**	**Noun**	**Verb**	**Total**
Single trials	96.9 (1.9)	97.9 (3.5)	97.4 (2.3)	97.3 (2.5)	97.9 (3.5)	97.6 (2.4)
Repeat trials	96.8 (2.6)	97.2 (6.1)	97.0 (3.8)	97.1 (2.8)	97.9 (3.1)	97.5 (2.7)
Switch trials	95.6 (5.2)	95.0 (6.9)	95.3 (4.9)	95.7 (4.4)	96.3 (6.8)	96.0 (4.2)
Total	96.4 (2.0)	96.7 (4.2)	96.6 (2.8)	96.7 (2.1)	97.4 (3.6)	97.0 (2.6)
Switch costs	1.2 (4.6)	2.2 (3.8)	1.7 (3.1)	1.4 (5.2)	1.6 (4.8)	1.5 (3.2)
Mixing costs	0.1 (2.5)	0.7 (5.6)	0.4 (3.1)	0.2 (3.2)	0 (1.6)	0.1 (1.7)

Language switching task. A repeated measures ANOVA was performed on accuracy and RTs) considering "Type of trial" (single, repeat, switch) and "Language" (L1, L2) as within-subject factors, and "Group" (controls, PD) as a between-subjects factor.

RTs. The main effect of Type of trial was significant [$F(2, 78)=70.45$, $p<0.01$, $\eta p^2=0.64$]. Post-hoc analyses showed that single trials were the fastest (928 ms), switch trials the slowest (1076 ms; $p<0.01$) and repeat trials in between (1017 ms, $ps<0.01$; see Fig. 2). The main effect of Group was also significant suggesting that individuals with PD were overall slower (1080 ms) than controls (934 ms) [$F(1, 39)=8.45$, $p<0.01$, $\eta p^2=0.18$]. Moreover, the interaction between Group and Type of trial was significant [F(2, 78)=8.47, $p<0.01$, $\eta p^2=0.18$] indicating a difference in the magnitude of the costs between the two groups.

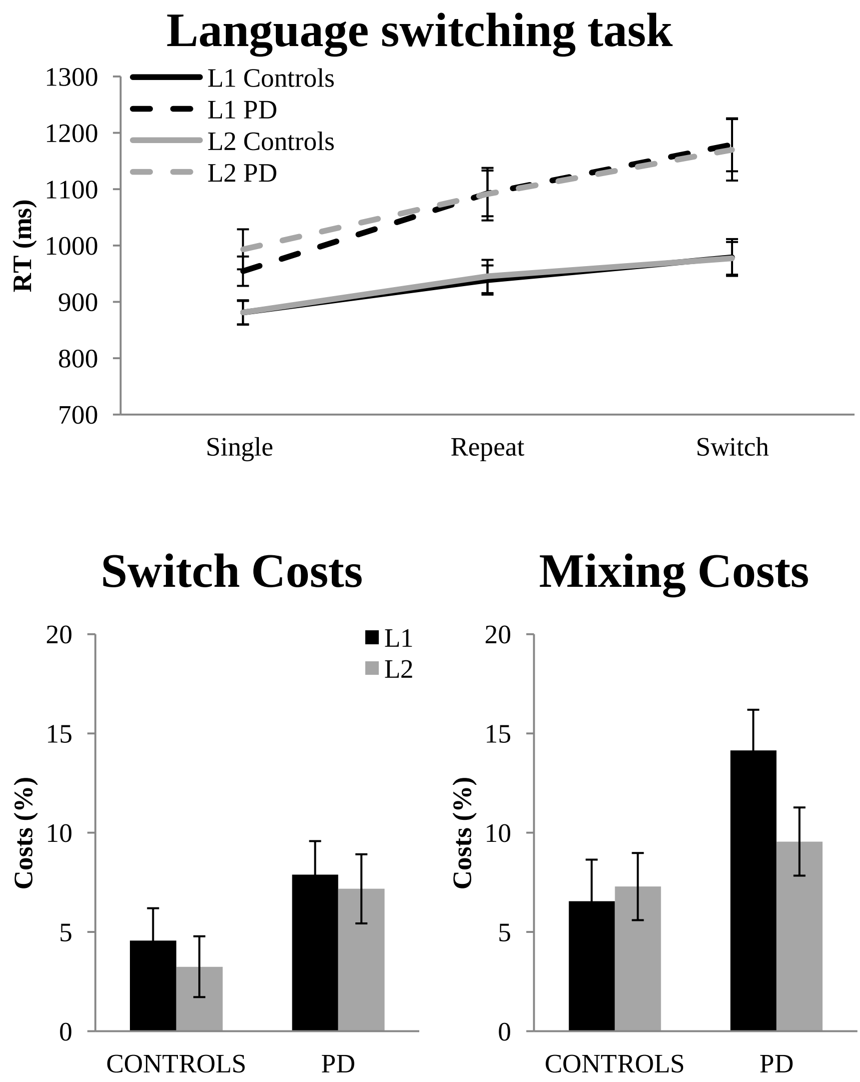

Figure 2. Reaction times and switch and mixing costs in the language switching task.

We therefore analyzed the magnitude of the proportional switch costs and mixing costs with an ANOVA with Group as a between-subjects factor. The results revealed that individuals with PD had increased switch costs compared to controls [7.4% and 3.7% respectively; $F(1, 39)=5.26$, $p<0.05$, $\eta p^2=0.12$], and increased mixing costs [11.7% and 6.8%; $F(1, 39)=4.69$, $p<0.05$, $\eta p^2=0.11$]. No other interaction or main effects resulted significant.

Accuracy. The main effect of Type of trial was significant [Type of trial: $F(2, 78)=22.64$, $p<0.01$, $\eta p^2=0.37$] and post-hoc analysis showed that participants were less accurate in switch trials (91.5%) compared to repeat (96.8%, $p<0.01$) and single (97.5%, $p<0.01$) trials, and performed equally in these two ($p=0.41$; see Table 4). Moreover, individuals with PD were less accurate (93.1%) than controls (97.3%) [Group: $F(1, 39)=5.27$, $p<0.05$, $\eta p^2=0.12$). No other interaction or main effect was significant.

