Neuropsychologia 66 (2015) 99–110

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

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

Gabriele Cattaneo [a,*], Marco Calabria [a], Paula Marne [a], Alexandre Gironell [b], Jubin Abutalebi [c,d], Albert Costa [a,e]

[a] Center for Brain and Cognition, Pompeu Fabra University, Barcelona, Spain
[b] Movement Disorders Unit, Neurology Department, Sant Pau Hospital, Barcelona, Spain
[c] University San Raffaele, Milan, Italy
[d] Division of Speech and Hearing Sciences, University of Hong Kong, Hong Kong
[e] ICREA, Institució Catalana de Recerca i Estudis Avançats, Barcelona, Spain

ARTICLE INFO

Article history:
Received 24 July 2014
Received in revised form
4 November 2014
Accepted 6 November 2014
Available online 11 November 2014

Keywords:
Bilingualism
Parkinson's disease
Executive control
Bilingual language control

ABSTRACT

The basal ganglia are critically involved in language control (LC) processes, allowing a bilingual to utter correctly in one language without interference from the non-requested language. It has been hypothesized that the neural mechanism of LC closely resembles domain-general executive control (EC). The purpose of the present study is to investigate the integrity of bilingual LC and its overlap with domain-general EC in a clinical population such as individuals with Parkinson's disease (PD), notoriously associated with structural damage in the basal ganglia.

We approach these issues in two ways. First, we employed a language switching task to investigate the integrity of LC in a group of Catalan–Spanish bilingual individuals with PD, as compared to a group of matched healthy controls. Second, to test the relationship between domain-general EC and LC we compared the performances of individuals with PD and healthy controls also in a non-linguistic switching task. We highlight that, compared to controls, individuals with PD report decreased processing speed, less accuracy and larger switching costs in terms of RT and errors in the language switching task, whereas in the non-linguistic switching task PD patients showed only increased switching cost in terms of errors. However, we report a positive correlation between the magnitudes of linguistic and non-linguistic mixing costs in individuals with PD. Taken together, these results support the notion of a critical role of the basal ganglia and connected structures in LC, and suggest a possible link between LC and domain-general EC.

1. Introduction

For successful communication bilingual speakers need to restrict lexicalization to one language in order to avoid cross-language interferences from the unintended language. The mechanisms that guarantee the success of communication are known as bilingual language control (LC) (Abutalebi and Green, 2007). Despite the fact that the underlying neurocognitive mechanisms are not fully understood, there is a general agreement that LC shares some of the processes involved in domain-general executive control (EC) such as working memory, task-monitoring, task execution, response selection and inhibition.

These control processes are thought to interact at different levels of the language production pipeline: from selection of a concept to be expressed, to the retrieval of its lexical counterpart and its phonological form, and to the planning and monitoring of the articulatory aspects of speech output (e.g., Roelofs and Piai, 2011; Ye and Zhou, 2009). It has been proposed that impairments of domain-general EC processes may have also a role in causing language production deficits (Roelofs and Piai, 2011). For instance, some recent theories have attributed impaired language performance in elderly adults to an overall slowing of mental processing, to a lack of inhibitory control, and to working memory deficits. Similarly, in individuals with Parkinson disease (PD), it has been proposed that deficits related to EC may be responsible for language production deficits (see Dirnberger and Jahanshahi (2013) for a review). Among the linguistic deficits reported in PD, recent studies reported deficits for word-finding (object/verb naming: Cotelli et al., 2007; word fluency: Henry and Crawford, 2004), grammatical rule-based transformations (Ullman et al., 1997), and comprehension of syntactical complex sentences (Grossman et al., 1992; Lieberman et al., 1992).

* Correspondence to: Center for Brain and Cognition, Universitat Pompeu Fabra, Carrer Tanger, 122-140, 08014, Barcelona, Spain.
E-mail address: lelecat3@gmail.com (G. Cattaneo).

http://dx.doi.org/10.1016/j.neuropsychologia.2014.11.006
0028-3932/

PD is considered a neurodegenerative disease characterized by decreased Dopamine production in the midbrain, in particular in substatia nigra pars compacta, affecting mesocortical and mainly nigro-striatal connections. PET studies have revealed that the metabolic dysfunctions in PD also extend to the frontal cortex through its dopaminergic connections (Narayanan et al., 2013). For instance, it has been shown that the dysfunctions in the circuitry connecting the frontal cortex and the basal ganglia, because of striatal dopamine deficiency, are at least in part responsible for the executive control deficits in PD (Brück et al., 2001; Marié et al., 1999; Owen et al., 1998; Polito et al., 2012). The caudate, being part of the striatum, is heavily afflicted by PD. Interestingly, the left caudate is both part of the domain general EC network and the LC network (Abutalebi and Green, 2007). Its role in LC in bilinguals has been well described in healthy individuals through functional and structural neuroimaging (see for review: Abutalebi and Green (2008) and Luk et al. (2012)) and in clinical populations such as bilingual aphasics (see for review: Abutalebi and Green (2008)), individuals with multiple sclerosis (Calabria et al., 2014), and with neurodegenerative diseases such as PD (Zanini et al., 2004, 2010).

In the present study we aim to investigate the functioning of bilingual LC, and its relation with EC, in a group of Catalan–Spanish bilingual individuals with PD. PD provides us with an unique opportunity to shed light into the interesting discussion whether LC in bilinguals and domain-general control are based on a common system.

1.1. Bilingual LC and frontal–subcortical circuits

Neuroimaging and single-case studies of bilingual aphasics have shown that basal ganglia are involved in those processes which allow bilinguals to control two languages (Abutalebi and Green, 2007). Luk et al. (2012) conducted a meta-analysis and found that the caudate, among other brain structures in frontal and temporal areas, is consistently activated during language production tasks in which the alternation between languages or translation across-languages is required, i.e., where LC is most required. Abutalebi et al. (2013) also report that this caudate activity is specific to bilinguals as opposed to monolinguals, and bilinguals were also reported to have increased gray matter densities in the left caudate (Zou et al., 2012). It was proposed that the caudate plays, functionally, a crucial role in bilingual language processing through a subcortical–frontal loop involved in language planning and control (Abutalebi and Green, 2008). Interestingly, selective lesions to the caudate may disrupt this control resulting in specific deficits such as pathological switching and mixing of languages (Abutalebi et al., 2000; Ansaldo et al., 2010; Mariën et al., 2005) or the inability to switch among languages (Aglioti et al., 1996). Therefore, bilingual individuals with PD may offer a good opportunity to further elucidate the role of the basal ganglia and connected structures for LC functions in bilinguals. This interesting field has not received much attention despite the fact that recent studies have shown that bilingual individuals with PD may have language production deficits. Indeed, in a first study by Zanini et al. (2004) the authors reported that Friulian–Italian bilingual speakers with PD were more impaired than controls in syntactic comprehension, and a further study by Zanini et al. (2010) also showed that spontaneous language production was impaired. Interestingly, in both studies it was found that bilingual individuals with PD were more impaired (compared to healthy controls) only when performing tasks in their L1 (Friulian) (for similar results see also Johari et al. (2013)). Similarly, a recent study by Adrover-Roig et al. (2011) suggested the implication of the basal ganglia in the lexicalization of the L1. The authors described a Basque–Spanish bilingual (J.Z.) who was characterized by more impaired language processing in his L1 (Basque) than L2 (Spanish) due to a brain lesion in the left basal ganglia. Interestingly, the fact that J.Z. also showed deficits in the domain of EC functions led the authors to conclude that the patient's impairment in his L1 was probably due to LC deficits. These data suggest that deficits in the EC following damage to the basal ganglia may affect language production, and sometimes in a relatively different manner for the two languages (see also Green et al. (2010), for the role of the EC deficits in bilingual aphasics).

In the present study we focus on dysfunctions of basal ganglia, and connected structures, and their impact on the efficiency of LC and domain general EC in bilinguals. We employed a language switching task in a group of bilingual individuals with PD and compared their performance to a matched control group of healthy individuals. In the task employed participants were required to name a series of pictures in different language conditions, with a cue indicating in which language to name the picture. In such a paradigm two kinds of trials result: switch trials (if the preceding picture was to be named in a different language) and repeat trials (if the preceding picture was to be named in the same language). It is commonly known that participants are slower and less accurate on switch trials than repeat trials, and the difference in reaction times (RTs) between these two types of trials is referred to as the language switching cost (e.g., Costa and Santesteban, 2004, 2006; Meuter and Allport, 1999). Language switching studies on low proficient bilinguals showed that participant have larger switch costs when they switch from their L2 into L1 than vice versa (Costa and Santesteban, 2004; Meuter and Allport, 1999). Conversely, it has been observed that high proficient bilinguals do not show this asymmetrical pattern of switch costs, that is they have the same magnitude of costs for L1 and L2 (Calabria et al., 2011; Costa and Santesteban, 2004).