Table 4. *Accuracy (%) of participants in the language switching task.*

Language switching task - Accuracy (%)

	PD patients			**Controls**		
	Mean (SD)			***Mean (SD)***		
	L1	**L2**	**Total**	**L1**	**L2**	**Total**
Single trials	95.7 (6.7)	97.0 (3.9)	96.4 (4.7)	98.9 (2.7)	98.7 (1.6)	98.8 (1.6)
Repeat trials	94.6 (8.7)	95.2 (8.0)	94.9 (8.0)	98.4 (2.2)	99.2 (1.7)	98.8 (1.7)
Switch trials	87.2 (12.6)	90.0 (10.8)	88.6 (10.9)	95.0 (5.7)	93.7 (2.4)	94.4 (4.5)
Total	92.5 (8.3)	94.1 (6.1)	93.3 (7.0)	97.4 (2.6)	97.2 (2.7)	97.3 (1.9)
Switch costs	8.5 (7.0)	7.0 (8.1)	7.8 (5.3)	3.9 (5.4)	5.0 (7.0)	4.4 (4.3)
Mixing costs	1.1 (6.8)	1.8 (7.7)	1.5 (7.0)	0.5 (2.6)	-0.5 (2.5)	0.0 (2.1)

3.1. Linguistic control tasks: comparisons and correlations

To explore the relationship between the mechanisms involved in the two language control tasks we compared and correlated the costs (switch and mixing) obtained. The rationale of this analysis was to explore if mechanisms of proactive and reactive control used to switch between languages (language switching) are the same used in other language control contexts (noun-verb switching).

***Comparison between linguistic tasks*.** A repeated measures ANOVA was performed on the proportional costs (switch and mixing) of the two linguistic tasks. “Task” (noun-verb switching, language switching) was considered as within-subjects factors and “Group” (controls, PD) as a between-subjects factor in the analysis.

For switch costs, the main effects of Task [$F(1, 39)=2.39$, $p=0.13$, $\eta p^2=0.06$] and Group [$F(1, 39)=0.79$, $p=0.38$, $\eta p^2=0.02$] were not significant, but the interaction between Task and Group was [$F(1, 39)=7.59$, $p<0.01$, $\eta p^2=0.16$] (See Fig.3). Post-hoc analysis revealed that controls did not show differences in switch costs between the two tasks (noun-verb switching= 4.8%; language switching= 3.7%; $t(16)=-1.07$, $p=0.30$), however PD patients had larger switch costs in the language switching task (7.4%) compared to the noun-verb switching task (3.4%; $t(23)=2.90$, $p<0.01$).

For mixing costs, we didn’t find a significant main effect of Task [$F(1, 39)=0.25$, $p=0.62$, $\eta p^2<0.01$] but a significant main effect of Group [$F(1, 39)=10.05$, $p<0.01$, $\eta p^2=0.21$]. This indicated that in both tasks PD patients showed an increased mixing cost (noun-verb switching=13.4%; language switching=11.7%) compared to controls (noun-verb switching=3.4%; language switching=6.8%). The interaction between Task and Group was marginally significant [F(1, 39)=2.99, p=0.09, ηp^2=0.07].

Correlations between costs. We ran the correlations of the costs (switch and mixing) between the two tasks. In order to gain more statistical power we ran the correlation with all participants. The results showed a non-significant correlation between the switch costs in the two linguistic tasks (r=0.20, p=0.22; see Fig. 3), but a significant and positive correlation between the two mixing costs (r=0.59, p<0.01, see Fig. 4).

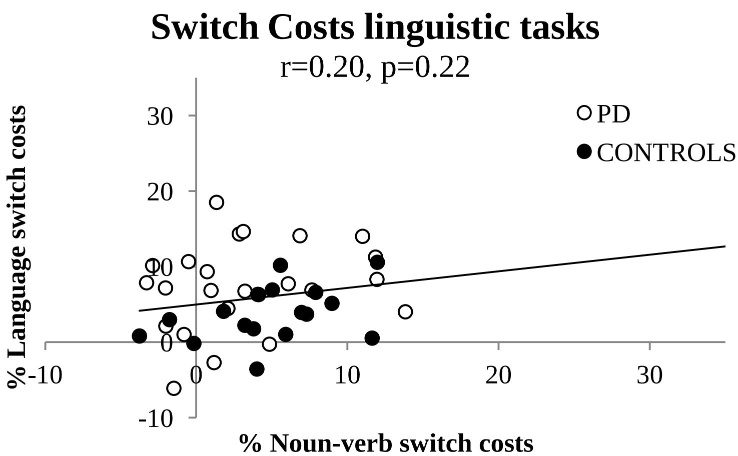

Figure 3. *Correlations of the switch costs of all participants in the two linguistic tasks.*

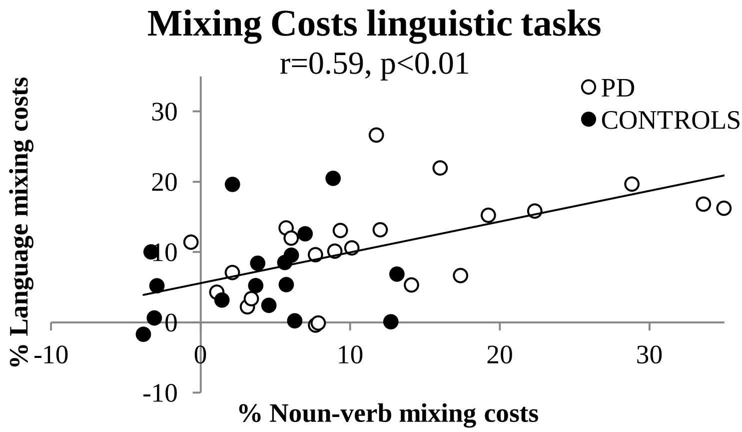

Figure 4. *Correlations of the mixing costs of all participants in the two linguistic tasks.*

When we ran the correlation separately for the two groups we found for PD patients a non-significant correlation between the switch costs in the two linguistic tasks (r=0.22, p=0.30), but a positive correlation between the two mixing costs (r=0.63, p<0.01). For the control group neither the switch costs (r=0.40, p=0.11) nor the mixing costs (r=0.19, p=0.48) were significantly correlated across tasks.

Interim summary of the results. The results from the noun-verb switching task demonstrate that individuals with PD, as compared to controls, were impaired in overall speed of processing and magnitude of mixing costs. The same PD patients behave differently in the language switching task. That is, they showed increased speed of processing, magnitude of both switch and mixing costs an increased error rate when compared to controls.

Therefore, the fact that the same patients show different performances in these two tasks would suggest that, to some extent, the mechanisms involved are not impaired in a similar fashion. Indeed, this is true for the magnitude of the switch costs and the error rate found to be larger in the language switching task but not in the noun-verb switching task for PD patients relative to controls. For mixing costs instead we found that in individuals with PD was increased similarly in both tasks.

This would suggest that while the underlying mechanisms of switch costs are differently involved in the two linguistic tasks, those reflected by mixing cost are similarly engaged in both linguistic contexts.