Moreover, it has also been reported that naming in a “blocked” language condition with one language only, RTs for these trials (single) are usually faster than repeat trials in the mixed condition (Weissberger et al., 2012). The difference of RTs between repeat and single trials is called the language mixing cost. Interestingly, these two types of cost seem to be related to relatively different mechanisms of control. Whereas switching costs would be associated with transient mechanisms of control such as conflict resolution between competing tasks and response selection, mixing costs would rather reflect sustained mechanisms of control such as conflict and response monitoring, and the cost of keeping two task-sets available (Braver et al., 2003; Kray and Lindenberger, 2000; Los, 1996; Rubin and Meiran, 2005; for a similar account in the domain of language see Guo et al. (2011)).

Interestingly, recent evidence points also to an age-related decline of bilingual LC efficiency. For instances, for language switching tasks, elderly bilinguals as compared to younger bilinguals are slower overall, more error-prone and have an increased language switch cost (Gollan and Ferreira, 2009; Kohnert et al., 1999; Weissberger et al., 2012). Given that aging is usually associated to a decline of EC functions, these results suggest a possible link between non-linguistic mechanisms and those of LC (Gollan et al., 2011; but see also Calabria et al. (2013), for a different pattern of results).

Furthermore, there is evidence that patients who experience pathological language switching (pLS) in this type of task produce more cross-language intrusions when required to switch languages (switch trials). For instance, Calabria et al. (2014) described a Catalan–Spanish bilingual speaker (RRT) who produced more cross-language intrusions in a language switching task when she switched into her dominant language (Catalan) from her non-dominant one (Spanish) than the opposite (in contrast with the typical symmetrical switching pattern in healthy high proficient bilinguals; Calabria et al., 2011; Costa and Santesteban, 2004).

As aforementioned, our hypothesis was that dysfunctions of the basal ganglia, and their projections, can impact the bilingual LC mechanisms, and then we also hypothesize a parallelism between impairment of LC and domain-general EC.

1.2. On the relationship between bilingual LC and EC

A second aspect related to LC impairments in bilinguals is to which extent such a deficit is paralleled by EC dysfunctions. In other words, to which extent is there a functional overlap between these two domains of control, linguistic and non-linguistic. Indeed, despite the fact that the nature of the relationship between these two domains of control is not fully understood, there is general agreement that at least some neural and cognitive mechanisms may be shared. Thus, it follows that to the extent the two systems overlap, both systems should be impaired, or at least partially impaired. Recent evidence from bilingual aphasia provides some initial support of this hypothesis. Kong et al. (2014) reported a trilingual aphasic from Hong Kong with pathological language switching that was paralleled by EC dysfunctions. However, to the best of our knowledge, there is no systematic study on groups of patients. Therefore, to test the hypothesis of an eventual shared neural basis for both types of control, we compare the performances in the language switching task (i.e., LC) with those of a non-linguistic switching task (i.e., domain-general EC) in the same group of participants, and investigate whether PD and dopamine dysfunctions similarly affect the control mechanisms in both domains.

Previous studies that have employed task switching in monolinguals individuals with PD suggested increased switch costs as compared to healthy controls, especially in those conditions that are more demanding for the EC system. For instance, Witt et al. (2006) found increased switch costs when the sequence of repeat and switch trials was not predictable (see also Rogers et al. (1998)). Moreover, Cools et al. (2001) found switching deficits in individuals with mild PD, only in those conditions in which stimuli were presented with conflicting information, that is carrying both the relevant and the irrelevant dimensions for task execution (for similar results see also Hayes et al. (1998)). These results have been interpreted as an impairment of EC processes in its attentional and monitoring components required when there is no foreknowledge of the upcoming trial, and/or deficits in avoiding interference from the competing task-set.

To test the efficiency of EC system in PD patients we will consider both switch costs and mixing costs in order to explore both transient and sustained non-linguistic mechanisms of cognitive control. Moreover, we will compare these measures of EC functioning with those of the language switching task. Previous studies, which compared bilingual older adults to young bilinguals, have found that aging affects linguistic and non-linguistic switching abilities in a different way. That is, linguistic and non-linguistic switch costs are not consistently reported as higher in older bilinguals compared to young bilinguals (see Calabria et al. (2013) and Weissberger et al. (2012)) whereas mixing costs have been shown to be more sensitive to aging in a non-linguistic domain (Kray and Lindenberger, 2000; Weissberger et al., 2012). Therefore, looking at the performance (speed of processing, accuracy and costs) of bilingual PD patients in the linguistic and non-linguistic switching tasks will allow gathering information on the degree of overlap of these two systems. That is, the extent to which the underlying common mechanisms of two systems are impaired will reveal the relationship between bilingual LC and EC. Moreover, the use of the two measures of cost, such as the switch cost and mixing cost, will afford a more precise idea whether these two types of control mechanisms (sustained and/or transient) overlap between the linguistic and non-linguistic domain or not.

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

a) the effect of PD and basal ganglia's network dysfunctions on bilingual LC, specifically for sustained and transient control mechanisms, by means of a language switching task;
b) the relationship between the two types of control mechanisms, respectively LC and domain-general EC, that is, the degree of the overlap between these two systems, by comparing the performance of the language switching task with that of a non-linguistic switching task.

2. Methods

2.1. Participants

28 bilingual individuals with a diagnosis of Parkinson's disease (10 female, mean age = 70.7 ± 5.8, mean education = 12.7 ± 3.7) and 24 healthy controls matched for age and education (17 female, mean age = 68.5 ± 7.6, mean education = 12.8 ± 4.8; $ps > 0.1$) took part in the experiment (see Table 1 for clinical and demographical data). All participants were early and high proficient Catalan–Spanish bilinguals, having acquired L2 before the age of 6. All subjects lived in the metropolitan area of Barcelona, and as such were regularly exposed to both languages.

Language proficiency and usage were assessed with a questionnaire. Participants self-rated their abilities of comprehension, reading, writing, fluency and pronunciation with a four-point scale (4 = perfect, 3 = good, 2 = sufficient 1 = poor).

All individuals with PD were recruited at the Movement Disorders Unit of the San Pau Hospital in Barcelona. A senior neurologist (AG) specialized in movement disorders performed the clinical diagnosis of PD according to the clinical criteria of UK Parkinson's disease Brain Bank (Hughes et al., 1992). All individuals were diagnosed with mild PD, according to UPDRS scale (mean = 15.4 ± 6.1 out of 159, range = 7–28; Fahn and Elton, 1987) and Hoehn and Yahr score (all rating from I to IIa; Hoehn and Yahr, 1967), and without dementia according to the MMSE score (Folstein et al., 1975; mean 28.8 ± 1.2, range = 26–30). All patients were stable, without motor fluctuations and on anti-Parkinsonian pharmacological treatment: Mao-B inhibitors ($n = 28$), dopa-agonists ($n = 13$), and L-dopa ($n = 8$). 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.

Healthy adults were relatives of the patients, recruited in the Hospital San Pau, or people recruited in a recreational association for elderly people (Casal d'avis del Congrés) in the metropolitan area of Barcelona. They present no cognitive impairment, as patients, according to the MMSE score; (Folstein et al., 1975; mean 29.2 ± 0.9, range = 27–30, $p > 0.1$).

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 individuals with PD 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

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

	PD (n=28) *Mean (SD)*	Controls (n=24) *Mean (SD)*	p Values
Age (years)	70.7 (5.8)	68.5 (7.6)	0.25
Education(years)	12.7 (3.7)	12.8 (4.8)	0.92
Disease duration (years)	3.7 (2.0)	–	–
UPDRS	15.4 (6.1)	–	–
Age of L2 aqcuisition	3.2 (2.3)	2.9 (2.4)	0.69
Self rating questionnaire			
Catalan			
Comprehension	4.0 (0.0)	3.9 (0.3)	0.24
Fluency	3.9 (0.2)	3.8 (0.5)	0.10
Pronounciation	3.9 (0.3)	3.8 (0.5)	0.12
Writing	1.8 (1.5)	2.7 (1.1)	0.01
Reading	3.3 (0.8)	3.5 (0.9)	0.34
Spanish			
Comprehension	4.0 (0.0)	4.0 (0.0)	–
Fluency	3.9 (0.2)	3.9 (0.2)	0.91
Pronounciation	3.8 (0.4)	3.9 (0.3)	0.41
Writing	3.4 (0.6)	3.7 (0.6)	0.06
Reading	3.8 (0.4)	3.9 (0.2)	0.13

Table 2
Neuropsychological assessment of individuals with PD and results of L1 and L2 naming task of all participants (PD and healthy controls).

Neuropsychological assessment	Raw score *Mean* (SD)	Adjusted score for age and education[a] *Mean* (SD)	Cut off
MMSE	28.8 (1.2)	–	≤ 24
Verbal Long term memory			
CERAD immediate recall	6.9 (1.6)	-	≤ 5
CERAD delayed recall	3.8 (2.0)	-	≤ 3
CERAD recognition	18.3 (1.3)	-	≤ 17
Short term memory			
DIGIT span forward	5.5 (0.9)	11.3 (2.6)	≤ 7
Executive functions			
DIGIT span backward	3.7 (0.9)	10.6 (2.3)	≤ 7
TMT A	55.2 (22.4)	9.2 (3.6)	≤ 7
Language production[b]			
Semantic fluency L1	34.4 (8.4)	5.9 (1.8)	≤ 7
Semantic fluency L2	34.1 (8.1)	6.2 (2.1)	≤ 7
Phonemic fluency L1	23.5 (10.8)	7.3 (2.6)	≤ 7
Phonemic Fluency L2	28.5 (12.2)	8.4 (2.7)	≤ 7
Accuracy naming task (%)[c]	**PD *Mean (SD)***	**Controls *Mean (SD)***	***p* Values**
Object Naming L1	90.3 (7.8)	96.4 (4.7)	< 0.01
Object Naming L2	89.2 (8.9)	95.8 (4.7)	< 0.01
Verb Naming L1	93.9 (6.0)	99.4 (1.3)	< 0.01
Verb Naming L2	93.7 (4.4)	98.0 (3.0)	< 0.01

[a] Mean scores corrected for age and education on the basis of the "Spanish multicenter Normative studies (NEURONORMA PROJECT)" (Peña-Casanova et al., 2009a, 2009b).

[b] A comparison between languages shows that individuals with PD performed similarly in L1 and L2 for semantic fluency [$t(27)=0.321$, $p=0.75$], whereas for phonemic fluency they perform worse in L1 than L2 [$t(27)=-3.669$, $p<0.01$].

[c] A comparison between languages shows that individuals with PD performed with similar accuracy in L1 and L2 in both object [$F(1, 27)=0.638$, $p=0.43$, $\eta p^2=0.02$] and action naming [$F(1, 27)=0.036$, $p=0.86$, $\eta p^2<0.01$].

Backward for short-term memory and working memory respectively (from Test Barcelona, Peña-Casanova, 2005); Part A of the Trial Making Test for an assessment of attentional abilities (Reitan and Wolfson, 1985); semantic and the letter fluencies in Spanish and Catalan for language production. The raw scores were corrected, for age and education, according to the "Spanish multicenter Normative studies (*NEURONORMA PROJECT)*" (Peña-Casanova et al., 2009a, 2009b).

Controls performed only MMSE for cognitive screening.

Moreover, all subjects performed an object and action naming task in L1 and L2 (see Table 2), in distinct sessions separated by a week apart. 90 black and white images (45 of objects and 45 of actions) were selected from Snodgrass and Vanderwart (1980) and from International Picture Naming Project Studies (Bates et al., 2003). This task was administered with a laptop and was controlled by the DMDX software (Forster and Forster, 2003), which recorded vocal and manual responses. Responses were analyzed off-line, and the naming latencies for the linguistic task were measured through Checkvocal software (Protopapas, 2007). Pictures appeared on the screen and participants were instructed to name the pictures and then to press the spacebar to move on to the next picture. Errors were classified as: "anomia" in case the participant did not name the object; "phonological" if there was a depletion, substitution or addition of phonemes to the correct word related to the picture; "semantic" if participants produced a word semantically related to the target; "Cross-language intrusion" if participants produced the correct word but in the non-requested language.

2.3. Materials and procedures

All participants were tested in the linguistic and the non-linguistic version of the switching task (similar to Calabria et al. (2011)) in two different experimental sessions a week apart. In one session they were tested for language switching and in the other session they were tested for non-linguistic task switching. The order of languages and tasks were counterbalanced across participants.

All of the experimental tasks were administered through a laptop (screen 15.6 in. and resolution of 1280×800) and were controlled by the DMDX software (Forster and 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 switching task

Eight pictures of objects were selected from Snodgrass and 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.

There were two types of blocks: single blocks and mixed blocks in a sandwich design such that participants completed two single blocks and 3 mixed blocks, followed by two more single blocks. In each single block (24 trials) the naming language was always the same, and each picture was repeated 3 times. There were a total of 96 trials, 48 single trials in Catalan and 48 single trials in Spanish.

The order of naming language in the single block was counterbalanced across participants. In the mixed blocks, instead, participants had to name the pictures in Spanish or Catalan according to a cue flag appearing on the screen with the pictures. In each mixed block each picture was repeated 4 times. There were two types of trials: repeat trials in which participants had to name the picture in the same language used in the previous trial, and switch trials in which participants were required to name with the language not used in the previous trial. A total of 96 trials were employed, 33 repeat trials in Spanish, 33 repeat trials in Catalan, 15 switch trials in Spanish and 15 switch trials in Catalan. This was done to keep the proportion of switch and repeat trials of 31% and 69% respectively. At the beginning of each block a word cue presented on the screen for 1000 ms indicated in which language

participants had to start to name the pictures (CATALÀ for Catalan, ESPAÑOL for Spanish). A fixation point (a white cross) appeared then in the center of the screen for 500 ms followed by the picture to be named for 2500 ms. The timeout to respond was 3000 ms. For the subsequent trial, after the fixation point, a cue flag appeared with the picture indicating language of naming for that trial.

2.3.2. Non-linguistic switching task

Three shapes (square, circle and triangle) and three colors (red, green and blue) were used in the non-linguistic task. Shapes and colors were combined resulting in a total of nine possible colored shapes. Participants were presented with an array containing three colored shapes, two at the top and one at the bottom of the screen. They were instructed to match one of the two colored shapes at the top with the colored shape at the bottom, according to the criteria of "color" or "shape". The array remained on the screen until the participant's response or with a maximum of 2500 ms. The timeout to respond again was set at 3000 ms.

Participants gave the response by pressing the two keys "M" or "V" on the keyboard according to the position of the matched picture at the top of the array. The "M" key had to be pressed when the correct answer was at the top-right part of the array and the "V" key when it was at the top-left part of the array. The criterion they had to use was indicated by a cue word appearing in the center of the array in each trial ("COLOR" for Color, "FORMA" for Shape). Type of blocks, type of trials and number of trials were the same as for the linguistic switching task.

3. Results

3.1. Linguistic switching task

A repeated measures ANOVA was performed on accuracy and naming latencies (RTs) considering "Type of trial" (single, repeat, switch) and "Language" (L1, L2) as within-subject factors, and "Group" (controls, PD) as a between-subject factor. Naming latencies exceeding 3 SDs above or below a given participant's mean and incorrect responses were excluded from the analyses.

Accuracy. Participants were less accurate in switch trials (90.8%) compared to repeat (95.8%, $p<0.01$) and single (97.3%, $p<0.01$) trials [Type of trial: $F(2, 100)=23.581$, $p<0.01$, $\eta p^2=0.32$] (see Table 3).

Importantly, individuals with PD were less accurate (91.9%) than controls (97.3%) [Group: $F(1, 50)=10.524$, $p=0.02$, $\eta p^2=0.17$) and accuracy was differently modulated by the type of trial in the two groups [Type of trial × Group interaction: $F(2, 100)=4.238$, $p=0.02$, $\eta p^2=0.08$], suggesting a difference in the costs, in term of accuracy, between the two groups. We then calculated the magnitude of the costs and performed a one-way ANOVA for each cost with Group as a between-subjects factor. "*Switch cost*" was calculated as the difference between the accuracy in switch trials and repeat trials, and "*mixing cost*" as a difference between the accuracy in repeat and single trials.

The analysis revealed that switch costs for accuracy were larger in PD (6.9%) than in controls (3.1%) [$F(1, 50)=5.413$, $p=0.02$, $\eta p^2=0.10$]. No difference was found between groups for the mixing cost [PD patients: 2.5%, controls: 0.6%; $F(1, 50)=1.344$, $p=0.25$, $\eta p^2=0.03$].