This consideration is also confirmed by the correlation analysis that revealed that while switch costs in the two tasks do not correlated the mixing costs did.

3.2. Non-linguistic control tasks

N-Back task. We used d' as an individual sensitivity index, calculated as the difference between the Z transformations of the percentages of hits and false alarms (d'= ZHit – ZFA, Macmillan & Creelman, 1990). The percentage of hits was calculated as the proportion of correct responses over the total number of targets, and the percentage of false alarms as the proportion of false alarms over the total number of non-target trials. A repeated measures ANOVA was performed on d' values considering the "Memory load" (n-0, n-

1 and n-2) as within-subjects factor and “Group” (controls, PD patients) as between-subjects factor.

The main effect of Memory load resulted significant [$F(2, 78)=101.74$, $p<0.01$, $\eta p^2=0.72$] and post-hoc analyses indicated that participants were better in the n-0 condition (5.1), compared to the n-1 (3.7, $p<0.01$) and in the n-1 better than in the n-2 condition (1.5, $p<0.01$). The main effect of Group resulted also significant [$F(1, 39)=3.98$, $p=0.05$, $\eta p^2=0.09$] indicating that PD patients performed the task poorer than controls (controls= 3.8; PD= 3.1).

Finally, we found a significant interaction between Memory load and Group [$F(2, 78)=3.01$, $p=0.05$, $\eta p^2=0.07$], suggesting differences in the performance of the two groups, depending on the memory load.

We further analyzed this interaction with a one-way ANOVA for each memory load condition separately. We did not find differences between controls and PD patients in the n-0 [$F(1, 39)=0.77$, $p=0.38$, $\eta p^2=0.02$] and in the n-2 conditions [$F(1, 39)=0.26$, $p=0.61$, $\eta p^2<0.01$]. However, in the n-1 condition we found that PD patients performed significantly worse than controls [$F(1, 39)=7.16$, $p<0.05$, $\eta p^2=0.16$; 3.1 and 4.4 respectively; see Table 5].

Table 5. *Performances of participants in the n-back task broken by memory load condition. Mean d' values and standard deviations.*

Memory load condition	PD Patients	Controls
	Mean (SD)	***Mean (SD)***
n-0	4.9 (1.9)	5.4 (1.2)
n-1	3.1 (1.5)	4.4 (1.6)
n-2	1.5 (0.7)	1.6 (0.6)

Spatial Stroop Task. We performed for each of the two conflict conditions a repeated measure ANOVA on accuracy and RTs considering the variable "Type of trial" (congruent, incongruent) as a within-subjects factor, and "Group" (controls, PD) as a between-subjects factor. The analyses were performed for the low conflict condition (75% of congruent trials, 25% of incongruent trials) and high conflict condition (25% of congruent trials, 75% of incongruent trials) separately.

Mostly congruent condition (75% congruent trials, 25% incongruent trials). For RTs, we found a significant main effect of Type of Trial, suggesting that participants performed slower in incongruent trials (824 ms) compared to congruent ones (703 ms) [$F(1, 39)=80.89$, $p<0.01$, $\eta p^2=0.67$]. However, neither the Group main effect [$F(1, 39)=1.01$, $p=0.32$, $\eta p^2=0.02$] nor the interaction between Type of Trial and Group resulted significant [$F(1, 39)=2.58$, $p=0.12$, $\eta p^2=0.06$], indicating no differences in the magnitude of spatial Stroop effect between groups (See Table 6).

For accuracy, also the main effect of Type of Trial was significant, indicating that participants were less accurate in incongruent trials

(93.6%) than in congruent (98.4%) ones [$F(1, 39)=26.58$, $p<0.01$, $\eta p^2=0.40$]. However, the main effect of group [$F(1,39)=1.83$, $p=0.18$, $\eta p^2=0.04$] and the interaction Type of trial x group [$F(1,39)=1.39$, $p=0.24$, $\eta p^2=0.03$] were not significant.

Mostly incongruent condition (25% congruent trials, 75% incongruent trials). For RTs, the main effects of Type of trial [$F(1, 39)=1.61$, $p=0.21$, $\eta p^2=0.04$] and the main effect of Group [$F(1, 39)=1.88$, $p=0.18$, $\eta p^2=0.05$] were not significant. However, we found a significant interaction between Type of Trial and Group [$F(1, 39)=9.01$, $p<0.01$, $\eta p^2=0.19$], indicating differences in the magnitude of spatial Stroop effect. We then compared the two groups of participants for the proportional spatial Stroop effect (RTs of the incongruent minus the congruent condition divided by the RTs of the congruent condition). The results showed that PD patients had increased costs compared to controls [$F(1, 39)=8.65$, $p<0.01$, $\eta p^2=0.18$] (See Table 6). Moreover, controls showed a negative cost (-3.3%) marginally different from zero [$t(16)=-2.00$, $p=0.06$] whereas PD patients showed a cost (2.7%) significantly different from zero [$t(23)=2.14$, $p<0.05$].

For accuracy, the main effect of Type of Trial was not significant [$F(1, 39)=0.44$, $p=0.51$, $\eta p^2=0.01$] revealing that participants were equally accurate in congruent (92.5%) and incongruent trials (93.3%). Also the main effect of Group [controls: 93.3%, PD: 92.5%; $F(1,39)=0.09$, $p=0.76$, $\eta p^2<0.01$] and the interaction Type of trial x group [$F(1,39)=2.22$, $p=0.14$, $\eta p^2<0.01$] were not significant.

Table 6. *Performance of participants in the spatial Stroop task. Mean RTs and standard deviations.*

	PD Patients	Controls
	MEAN (SD)	**MEAN (SD)**
Mostly congruent condition		
RT's congruent trials	658 (152)	748 (262)
RT's incongruent trials	801 (195)	847 (274)
Spatial Stroop effect (ms)	142 (79)	99 (92)
Spatial Stroop effect (%)	21 (10)	15 (14)
Mostly incongruent condition		
RT's congruent trials	747 (197)	867 (258)
RT's incongruent trials	763 (193)	829 (224)
Spatial Stroop effect (ms)	15 (50)	-38 (63)
Spatial Stroop effect (%)	3 (6)	-3 (7)

3.3. Linguistic and non-linguistic EC tasks: correlations

To explore the relationship between the mechanisms of language control and EC mechanisms we correlated the linguistic costs with the performance in the n-back and the spatial Stroop tasks. The hypothesis was that if the underlying mechanisms of proactive language control are related to working memory and/or monitoring we should expect a significant correlation between the magnitude of the mixing costs and the performance in the n-back task and spatial Stroop Task.