Moreover, the interaction between Language and Group was significant [$F(1, 50)=4.970$, $p=0.03$, $\eta p^2=0.09$]. Post-hoc analyses revealed that individuals with PD tended to be less accurate in L1 (91.0%) than in L2 (92.9%; $t=-1.775$, $p=0.09$) whereas controls showed the opposite, i.e., a tendency to be less accurate in their L2 (96.8%; $t=1.869$, $p=0.07$) than in L1 (97.7%). Finally, no other interaction was significant.

Qualitatively, the errors made by individuals with PD were missing responses (no response or after the timeout of 3000 ms), semantic and cross-language intrusions. The percentage of missing responses was similar across types of trials (single: 3.1%; repeat: 3.9%; switch: 5.5%) and the same for semantic errors (single: 0.4%; repeat: 0.3%; switch: 0.4%). Interestingly, cross-language intrusions showed a trend to increase from single trials (0.6%) to repeat (2.4%) and switch trials (7.6%).

RTs. The main effect of Type of trial was significant [$F(2, 100)=78.701$, $p<0.01$, $\eta p^2=0.61$]. Post-hoc analyses showed that single trials (929 ms) were faster than repeat trials (1022 ms, $p<0.01$), and these faster than switch trials (1091 ms; $p<0.01$). The main effect of Language was also significant [$F(1, 50)=4.140$, $p=0.05$, $\eta p^2=0.08$], indicating that participants were faster when naming in L1 (1003 ms) than in L2 (1025 ms) (see Table 3).

Crucial for our purpose, we found a significant main effect of Group revealing that individuals with PD were overall slower (1068 ms) than controls [961 ms; $F(1, 50)=4.276$, $p=0.04$, $\eta p^2=0.08$], and the significant interaction between Type of trial and Group [$F(2, 100)=4.106$, $p=0.02$, $\eta p^2=0.08$], suggesting a difference in the magnitude of the costs between the two groups.

As before, we analyzed the magnitude of the switch costs and mixing costs separately with an ANOVA with Group as a between-subject factor. As for accuracy the results revealed that individuals with PD had increased switch costs compared to controls [87 ms and 51 ms respectively; $F(1, 50)=3.832$, $p=0.05$, $\eta p^2=0.07$], but not increased mixing costs [112 ms and 74 ms; $F(1, 50)=2.555$, $p=0.12$, $\eta p^2=0.05$]. No other interaction resulted significant.

To sum up, individuals with PD showed impaired performance compared to controls for: 1) overall speed of processing and accuracy; 2) accuracy and magnitude of switch costs in both languages; 3) a pattern of errors (cross-language intrusions) that suggests difficulties in avoiding interferences from the language not in use in the more demanding naming condition (mixed languages).

3.2. Non-linguistic switching task

A repeated measures ANOVA was performed on accuracy and RTs considering "Type of trial" (single, repeat, switch) and "Criteria" (color, shape) as within-subjects factors, and "Group" (controls, PD) as a between-subjects factor. Incorrect responses and RTs exceeding 3 SD below or above a given participant's mean were excluded from the analysis.

Accuracy. The main effect of Type of trial was significant [$F(2, 100)=13.741$, $p<0.01$, $\eta p^2=0.22$] and post-hoc analyses showed that participants were less accurate in switch trials (96.1%) compared to repeat (99.0%; $p<0.01$) and single trials (98.1%; $p<0.01$) (see Table 4).

The interaction between trial and group was also significant [$F(2, 100)=8.054$, $p<0.01$, $\eta p^2=0.14$] suggesting a difference between the two groups in the costs in term of accuracy. Then, two one-way ANOVAs were performed for switch and mixing costs separately in which we compared the magnitudes between groups. The results revealed that switch costs were larger for PD compared to controls [PD: 4.5%, controls: 1.3%; $F(1, 50)=8.497$, $p<0.01$, $\eta p^2=0.15$), whereas mixing costs was similar for the two groups [PD: −0.4%, controls: −1.4%; $F(1, 50)=1.465$, $p=0.23$, $\eta p^2=0.03$]. No other interaction resulted significant.

RTs. The main effect of Type of trial was significant [$F(2, 100)=43.227$, $p<0.01$, $\eta p^2=0.46$], and post-hoc analyses showed that single trials (893 ms) were faster than repeat ones (955 ms, $p<0.01$), and these were faster than switch trials (1018 ms, $p<0.01$) (see Table 4).

Table 3
Reaction times (ms) and accuracy (%) of PD patients and controls in the linguistic switching task.

	Controls *Mean (SD)*			PD *Mean (SD)*		
	L1	**L2**	**TOT**	**L1**	**L2**	**TOT**
Linguistic Task *Accuracy* (%)						
Single	99.4 (1.5)	97.9 (2.8)	98.7 (1.7)	94.6 (6.9)	97.1 (1.8)	95.9 (4.3)
Repeat	98.1 (2.4)	98.1 (2.4)	98.1 (2.2)	92.1 (9.9)	94.7 (8.0)	93.4 (8.5)
Switch	95.6 (5.3)	94.4 (4.6)	95.0 (4.0)	86.2 (15.2)	86.9 (13.3)	86.5 (13.8)
Total	97.7 (2.2)	96.8 (2.5)	97.3 (2.1)	91.0 (9.4)	92.9 (6.7)	91.9 (7.6)
SC	2.5 (5.6)	3.7 (4.2)	3.1 (3.6)	5.9 (8.2)	7.8 (11.0)	6.9 (7.0)
MC	1.3 (2.2)	-0.2 (2.8)	0.6 (1.5)	2.5 (8.3)	2.4 (7.9)	2.5 (7.9)
Linguistic Task *RT* (ms)						
Single	879 (119)	910 (116)	894 (113)	951 (150)	977 (171)	964 (156)
Repeat	955 (163)	982 (142)	968 (146)	1068 (242)	1083 (233)	1076 (232)
Switch	1001 (184)	1038 (189)	1019 (178)	1167 (275)	1160 (254)	1163 (257)
Total	945 (148)	977 (140)	961 (140)	1062 (218)	1073 (214)	1068 (212)
SC	46 (72)	56 (96)	51 (59)	99 (90)	77 (81)	87 (70)
MC	75 (87)	72 (80)	74 (73)	117 (112)	106 (97)	112 (92)

Moreover, the main effect of Criteria was also significant [$F(1,50)=158.810$, $p<0.01$, $\eta p^2=0.76$] revealing that participants were faster sorting by color (852 ms) than by shape (1058 ms).

Importantly, no differences were found between PD and controls neither for the speed of processing [PD: 991 ms; controls: 919 ms; Group: $F(1, 50)=2.229$, $p=0.14$, $\eta p^2=0.04$] nor for the magnitude of the switch nor mixing costs [Group × Type of trial interaction: $F(2, 100)=0.653$, $p=0.52$, $\eta p^2=0.01$]. Any other interaction was not significant.

To sum up, in the non-linguistic task individuals with PD were only overall more error prone compared to controls, especially in switch trials, showing increased switch cost only in terms of accuracy.

3.3. Interim summary of the results

The results from the linguistic version of the task switching demonstrate that individuals with PD, as compared to controls, were impaired in several measures such as overall speed of processing and accuracy; and in terms of accuracy and magnitude of switch costs in both languages. Moreover, the presence of cross-language intrusions may suggest that individuals with PD had difficulties in avoiding interferences from the language not in use in the more demanding naming condition (mixed languages). Finally, despite the fact the mixing costs were not statistically significant, its magnitudes was larger for PD patients (112 ms) compared to controls (74 ms).

Interestingly, the same PD individuals behaved differently in the non-linguistic switching task. That is, they only showed an increased switching cost in error rate when compared to controls, without any difference in the magnitude of the costs.

Therefore, the fact that the same patients show different performance 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 speed of processing and the magnitude of the switch costs found to be larger in the linguistic but not in the non-linguistic task for PD relative to controls (see Fig. 1). This would suggest that the underlying mechanisms between language and domain general control may not be fully shared.

For mixing costs, associated to more sustained control mechanisms, we found that in individuals with PD was increased in both tasks. However, there were no statistically significant differences in mixing costs between groups, suggesting that perhaps this was driven by the increased variability in the patients' performance. We suggest that there may be different degrees of EC impairment in the PD group. To explore this hypothesis we divided

Table 4
Reaction times (ms) and accuracy (%) of PD patients and controls in the non-linguistic switching task.