For reasons of clarity and simplicity in what follows we will report only significant correlations.

N-back task. When all participants were considered, d' values of the n-1 condition negatively correlated with the noun-verb mixing costs (r=-0.49, p<0.01; Fig.4) and marginally with the language mixing costs (r=-0.25, p=0.06; Fig.5). When we ran correlations in PD patients, we found that only the noun-verb mixing costs significantly correlated with d' values in the n-1 condition (r=-0.53, p<0.01). For controls none correlation resulted significant.

Spatial Stroop task. When all participants were considered, the proportional spatial Stroop effects (mostly incongruent and mostly congruent conditions) were marginally significant correlated with the noun-verb mixing costs (r=0.24, p=0.06) and with the language mixing costs (r=0.27, p=0.05; see Fig.5) respectively. However, when we ran the correlations for the two groups separately we did not found any significant correlation.

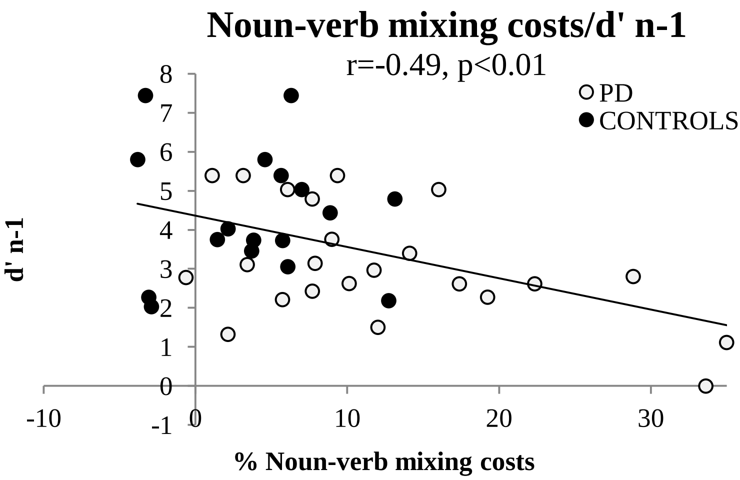

Figure 5. *Correlations of the mixing costs of all participants in the noun-verb switching tasks with the n-back task.*

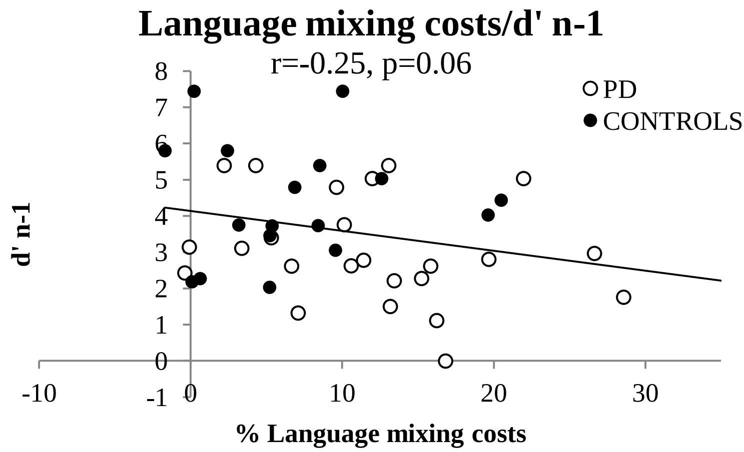

Figure 6. *Correlations of the mixing costs of all participants in the language switching tasks with the n-back task.*

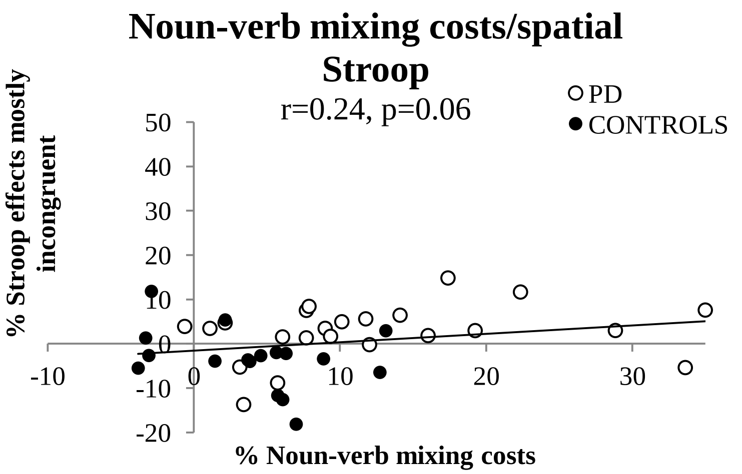

Figure 7. *Correlations of the mixing costs of all participants in the noun-verb switching tasks with the spatial Stroop effect in the mostly incongruent condition.*

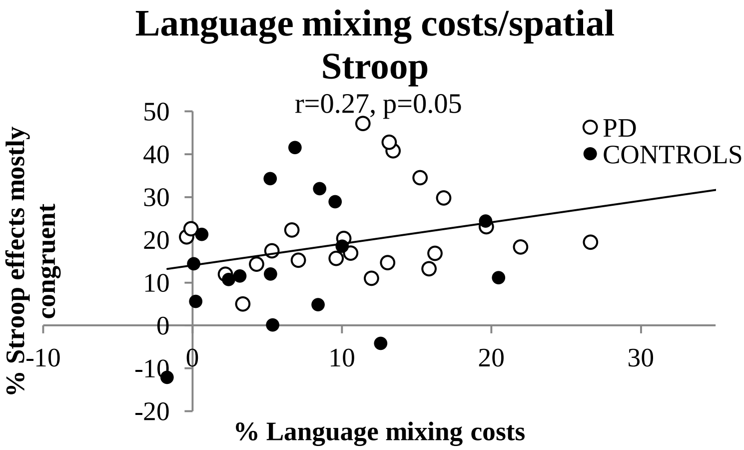

Figure 8. *Correlations of the mixing costs of all participants in the language switching tasks with the spatial Stroop effect in the mostly congruent condition.*

4. Discussion

In this study we investigated the nature of bLC mechanisms by exploring their overlap with other domains of control. Specifically, with language control when the two languages are not involved and with two EC components, working memory and conflict monitoring. The results are discussed below separately for the overlap with language control and EC.