	Controls *Mean (SD)*			PD *Mean (SD)*		
	Color	**Shape**	**TOT**	**Color**	**Shape**	**TOT**
Non-Linguistic Task *Accuracy* (%)						
Single	99.3 (2.9)	96.4 (4.2)	97.9 (2.4)	99.1 (2.0)	97.6 (3.7)	98.3 (3.7)
Repeat	99.5 (1.9)	99.1 (1.4)	99.3 (1.4)	98.7 (1.7)	98.7 (3.8)	98.7 (3.8)
Switch	97.8 (3.7)	98.3 (3.5)	98.0 (2.5)	94.5 (5.6)	93.9 (4.8)	94.2 (4.8)
Total	98.9 (1.8)	97.9 (2.3)	98.4 (1.4)	97.4 (2.3)	96.7 (4.4)	97.1 (2.5)
SC	1.7 (4.2)	0.8 (3.2)	1.3 (2.9)	4.2 (5.8)	4.8 (6.8)	4.5 (4.6)
MC	-0.2 (3.6)	-2.7 (4.5)	-1.4 (2.9)	0.4 (2.3)	-1.1 (6.9)	-0.4 (3.5)
Non-Linguistic Task *RT* (ms)						
Single	756 (127)	974 (160)	866 (137)	820 (163)	1020 (206)	920 (168)
Repeat	811 (140)	1018 (148)	915 (136)	879 (201)	1108 (233)	993 (204)
Switch	895 (167)	1057 (186)	976 (167)	950 (207)	1168 (265)	1059 (225)
Total	821 (133)	1016 (155)	919 (137)	883 (177)	1099 (227)	991 (193)
SC	84 (56)	39 (76)	61 (53)	71 (115)	60 (83)	66 (72)
MC	55 (111)	44 (96)	49 (98)	59 (96)	88 (128)	73 (99)

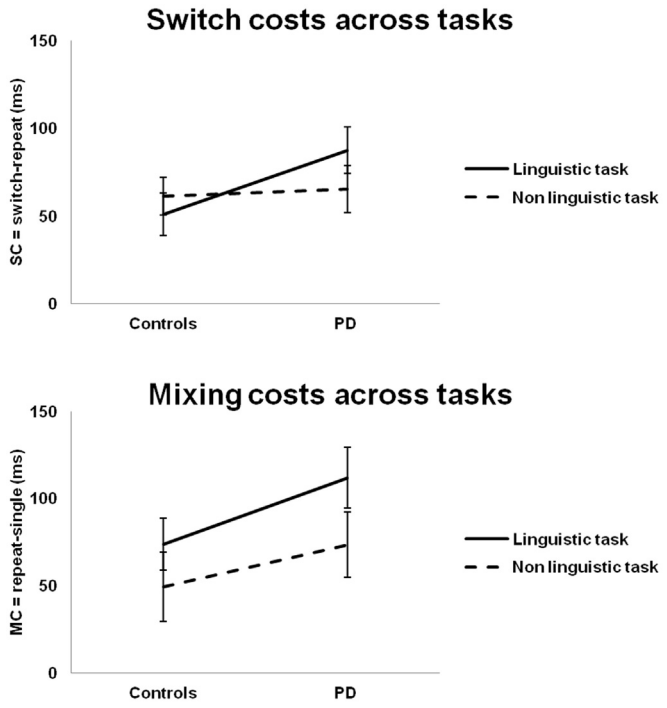

Fig. 1. Comparison of the switch and mixing costs of the two groups in the linguistic and non-linguistic task switching.

the PD group in two sub-groups: those with EC impairment and those without, according to the accuracy scores of the control group. We then analyzed the data comparing the two resulting PD groups against the controls in order to examine the relationship between EC impairment and bilingual LC in a more direct way.

3.4. Subgroups of PD with and without EC impairments

We split the individuals with PD into two sub-groups: below or above the mean accuracy of the controls in the mixed blocks of the non-linguistic switching task minus two standard deviations (95.9%). Therefore, those individuals with PD who scored below this value were classified as "EC impaired" ($n=12$; mean accuracy=93.3%) and those scoring above were classified as "EC unimpaired" ($n=16$; mean accuracy=98.2%). These two groups had the same age (age: 72.0 vs. 69.7, $p=0.32$), education (13.7 vs. 11.9, $p=0.24$), degree of motor impairment (UPDRS scale: 15.4 vs. 15.1, $p=0.92$), and absence of dementia (MMSE: 28.3 vs. 29, $p=0.11$). On neuropsychological assessment, EC impaired subjects reported significant poorer performances than EC unimpaired subjects in some tests involving EC such as: letter fluencies both in L1 (17.6 vs. 27.9, $p=0.01$) and in L2 (22.2 vs. 33.1, $p=0.02$), and in the Trial Making Test (68.1 vs. 45.6, $p<0.01$).

We, then, compared the two PD groups to controls in the linguistic and non-linguistic switching tasks as follows.

3.4.1. Linguistic switching task: EC impaired and unimpaired patients

A repeated measures ANOVA was performed on accuracy and naming latencies considering "Type of trial" (single, repeat, switch) and "Language" (L1, L2) as within-subjects factors, and "Group" (controls, EC unimpaired, EC impaired) as a between-subjects factor.

Accuracy. Participants were less accurate in switch trials (88.8%) compared to repeat (94.6%; $p<0.01$) and single trials (96.8%; $p<0.01$) [Type of trial main effect: $F(2, 98)=37.427$, $p<0.01$, $\eta p^2=0.43$]. The main effect of Group was also significant [$F(2, 49)=10.851$, $p<0.01$, $\eta p^2=0.31$] and post-hoc analyses revealed that EC impaired subjects were less accurate (88.3%) than controls (97.3%, $p<0.01$) and EC unimpaired subjects (94.7%, $p<0.01$).

Moreover, and important for our scope, accuracy was differently modulated by the type of trials in the three groups [Type of trial × Group interaction: $F(4, 98)=7.116$, $p<0.01$, $\eta p^2=0.22$]. Separate one-way ANOVAs were performed for each cost using the variable Group as a between-subjects factor. The analysis revealed a significant effect of Group both for switch cost [$F(2, 49)=5.051$, $p=0.01$, $\eta p^2=0.17$] and for mixing cost [$F(2, 49)=5.261$, $p<0.01$, $\eta p^2=0.18$]. Post-hoc analyses showed that switch costs were larger for EC impaired subjects (9.4%) compared to controls (3.1%, $p<0.01$) and EC unimpaired subjects (4.9%, $p=0.04$). Also, mixing costs were significantly larger for the EC impaired group (6.0%) compared to the other two (Controls: 0.5%, $p=0.02$; Unimpaired: −0.2%, $p=0.01$). No differences were found between controls and EC unimpaired subjects for the two costs [switch cost: $p=0.94$; mixing cost: $p>0.9$]. No other interaction was significant.

We also looked at the percentage of cross-language intrusions as an indicator of bilingual LC deficits. Specifically, the hypothesis is that if domain-general EC deficits are to some extent responsible for LC deficits, those patients who are more EC impairment will show also more cross-language intrusions. In a further analysis we compared the two groups of PD with controls in the percentage of cross-language intrusions. The results showed a tendency of increased cross-language intrusions in those subjects having more EC impairments (4.3%) compared to controls (2.1%, $p=0.07$) but no differences were found between the two groups of PD individuals (EC unimpaired=3.0%, $p=0.58$). Interestingly, this was especially true in switch trials in which the percentage of cross-language intrusions was higher, that is, 4.4% for controls, 6.4% for EC unimpaired and 9.2% for EC impaired individuals.

RTs. The main effect of Type of trial was significant [$F(2, 98)=100.354$, $p<0.01$, $\eta p^2=0.67$]. Post hoc analysis indicated that single trials (945 ms) were faster than repeat ones (1048 ms, $p<0.01$), and these were faster than switch trials (1126 ms, $p<0.01$). Important was the significant main effect of Group F(2, 49)=5.170, $p<0.01$, $\eta p^2=0.17$] and post-hoc analyses, that revealed that EC impaired subjects (1160 ms) were overall slower than EC unimpaired subjects (998 ms; $p=0.02$) and controls (961 ms; $p<0.01$), whereas no difference was found between EC unimpaired and controls ($p=0.51$) (see Table 5).