4.1. Reactive and proactive control in the linguistic domain

Switch and mixing costs were the two indexes used to measure reactive and proactive control in our participants. For these two measures we observed dissociations between tasks. Indeed, the magnitude of switch costs increased in PD patients compared to controls in the language switching task but not in the noun-verb switching task. For mixing cost instead we observed that PD patients were similarly impaired in both tasks. Thus, the dissociation of impairments for switch cost suggests that reactive control is specific to bLC. Moreover, support to this findings come from the non-significant correlation between switch costs in the two linguistic tasks.

Interestingly, this specificity of the reactive control to bLC is consistent with previous studies that also found no correlation between linguistic and non-linguistic switch cost or differential effects of aging for the two domains (Calabria et al., 2013, 2011; Cattaneo et al., 2015; Prior & Gollan, 2013; Weissberger et al., 2012).

In contrast, given that mixing cost was similarly impaired in both tasks this suggests that proactive control is a shared mechanism in different domains of language control.

The domain-general nature of proactive control confirmed the observation of our previous study in which we found overlap between bLC and EC in PD for these control mechanisms (Cattaneo et al., 2015).

One way to explain this result is based on the role of basal ganglia in bilingual language production. According to the results of Abutalebi et al. (2008)'s study the left caudate was specifically activated when German-Italian bilinguals switched between languages but not when participants were asked to switch between naming objects or actions in the same language. Similarly, our results show that when basal ganglia are affected by a neurodegenerative disease, as in our PD patients, only reactive mechanisms needed for language switching are affected.

Then the question is whether the reactive control impaired by PD might be explained in terms of inhibitory mechanisms, as proposed by the IC model (Green, 1998). According to the IC model, these mechanisms would be domain-general and therefore they should overlap with those of the EC system. However, our current and previous data does not support a domain-general nature of reactive control mechanisms of bLC. Thus these mechanisms could not be explained in terms of inhibition as proposed by the IC model (for reviews, see also Bobb & Wodniecka, 2013; Declerck & Philipp, 2015). Indeed, reactive control has been also explained by alternative accounts such as the results of persisting activation mechanisms (Philipp, Gade, & Koch, 2007) or as different types of inhibitory control systems (e.g., Colzato et al., 2008).

Our results seem to suggest that whatever the mechanisms of reactive control are, they are not involved in other linguistic contexts in which bilinguals do not switch between the two languages. One possible explanation relies on what proposed by neural models of bLC for basal ganglia, as also the brain region supposed to be affected by PD. For instance, according to what proposed by Abutalebi & Green (2008, 2016) basal ganglia would be in charge of managing cross-language interference and supervising the selection of the correct language. Therefore, reactive control in language switching contexts might rely on specific mechanisms of response selection or conflict resolution between the two languages, but not on other types of control.

Conversely, our results show that proactive control was not modulated by the language context, as it was similarly affected in patients when required to switch between languages or between grammatical categories. Also, in contrast to what we found for switch costs, mixing costs correlated between two versions of the linguistic tasks. Moreover, as we reported in our previous study with PD patients, linguistic proactive control overlapped with non-linguistic proactive control (Cattaneo et al., 2015). Indeed, we found a correlation between linguistic and non-linguistic mixing costs, suggesting a domain-general nature of proactive control (for similar results see Prior & Gollan, 2013). Therefore, the domain-general nature of the proactive control, in contrast to the specificity of reactive control, may reflect the need to manage globally the levels of activation of task-sets, linguistic or not.

Differences between the mechanisms at play according to language context have been proposed also by Green and Abutalebi (2013) in their "adaptive control hypothesis". According to this hypothesis, the involvement of language control mechanisms would be flexible and their engagement would depend on the interactional context. That is, in a single-language context bilinguals reduce (or eliminate) the cross-language interference whereas in the dual-language context several mechanisms would be involved such as task goal maintenance, conflict monitoring, and interference resolution. This second context, the more demanding one, would also require more flexibility in order to change the goal (speak in language B) in response to environmental cues. Therefore, the differential engagement of proactive and reactive control might adapt to the context, that is, is dependent on the demand of the interactional contexts.

4.2. Language control and EC components

Our second aim was to explore the overlap of proactive and reactive language control with working memory and conflict monitoring. As mentioned before, we used these two EC components because they have been proposed as the two mechanisms most related to proactive control (Braver et al., 2003; Kray & Lindenberger, 2000; Mayr, 2001; Rogers & Monsell, 1995; Pettigrew & Martin, 2015; Rubin & Meiran, 2005; Philipp, Kalinich, Koch, & Schubotz, 2008; Prior & Gollan, 2013; Prior & Macwhinney, 2010).

Our results suggest that proactive language control mechanisms are functionally linked to working memory abilities and to monitoring, to a lesser extent. However, reactive control appears to be completely unrelated with these EC components.

Indeed, despite PD patients having scored poorer than controls in n-back task and in the spatial Stroop task, as expected based on previous studies (Bradley, Welch, & Dick, 1989; Metzler-baddeley, 2007; Owen et al., 1993, 1995; Owen, Iddon, Hodges, Summers, & Robbins, 1997; see Pagonabarraga & Kulisevsky, 2012 for a review), different patterns of correlations were found for proactive and reactive control. That is, proactive control significantly correlated with EC tasks while reactive control didn't.

Specifically, the performance of participants in the n-back task (n-1 memory load condition) negatively correlated with linguistic mixing costs, more consistently in patients and for the noun-verb switching task. For conflict monitoring the results were less clear because the correlations with mixing costs were less strong and only significant when all participants (patients and controls) were included. Therefore, if anything, it seems that the results from the correlations would support the proposal that proactive language control reflects working memory mechanisms, such as the demand to maintain goals available in a dual-task situation (Braver et al., 2003; Kray & Lindenberger, 2000; Mayr, 2001; Rogers & Monsell, 1995; Pettigrew & Martin, 2015).

To further confirm this observation we assessed the correlation with some of the neuropsychological measures of EC. Interestingly, we found significant correlations between mixing costs in both linguistic tasks and the backward digit span (noun-verb switching= $r=-0.50$, $p<0.01$; language switching= $r=-0.33$, $p<0.05$), supposed to measure working memory efficiency (Lefebvre, Marchand, Eskes, & Connolly, 2005). Instead the correlation with the other EC test (Trial Making Test, TMT) was only found to significantly correlate with the mixing cost in the noun-verb switching task (TMT part A= $r=0.30$, $p<0.05$; TMT part B= $r=0.44$, $p<0.01$).