We report also a significant interaction between Type of trial and Group [$F(4, 98)=5.557$, $p<0.01$, $\eta p^2=0.18$], suggesting differences in terms of the magnitude of the costs between the three groups of participants. To explore this interaction we performed two one-way ANOVAs for each cost (switch cost and mixing cost) in which we compared the performances of the three groups. Interestingly, the main effect Group was significant both for switch cost [$F(2, 49)=4.202$, $p=0.02$, $\eta p^2=0.15$] and mixing cost [$F(2, 49)=3.908$, $p=0.03$, $\eta p^2=0.14$]. Post-hoc analyses revealed that switch cost was larger for EC impaired patients (117 ms) compared to EC unimpaired (65 ms; $p=0.04$) and controls (51 ms; $p<0.01$). Also for mixing cost, EC impaired patients showed a larger cost (152 ms) compared to controls (74 ms; $p=0.01$) and EC unimpaired patients (82 ms; $p=0.03$). Importantly, no differences were found between EC unimpaired subjects and controls for neither switch cost ($p=0.49$) nor mixing cost ($p=0.77$).

To sum up, the results indicated that EC impaired subjects compared to the other two groups had poorer performances in: 1) overall speed of processing and accuracy; 2) accuracy and magnitude of switch costs and mixing costs in both languages; 3) a pattern of cross-language intrusions that suggests more difficulties in avoiding interferences from the language not in use in the more demanding naming condition (mixed languages).

Table 5
Reaction times (ms) of EC impaired patients, EC unimpaired patients and controls in the linguistic switching task.

	Controls *Mean (SD)*			EC unimpaired *Mean (SD)*			EC impaired *Mean (SD)*		
	L1	**L2**	**TOT**	**L1**	**L2**	**TOT**	**L1**	**L2**	**TOT**
Linguistic Task *RT* (ms)									
Single	879 (119)	910 (116)	894 (113)	908 (136)	937 (156)	922 (142)	1008 (148)	1031 (176)	1020 (155)
Repeat	955 (163)	982 (142)	968 (146)	998 (229)	1009 (202)	1004 (210)	1162 (227)	1182 (235)	1172 (226)
Switch	1001 (184)	1038 (189)	1019 (178)	1067 (250)	1072 (218)	1069 (225)	1298 (249)	1279 (250)	1289 (245)
Total	945 (148)	977 (140)	961 (140)	991 (201)	1006 (187)	998 (190)	1156 (202)	1164 (214)	1160 (241)
SC	46 (72)	56 (96)	51 (59)	69 (68)	62 (71)	65 (46)	136 (100)	97 (88)	117 (85)
MC	75 (87)	72 (80)	74 (73)	90(113)	73 (74)	82 (81)	154 (100)	151 (105)	152 (90)

3.4.2. Non-linguistic switching task: EC impaired and unimpaired patients

Despite the fact that the two groups of individuals with PD were classified according to the accuracy of the controls in the non-linguistic task, we sought to explore if RTs and costs were also different between these two groups. For this reason, we also analyzed the performances of the three groups of participants in the non-linguistic task.

A repeated measures ANOVA was performed on the RTs considering "Type of trial" (single, repeat, switch) and "Criteria" (color, shape) as within-subjects factors, and "Group" (controls, EC unimpaired, EC impaired) as a between-subjects factor.

RTs. The main effect of Type of trial was significant [$F(2, 98)=55.910$, $p<0.01$, $\eta p^2=0.53$]. Post hoc analysis indicated that single trials (907 ms) were faster than repeat ones (978 ms, $p<0.01$), and these were faster than switch trials (1043 ms, $p<0.01$). The main effect of Criteria was also significant [$F(1, 49)=15.976$, $p<0.01$, $\eta p^2=0.75$], revealing that participants were faster sorting by color (870 ms) than by shape (1081 ms) (see Table 6).

Moreover, the main effect of Group was significant [$F(2, 49)=5.570$, $p<0.01$, $\eta p^2=0.18$]. Post-hoc analyses revealed that EC impaired subjects (1093 ms) were slower than both EC unimpaired (913 ms, $p<0.01$) and controls (919 ms, $p<0.01$). Importantly, the significant interaction between Group and Type of trial [$F(4, 98)=5.159$, $p<0.01$, $\eta p^2=0.17$] suggested that the magnitudes of the costs were different between groups. We further analyzed the two costs in separate one-way ANOVAs considering Group as a between-subjects factor. Crucially, the results revealed that there were differences between groups for the magnitude of the mixing cost [$F(2, 49)=6.180$, $p<0.01$, $\eta p^2=0.20$] but not for the switch cost [$F(2, 49)=0.315$, $p=0.73$, $\eta p^2=0.01$]. Indeed, post-hoc analyses revealed that the mixing costs were larger for EC impaired (141 ms) compared to controls (50 ms, $p<0.01$) and EC unimpaired (23 ms, $p=0.01$).

Moreover, the significant interaction between Type of trial, Criteria and Group [$F(4, 98)=2.666$, $p=0.04$, $\eta p^2=0.10$] suggested that sorting criteria differently modulated the magnitude of the costs in the three groups. Post-hoc analyses revealed that, on the one hand, controls showed larger switch costs for color (84 ms) than for shape (39 ms) ($p=0.016$), whereas the same magnitude was found for the two sorting criteria in terms of the mixing cost (color: 55 ms; shape: 43; $t=0.724$ $p=0.48$). On the other hand, EC impaired and EC unimpaired subjects did not show significant differences in the magnitudes of the costs for color or shape (all $ps>0.05$).

To sum up, the results indicated that EC impaired subjects compared to the other two groups had poorer performances in: 1) overall speed of processing; 2) magnitude of mixing costs.

3.4.3. Summary of the results

The aim of these analyses was to explore the relationship between domain-general EC and LC in bilinguals in a more direct way by considering the performance in a language switching task of those PD subjects showing deficits in the non-linguistic task. Several interesting results were found.

First of all, whereas EC unimpaired subjects performed the tasks similarly to controls in all measures, EC impaired subjects showed an overall slower speed of processing, lower accuracy in both tasks, increased switch costs in the linguistic tasks and increased mixing costs in both tasks. This suggests a more direct relationship between these two systems and their impairments. However, this cross-talk between the two types of control (linguistic and non-linguistic) seems to be specific to some of the common underlying mechanisms.

Indeed, if we look at the pattern of results of EC impaired patients, the switch cost was larger in the linguistic version of the task, but not in the non-linguistic version (see Fig. 2), suggesting that these two costs may not have necessarily common underlying mechanisms.

This result was also supported by a further analysis in which we used the accuracy in the non-linguistic switching task as a covariate. Indeed, in two separate one-way ANOVAs (one for each cost) we found that the accuracy was significant for the linguistic

Table 6
Reaction times (ms) of EC impaired patients, EC unimpaired patients and controls in the linguistic switching task.

	Controls *Mean (SD)*			EC unimpaired *Mean (SD)*			EC impaired *Mean (SD)*		
	Color	**Shape**	**TOT**	**Color**	**Shape**	**TOT**	**Color**	**Shape**	**TOT**
Non-Linguistic Task *RT* (ms)									
Single	756 (127)	974 (160)	866 (137)	786 (179)	972 (177)	879 (171)	865 (126)	1083 (224)	974 (147)
Repeat	811 (140)	1018 (148)	915 (136)	800 (171)	1004 (184)	902 (163)	985 (188)	1245 (219)	1115 (190)
Switch	895 (167)	1057 (186)	976 (167)	843 (154)	1075 (227)	959 (183)	1091 (181)	1292 (263)	1191 (207)
Total	821 (133)	1016 (155)	919 (137)	810 (159)	1017 (192)	913 (168)	980 (151)	1207 (226)	1093 (175)
SC	84 (56)	39 (76)	61 (53)	43 (100)	71 (71)	57 (64)	106 (125)	46 (95)	76 (80)
MC	55 (111)	44 (96)	49 (98)	14 (72)	32 (87)	23 (69)	120 (91)	151 (105)	141 (94)

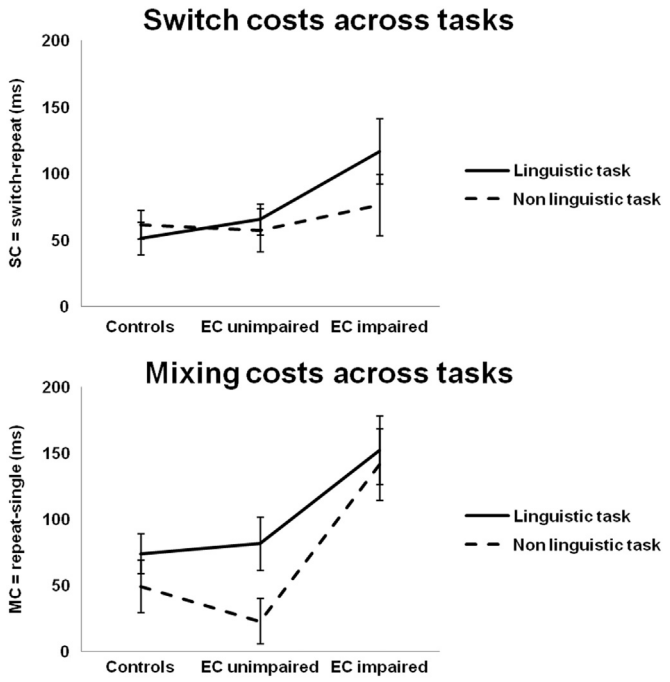

Fig. 2. Comparison of the switch and mixing costs of the three groups in the linguistic and non-linguistic task switching.

mixing costs [$F(1, 49)=9.099$, $p<0.01$, $\eta p^2=0.16$], but not for the linguistic switching costs [$F(1, 49)=0.793$, $p=0.38$, $\eta p^2=0.01$].

Second, the results for the mixing costs allow us to redefine the general but not significant trend of increase found for PD subjects when compared to controls as a whole. In other words, EC impaired subjects showed increased magnitude of mixing costs in both tasks when compared to their EC unimpaired peers and controls, suggesting that sustained control may be a common mechanism of the two domains. Therefore, to explore this possibility we further analyzed our data by correlating the magnitudes of costs in linguistic and non-linguistic switching tasks.

3.5. Correlations between the two tasks

To explore the relationship between the domain-general EC and LC we correlated the costs in the linguistic and non-linguistic tasks, as done in previous studies (Calabria et al., 2013). The general assumption is that if switch costs and mixing costs reflect the efficiency/deficits of both types of control in the same way, we may expect the magnitude of the costs (linguistic and non-linguistic) to vary in the same manner in participants. In order to do so, we correlated switch costs and mixing costs of the linguistic and the non-linguistic tasks (collapsing languages and sorting criteria) for each group of participants.

For the switch cost, we did not find any significant correlation in any group (PD: $r=0.01$, $p=0.95$; controls: $r=0.34$, $p=0.10$; see Fig. 3). However, the correlation was significant for the mixing cost in PD subjects ($r=0.48$, $p<0.01$; for similar results see also Prior and Gollan (2013)), but not for controls ($r=0.04$, $p=0.84$; see Fig. 4).

Moreover, since we found differences in RTs (linguistic switching task) between groups of participants, we also calculated the costs as percentages for each individual. For switch costs we divided the magnitude of the switch cost by its RTs in the repeat trials. For mixing costs we divided the magnitude of the mixing cost by its RTs in the single trials. We then correlated the costs as percentages (linguistic and non-linguistic) in both groups of participants. We did not find any significant correlation for switch costs in any group (PD: $r=0.11$, $p=0.58$; controls: $r=0.07$, $p=0.73$). However, the correlation was significant for the mixing cost in PD subjects ($r=0.52$, $p<0.01$) but not for controls ($r=0.22$, $p=0.31$). These results confirm those we found for the correlations with RTs.

This suggests that a possible functional link between the bilingual LC and the EC systems should be related to the cognitive processes associated to mixing costs, for example, sustained control (see Discussion for details).

4. Discussion

In the present study we explored bilingual LC abilities in a group of individuals with PD and age-matched healthy controls. Specifically, we investigated the performances of our subjects by looking at the integrity of the bilingual LC system, assuming that dysfunctions in the basal ganglia and connected structures may lead to deficits in the ability to control the two languages. Moreover, we explored the relationship between the LC and domain-general EC system by comparing bilinguals with PD to controls in a linguistic version of task switching and in a non-linguistic version of task switching.

In this view the first aim was to explore the effect of PD and basal ganglia's network dysfunctions on the bilingual LC system, specifically for sustained and transient control mechanisms. In the language switching task we found that individuals with PD were

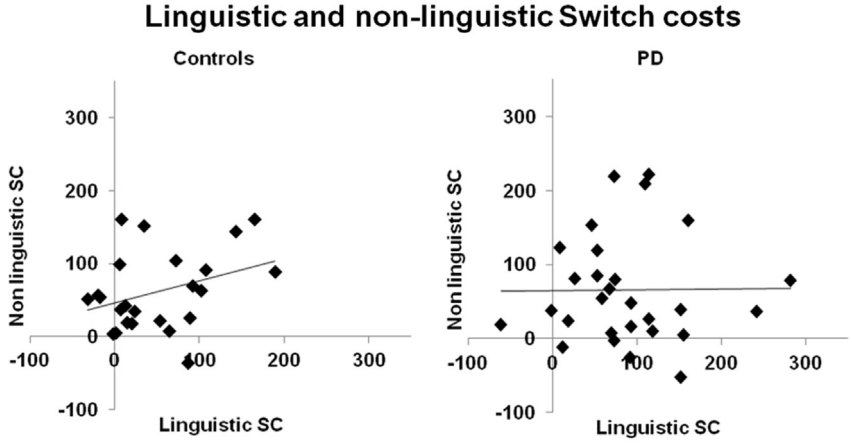

Fig. 3. Correlations of the switch costs of PD patients and controls in the two tasks.

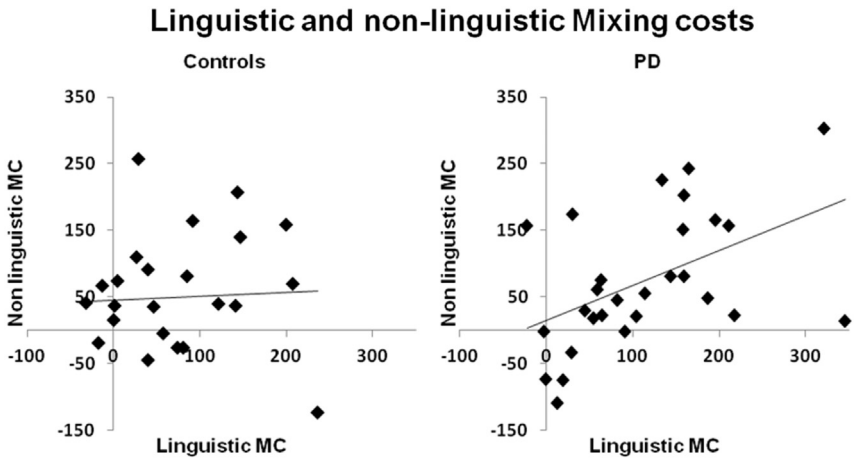

Fig. 4. Correlations of the mixing costs of PD patients and controls in the two tasks.

slower compared to controls, made more errors, and had increased switch costs in terms of magnitude and errors. These results suggest that lesions in the basal ganglia and connected structures, may, indeed, lead to difficulties in the control of two languages. However, mixing costs were not different between the two groups of participants. Some authors have proposed that mixing costs and switch costs may reflect sustained and transient control mechanisms respectively (Braver et al., 2003; Kray and Lindenberger, 2000; Rubin and Meiran, 2005). Switch costs seem to reflect transient mechanisms needed to resolve conflict and interference between tasks, and to select the correct task-set. Mixing costs, instead, are believed to reflect more general and sustained mechanisms of conflict and response monitoring, and the cognitive demand of keeping two task-sets available (Braver et al., 2003; Kray and Lindenberger, 2000; Los, 1996; Rubin and Meiran, 2005).

Our results suggest that dysfunctions in the basal ganglia's network affect the ability to select the target language by avoiding cross-language interference when competition is high, as in the mixed language condition. This observation is also confirmed by the pattern of errors, showing the presence of cross-language intrusions almost only in the mixed condition, and especially in switch trials. This is in accordance with neuroimaging and neuropsychological studies highlighting the involvement of subcortical structures, such as the caudate, in the control of two languages (Abutalebi and Green, 2008; Luk et al., 2012). Moreover, the PD group showed a tendency to be less accurate in L1 than L2, whereas controls showed the opposite pattern (L1 more accurate than L2). This observation is in line with other studies of language production of PD patients or aphasic patients with basal ganglia damage (Adrover-Roig et al., 2011; Johari et al., 2013; Zanini et al., 2010), which suggests the implication of the basal ganglia in bilingual language production and control, and in the lexicalization of the L1. However, the relatively larger impairment of L1 than L2 in our patients was restricted only to the specific task context where LC is more required such as in the language switching task. Moreover, we found that in the phonemic fluency test, a neuropsychological task which measures executive control involvement in language production (Polito et al., 2012), PD patients scored poorer in their L1 than in L2. Conversely, the differential impairment of two languages was not found in those language tasks which require less involvement of the executive control system. Indeed, in the simple naming tasks the PD group performed poorer, compared to controls, in both object and action naming but with low presence of cross-language intrusions (anomia=0.5%; semantic=5.0%; cross-language intrusions=2.4%; phonemic=0.3%), and with a similar accuracy in both languages.