The role of working memory in language processing has also been proposed in several contexts. From Baddeley and Hitch (1974) to more recent views, most of them consider working memory as a cognitive process in charge of controlling and maintaining information available during language learning, comprehension, reading, writing and speech production (Baddeley, 2003; Baddeley, Gathercole, & Papagno, 1998; Collette, Van der Linden, & Poncelet, 2000; Van der Linden et al., 1999). Specifically with regards to speech production, some models proposed working memory as having a central role in word planning, maintaining and updating the task goal driving lexical selection. In the same line, specific language impairments or difficulties in word production have been explained as due to limited capacity of working memory (see Roelofs & Piai, 2011; Weismer, Plante, Jones, & Tomblin, 2005; for reviews). Recently, it has also been shown its role in managing lexical-semantic interference (Belke, 2008) and in high demanding conditions such as dual-task interference (Piai & Roelofs, 2013). Similarly, in the context of bilingualism the involvement of working memory has been related to more demanding situations such as second language (L2) processing (e.g., Ardila, 2003; Harrington, 1992; McLaughlin, 1995; Linck, Osthus, Koeth, & Bunting, 2014).

However, given the relation of working memory and proactive control it seems more reasonable to explain this link in terms of updating and top-down mechanisms at play in demanding contexts. For instance, it has been proposed that updating abilities are necessary for task goal maintenance and reconfiguration of set trial by trial (Shao, Roelofs, & Meyer, 2012; Unsworth, Redick, Lakey, & Young, 2010). Therefore, as proactive control is reflected by the mechanisms at play by comparing dual task (mixed blocks) versus single task (single blocks) conditions, it seems reasonable that updating is one of such underlying abilities.

Conversely, our results seem to suggest that conflict monitoring is less related to proactive control. One of the possible reasons of the weaker correlations found between mixing costs and the performance in spatial Stroop task might be that the two tasks differ in terms of material, that is, verbal versus non-verbal.

Or, it is also possible that monitoring is at play to a smaller extent to resolve conflict at the stimulus or response level in linguistic tasks (Branzi, Della Rosa, et al., 2016). Indeed, Branzi et al. (2016) found that monitoring processes are involved in language control only during L2 production in bilinguals with a rather unbalanced use of the two languages. Therefore, this suggests that the involvement of non-linguistic control in language production may be modulated by the bilinguals’ linguistic experience. Given that our participants were highly proficient bilinguals and used to frequently switch between languages in their everyday life, it might be the case that monitoring is engaged to a lesser degree than in other types of bilinguals (Prior & Gollan, 2011; Rodriguez-Fornells, Krämer, Lorenzo-Seva, Festman, & Münte, 2011).

To conclude, this study contributes to advancing our knowledge of the bLC in two ways. First, we showed that proactive control compared to reactive control has a less specific nature in the context of language control. Second, our results seem to suggest that proactive control mechanisms are functionally linked to working memory abilities and to monitoring to a lesser extent.

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3. GENERAL DISCUSSION

The general aim of this thesis was to explore the nature of the control mechanisms involved in bilingual language production. The approach was to investigate their relation with those of the domain-general EC and those involved in language control but without language switching. Given the complexity of the control system, the focus was mainly on two types of mechanisms, namely proactive and reactive control. Indeed, these are the two types of control that are now suggested as being behind switching abilities in different control domains.

The research has been conducted with PD patients that offered the possibility to explore these different types of control in terms of similar or differential impairment across domains. Moreover, a further way to investigate this issue was to correlate the individuals' performance across tasks for reactive and proactive control.

The main findings of this dissertation can be summarized as follows:

1. Reactive control mechanisms are specific to bLC. This result has been consistently found both in the first and in the second study. Indeed PD patients showed higher switch costs compared to healthy controls in language switching, but not in the noun-verb switching or in non-linguistic task switching.
2. Proactive control mechanisms are domain-general. Indeed PD patients showed higher mixing costs in all the three versions of the switching tasks used.

Moreover, correlational analyses confirmed this pattern of associations and dissociations across tasks for the two types of control. That is, non-significant correlations were found for switch costs but significant for mixing costs.

3. Working memory and conflict monitoring are two EC processes that may underline proactive control. Evidence of this comes from significant correlations found between mixing costs in the linguistic switching tasks and the performance in n-back and spatial Stroop tasks.

In the next sections, I will discuss in more detail these findings and their implications for the control system in the bilingual language production.

3.1 Reactive control and its domain-specific nature

One of the most debated issues in the context of bilingualism is whether bLC is an instance of other mechanisms of control in the linguistic domain or domain-general EC. One of the most influential models, such as ICM (Green, 1986, 1998), proposes that inhibitory control mechanisms used by bilinguals in lexical selection are the same as those for domain-general EC.

In the first study, I specifically explored this overlap in high proficient Catalan/Spanish individuals affected by PD, and healthy controls, using a linguistic and non-linguistic switching task. The hypothesis was that if the same EC control mechanisms are involved in bLC, I should find similar impairments (increased costs) in patients compared to healthy controls. The hypothesis of similar impairments of the two systems was based on two types of evidence. First, PD affects the functioning of brain areas involved in both bLC and EC (Abutalebi & Green, 2007). Second, the contribution of the EC deficits in linguistic impairment in PD patients (for reviews see Altmann & Troche, 2011; Murray, 2008; Colman & Bastiaanse, 2011).

The results revealed that PD patients, compared to controls, had increased switch and mixing costs in the language switching task. They also made more errors and were more prone to produce cross-language intrusions in switch trials. Therefore this suggests that PD patients were impaired in selecting and preparing the correct response when required to reconfigure the language set. However, this was not the case for the non-linguistic task, in which their switch costs were similar to controls. This integrity of non-linguistic reactive control was also true for those patients that made more errors and have EC deficits in neuropsychological EC tests, such as the Trial Making Test and letter fluency.

Furthermore, the switch costs across tasks were uncorrelated, similar to what has been reported in young and older healthy bilinguals (Branzi, Calabria, Boscarino, & Costa, 2016; Calabria, Branzi, Marne, Hernández, & Costa, 2013; Calabria, Hernandez, Branzi, & Costa, 2011).

Therefore, the differential impairment in the two tasks and the lack of correlation between the indexes of reactive control suggest that bLC and domain-general EC mechanisms do not overlap for these control mechanisms.

Interestingly, results from the second study shows that reactive control mechanisms of bLC are also not overlapping with those used in other language control contexts. In the second study, the comparison was between a language switching task and a noun-verb switching in one language.

Once again the hypothesis was that if the same mechanisms of control are equally engaged in the two linguistic tasks, I should find similar impairments in both tasks for PD patients.

However, the differential impairments found in the two tasks suggest an incomplete overlap of the switch mechanisms. Indeed PD patients, compared to controls, showed increased switch costs only when they switched between languages.

Therefore, the specific impairment of PD patients in reactive control in language switching seems to suggest that they have specific difficulties in managing cross-language interferences and/or response language reactivation. This evidence indicates a further specificity within the linguistic domain. That is, reactive control mechanisms of bLC seem not only specific to the linguistic domain (as seen in the first study), but also engaged only when both languages are highly activated.

One may consider these mechanisms as inhibitory control, but probably not as proposed in the ICM by Green. Indeed, according to the ICM, inhibition involved in bLC is an instance of that one used in non-linguistic control. However, the results from our PD patients do not support this view. That is, our results seem to support the view that highly domain-specific mechanisms are at play during bilingual language production, at least for inhibitory/reactive control.

Other models have been proposed as alternative views for explaining the nature of these control mechanisms used by bilinguals (Costa & Caramazza, 1999; Finkbeiner, Gollan, & Caramazza, 2006; La Heij, 2005). For instance, some of them have suggested that lexical access, at least in high proficient bilinguals, is not implemented by domain-general EC mechanisms but by language specific selection mechanisms (Costa & Santesteban, 2004; Schwieter & Sunderman, 2008). It has also been proposed that as L2 proficiency increases, bilinguals shift from the use of EC mechanisms (e.g., inhibition) to more language-specific mechanisms ("selection by proficiency model", Schwieter & Sunderman, 2008).

Therefore, reactive control should be explained in a different way than that proposed by the IC model (inhibition; for reviews, see also Bobb & Wodniecka, 2013; Declerck & Philipp, 2015). The alternative accounts that have tried to explain the underlying mechanisms of switch costs have proposed other types of inhibitory control systems (e.g., Colzato et al., 2008) or persisting activation

(Altmann & Gray, 2008; MacLeod, 2003; Philipp, Gade, & Koch, 2007), as possible mechanisms.

Concretely, switch costs may be generated by the carry-over effect of the persisting activation of the previously used language. In this view, the extra time needed to change language would be the time needed to overcome this persistent activation (see Koch, Gade, Schuch, & Philipp, 2010 for a review about alternative interpretations of the switch cost).

Similarly, in the task switching literature, Yeung and Monsell (2003) proposed that switch cost reflects mechanisms of active control (activation) and priming. Active control serves to increase the activation of the currently relevant task-set while priming represents the temporal persisting activation of the previously performed task. In this view, switch costs are generated by extra-activation of the relevant task-set to overcome the aftereffects (priming) generated by the previous trial.

However, in order to reconcile these different interpretations, it has also been proposed that switch costs may result from balancing between both activation and inhibition mechanisms (for reviews see Koch et al., 2010; Monsell, 2003).

To conclude, all in all the results from both studies do not support those proposals that consider the nature of reactive mechanisms involved in bilingual language production as domain-general.

Future models of bilingual language production should take into account this specificity, and future research needs to investigate the possible factors that modulated reactive control of bLC to further detail its components.

3.2 Proactive control and its domain-general nature

Besides explore reactive control, both studies also investigated the overlap between proactive control mechanisms in language and non-linguistic domains. Again, the hypothesis was that if the same proactive mechanisms are involved in the different tasks I should find similar impairments in PD patients compared to healthy controls.

In the first study, the results showed similar increased mixing costs in language switching and non-linguistic switching, in particular for more EC impaired patients. Therefore, as opposed to reactive control, these results suggest a domain-general nature of proactive control mechanisms, indexed by the mixing cost.

Moreover, this overlap of the control mechanisms was supported by the significant correlation between mixing costs in the two tasks, in line with what was found for young bilinguals (Prior & Gollan, 2013).

The second study showed that proactive control mechanisms of bLC are also overlapping with those of general language control engaged in different linguistic contexts. Indeed, PD patients showed similar impairments (increased mixing costs) in both the language switching and in the noun-verb switching task. Moreover, as in the first study, we found a positive correlation between mixing costs, especially for PD patients.

Therefore, the consistency of the results from both studies suggests that proactive mechanisms are domain-general. That is, these mechanisms are at play irrespective of the domain of control. However, the concept of proactive control has been used for many different tasks in the context of EC and it is a broad term in which its nature is not completely clear.

For some authors, it reflects the working memory demand to maintain the task sets active during multitasking situations (e.g., mixed blocks in task switching; Braver et al., 2003; Kray & Lindenberger, 2000; Mayr, 2001; Rogers & Monsell, 1995; Pettigrew & Martin, 2015). Alternatively, it has been suggested that it reflects a set of mechanisms in charge of monitoring and resolving the conflict between interfering stimulus dimensions (Rubin & Meiran, 2005; Philipp, Kalinich, Koch, & Schubotz, 2008; Prior & Gollan, 2013; Prior & Macwhinney, 2010). In order to disentangle its nature, based on these two proposals, I examine the performance of PD patients in two EC tasks supposed to tap into working memory and conflict monitoring.

The results showed that mixing costs in the two linguistic tasks correlated with the d' values of the working memory task (n-1 load condition) more consistently for PD patients. Conversely, mixing costs correlated with the performance in the conflict monitoring task (spatial Stroop) only when all participants were considered in the analysis.

Therefore, the fact that the correlations with the n-back were more consistent suggests that working memory could have a more important role in proactive control mechanisms. This is not surprising given the evidence indicating that working memory is related to bilingual language processing especially in more demanding and controlled contexts (e.g., Ardila, 2003; Harrington, 1992; McLaughlin, 1995; Linck, Osthus, Koeth, & Bunting, 2014). Moreover, working memory is also one of the EC functions in which bilinguals outperform monolinguals (Bialystok, Poarch, Luo, & Craik, 2014; Tse & Altarriba, 2014; for a meta-analysis see Grundy & Timer, in press), indicating a potential link between EC and bLC.

However, the less consistent correlation between mixing costs and the performance in conflict monitoring would indicate a partial contribution of this mechanism in proactive control. One possibility is that it reflects the flexibility of the control system in demanding situations. Hence, given that it seems less correlated to linguistic tasks, it is possible that monitoring is at play to a little extent in these tasks of language control, or less involved because these are not really demanding conditions for highly proficient bilinguals (Branzi, Della Rosa, Canini, Costa, & Abutalebi, 2016). For instance Branzi et al. (2016) found that monitoring processes were involved in language control only during more demanding L2 production in bilinguals with an unbalanced use of the two languages.

However, it is important to acknowledge that the correlations between the EC tasks and proactive control were not so strong in terms of power, leaving open the possibility that both or other mechanisms might contribute to this set of control abilities. Then the question is whether they are exclusively engaged for language control, or used according to the degree of task demand.

All in all, the fact that proactive language control was correlated to these EC processes once again suggests its domain-general nature. Furthermore, the similar pattern of results in the three switching task seems to indicate its involvement in maintaining and adjusting the goals of two tasks, being either languages, grammatical categories or non-linguistic tasks.

The findings of an overlap between language control abilities and EC may also offer a way to understand the origin of the debated nature of the bilingual advantage. Indeed one of the main hypotheses behind it is that the constant use of bLC transfers its positive effect to EC, making bilinguals more efficient on performing non-linguistic control tasks than monolinguals (Bialystok, Craik, Green, & Gollan, 2010). In this view, proactive control and its underlying EC mechanisms may be therefore one of the locus of such bilingual advantage, given the overlap of the two systems. Indeed some interpretations of the positive effect of bilingualism on EC indicate that it is the case for tasks supposed to involve proactive control (Wiseheart, Viswanathan, & Bialystok, 2016) but also working memory (Bialystok et al., 2014; Tse & Altarriba, 2014) and monitoring (Costa, Hernandez, Costa-Faidella, & Sebastian-Galles, 2009).

However, given that the presence of the bilingual advantage has been extensively questioned, this is a speculation that is not completely supported by experimental evidence (for reviews see (Hilchey & Klein, 2011; Paap & Greenberg, 2013; Valian, 2015).

3.3 Implications for language impairments in bilingual Parkinson's disease patients

Despite the fact that the main aim of this thesis was not specifically to investigate the language deficits of PD patients, some findings also have implications in this sense. Moreover, this is of great interest since the evidence of language impairments in PD mostly comes from monolingual speakers (for reviews see Altmann & Troche, 2011; Murray, 2008; Colman & Bastiaanse, 2011).

Only a few studies explored the impact of PD in bilingual language processing. Two studies showed that PD led to difficulties in syntactic sentence comprehension, and one study also demonstrated spontaneous speech deficits in these patients (Johari et al., 2013; Zanini et al., 2004; Zanini, Tavano, & Fabbro, 2010). Particularly consistent across studies is the evidence of differential language impairment, where the first and dominant language was the most affected.

The general interpretation of such impairment relies on a deficit of procedural memory. According to Ullman's proposal (1997, 2001) the dominant and early acquired language is learned implicitly and depends more on procedural memory, while a second language acquired late and explicitly (e.g., at school) depends on declarative memory. Given that the procedural memory is processed by the fronto-basal ganglia network, this explains why bilingual PD patients have grater deficits in the dominant language.

However, in one study by Zanini et al. (2004) a correlation was found between the individuals' performance in linguistic and non-linguistic EC tasks. Therefore, this result might indicate that, at least in part, EC deficits have contributed to the comprehension deficits, as suggested in other studies with monolingual PD and sentence processing (Grossman, Lee, Morris, Stern, & Hurtig, 2002; Hochstadt, Nakano, Lieberman, & Friedman, 2006).

Similarly, also aphasic bilinguals sometimes show asymmetrical impairments where the dominant language is more affected than their non-dominant language after subcortical damage (Adrover-Roig et al., 2011; Aglioti & Fabbro, 1993; Abutalebi et al., 2000; Garcia, Barquero, & Egido, 2010; Mariën et al., 2005). Also in these cases it has been suggested that the differential language impairment might have its origins in EC dysfunctions (Adrover-Roig et al., 2011; Kong et al., 2014; Leemann et al., 2007). Currently, the idea that non-linguistic control may contribute to the pattern of language impairment and recovery after brain damage is one of the more focused issues in bilingual aphasia research (Green et al., 2010; Dash & Kar, 2014; Gray & Kiran, 2016; Verreyt, De Letter, Hemelsoet, Santens, & Duyck, 2013).

Interestingly, our bilingual PD patients in language switching showed an increased error rate and cross-language intrusions particularly in their L1. However, this differential impairment was restricted only to more demanding conditions such as language mixed naming and letter fluency, a neuropsychological test that requires more EC efforts.

In the context of neurodegenerative diseases, one open question is about how this differential language impairment is disease specific. That is, to which extent can we expect to find it in other diseases having different neuropathologies and cognitive symptoms that are not always related to EC. For instance, studies with Alzheimer's disease (AD) have found that in most cases, patients have a parallel impairment of the two languages (for a review see Stilwell, Dow, Lamers, & Woods, 2016; see also Calabria et al., 2016 in appendix I for our recent longitudinal study). Moreover, when differential language impairment has been found in AD patients, it was more for the L2, and to our knowledge, only one study reported a more affected L1 (Gollan, Salmon, Montoya, & da Pena, 2010).

Finally, the degree of demand on control mechanisms might contribute to showing differential linguistic deficits. For instance, when PD patients were tested in naming in the first study, they scored the same in both languages. Specifically, they were tested in action and object naming, the two grammatical categories that sometimes dissociate in these patients (Bertella et al., 2002; Cotelli et al., 2007; Rodríguez-Ferreiro, Menéndez, Ribacoba, & Cuetos, 2009). Our participants however scored similarly in action and object naming, but importantly without difference between languages.

Therefore, these results suggest that only more demanding situations of language production would lead to relative different impairment of the two languages. This is a sort of speculation that comes from the comparison of the performance of PD patients in simple naming and in language switching condition. However, given the limited number of studies with bilingual PD patients, it is hard to conclude something definitive on this issue.

3.3 Conclusions

The studies presented in this thesis aimed to advance our knowledge about the nature of mechanisms of bLC. First, it has been found that reactive mechanisms of bLC are not overlapping with those of other domains of control. These mechanisms indeed seem to be engaged only when both languages are highly activated and must be used, namely a dual-language context. Second, proactive control is domain-general in nature and it overlaps across domains. Moreover, this type of control seems to be related to working memory and conflict monitoring.

Finally, PD patients show language production deficits, especially in more demanding situations, highlighting the importance of EC in the interpretation of language deficits.

These findings have clear implications for a more general framework of bilingual language production which includes non-linguistic components. Indeed the effort to study language control and EC in bilinguals together has helped clarify what the first may contribute on the second. Moreover, this opens new perspectives on how to integrate both systems but also on the study of bilingualism and neurodegenerative diseases.

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Appendix A

Language deterioration in bilingual Alzheimer's disease patients: A longitudinal study

Calabria M, Cattaneo G, Marne P, Hernández M, Juncadella M, Gascón-Bayarri J, et al. Language deterioration in bilingual Alzheimer's disease patients: A longitudinal study. J Neurolinguistics. 2017 Aug 1;43:59–74. DOI: 10.1016/j.jneuroling.2016.06.005