The second aim was to compare the performances in the linguistic and non-linguistic switching tasks in order to investigate the relationship between domain-general EC and bilingual LC. In the non-linguistic version of the task the individuals with PD, were only impaired in terms of accuracy compared to controls, making more errors in switch trials. Despite the fact that the two tasks are not completely the same, and therefore they may have different sensitivity, at a first glimpse this finding would suggest rather some differences between the mechanisms involved in domain-general EC and LC.

However, to better investigate the relation between these two types of control mechanisms, we sought to investigate the performances of those individuals who reported more EC impairment (as indexed by their accuracy in the non-linguistic version of the task). The greater impairment in executive functions in these subjects was also confirmed by their poorer scores on neuropsychological testing sensitive to EC dysfunctions such as the Trial Making Test and letter fluencies in both languages. Interestingly, we observed that those subjects who were more impaired in EC had also increased mixing costs in both linguistic and non-linguistic tasks, but increased switch costs only in the linguistic task. Moreover, we found an increase of cross-language intrusions in individuals with EC deficits, suggesting that the abilities of LC become clearly impaired only when the non-linguistic abilities are affected by the disease.

Hence, whereas mechanisms underlying switch costs seems to be to some extent differently affected in the two versions of the task, the mechanisms related to mixing costs showed the same pattern across tasks. This finding supports the hypothesis that some mechanisms of bilingual LC are not necessarily subsidiary to those of domain-general EC as found in previous studies with young and older bilingual adults (Calabria et al., 2013; Weissberger et al., 2012; but see also Gollan et al. (2011)).

Finally, we also performed a correlation analyses between linguistic and non-linguistic costs in order to corroborate our latter finding. Interestingly, the magnitude of the switch cost in the two tasks did not correlate, whereas mixing costs for the linguistic and non-linguistic tasks did, but only overall in the PD group.

We acknowledge that a lack of significance in the correlation analysis for the switch costs do not necessarily imply a dissociation of mechanisms across the linguistic and non-linguistic domain. Nevertheless this finding, together with the other results commented above, would suggest more differences than similarities in the mechanisms of control for the linguistic and non-linguistic domain. Indeed, if any, the only similarity across tasks is that PD patients have larger switch costs than mixing costs, but only in terms of accuracy. This is not to say that the two systems

are not overlapping, but these results would indicate that at least some of these mechanisms are not shared across domains (for similar conclusions for the switch costs see Calabria et al. (2012, 2013); and see also Weissberger et al. (2012)). Moreover, a recent study by Prior and Gollan (2013) found a similar correlation for mixing costs, leading the authors to conclude that similar sustained mechanisms of monitoring are involved in bilingual LC and domain-general EC functioning. This is in line with what we found in our study for the correlation between linguistic and non-linguistic mixing costs in PD patients.

Several studies have endeavored to shed light on the mechanisms and the origin of mixing costs, and the general view is that this cost reflects more the sustained mechanisms of control involved in conflict and response monitoring, and/or keeping two task-sets available (Braver et al., 2003; Koch et al., 2005; Kray and Lindenberger, 2000; Rubin and Meiran, 2005). For instance, Rubin and Meiran (2005) claim that mixing costs are the expression of the mechanisms of management of competitive task-sets in mixed blocks, that is, in conditions in which participants are required to switch back and forth. They proposed that mixing costs reflect the involvement of a set of top-down control mechanisms that monitor the continuous bottom-up competition (stimulus-driven) between tasks. Similarly, other authors have suggested that mixing costs reflect a set of mechanisms used in order to prevent perseverations, and to facilitate cognitive flexibility in demanding switching context (Marí-Beffa et al., 2012). The underlying neural network of these two types of control needs to be more explored in PD patients. Indeed, we know that PD not only affects the activity of basal ganglia, but also frontal areas are involved in executive control processes (for a relation between the dopaminergic dysfunctions, frontal areas and executive dysfunctions in PD see Narayanan et al. (2013), Brück et al. (2001), Marié et al. (1999), Owen et al. (1998), and Polito et al. (2012)). We acknowledge that in our study we were not able to explore the specific contribution of each structure within this network to the executive deficits. Further research would take into account this aspect in order to better define which brain structures are involved in the sustained or transient mechanisms of LC and non-linguistic control.

To conclude, this study provides novel evidence on the role of the basal ganglia and connected structures in bilingual language production and LC. First, as here reported the LC system of bilinguals is crucially affected by PD and in particular in those mechanisms that allow resolving transient interferences between two languages. Second, the underlying mechanisms between LC and domain-general EC systems are probably not fully subsidiary. Our findings would suggest that these two systems would share those mechanisms which are responsible of sustained control and monitoring that allow the management of competitive task sets and/or to promote cognitive flexibility.

Acknowledgments

This work was supported by grants from the Spanish Government (PSI2008-01191, PSI2011-23033, Consolider Ingenio 2010 CSD2007-00048), the Catalan Government (Consolidat SGR 2009-1521), and by one grant from the European Research Council under the European Community's Seventh Framework (FP7/2007-2013 Cooperation grant agreement 613465-AThEME).

Marco Calabria was supported by a postdoctoral fellowship from the Spanish Government (Juan de la Cierva fellowship). A special thanks to Joanna D. Corey for her useful corrections, and to the “Casal per a la gent gran del Congrés” of Badalona (Barcelona) for their collaboration.

References

Abutalebi, J., Della Rosa, P.A., Gonzaga, A.K.C., Keim, R., Costa, A., Perani, D., 2013. The role of the left putamen in multilingual language production. Brain Lang. 125 (3), 307–315.
Abutalebi, J., Green, D.W., 2007. Bilingual language production: the neurocognition of language representation and control. J. Neurolinguist. 20, 242–275.
Abutalebi, J., Green, D.W., 2008. Control mechanisms in bilingual language production: neural evidence from language switching studies. Lang. Cogn. Processes 23 (4), 557–582.
Abutalebi, J., Miozzo, M., Cappa, S.F., 2000. Do subcortical structures control “language selection” in polyglots? Evidence from pathological language mixing. Neurocase 6, 51–56.
Adrover-Roig, D., Galparsoro-Izagirre, N., Marcotte, K., Ferré, P., Wilson, M.A., Inés Ansaldo, A., 2011. Impaired L1 and executive control after left basal ganglia damage in a bilingual Basque–Spanish person with aphasia. Clin. Linguist. Phon. 25, 480–498.
Aglioti, S., Beltramello, A., Girardi, F., Fabbro, F., 1996. Neurolinguistic and follow-up study of an unusual pattern of recovery from bilingual subcortical aphasia. Brain: J. Neurol. 119 (5), 1551–1564.
Ansaldo, A.I., Saidi, L.G., Ruiz, A., 2010. Model driven intervention in bilingual aphasia: evidence from a case of pathological language mixing. Aphasiology 24 (2), 309–324.
Bates, E., D'Amico, S., Jacobsen, T., Székely, A., Andonova, E., Devescovi, A., Herron, D., et al., 2003. Timed picture naming in seven languages. Psychon. Bull. Rev. 10 (2), 344–380.
Braver, T.S., Reynolds, J.R., Donaldson, D.I., 2003. Neural mechanisms of transient and sustained cognitive control during task switching. Neuron 39 (4), 713–726.
Brück, A., Portin, R., Lindell, A., Laihinen, A., Bergman, J., Haaparanta, M., Solin, O., et al., 2001. Positron emission tomography shows that impaired frontal lobe functioning in Parkinson's disease is related to dopaminergic hypofunction in the caudate nucleus. Neurosci. Lett. 311 (2), 81–84.
Calabria, M., Branzi, F., Marne, P., Hernandez, Costa, A., 2013. Age-related effects over bilingual language control and executive control. Bilingualism: Lang. Cogn., 1–14.
Calabria, M., Hernandez, M., Branzi, F.M., Costa, A., 2011. Qualitative differences between bilingual language control and executive control: evidence from task-switching. Front. Psychol. 2, 399.
Calabria, M., Marne, P., Romero-Pinel, L., Juncadella, M., Costa, A., 2014. Losing control of your languages: a case study. Cogn. Neuropsychol. 31 (3), 266–286.
Cools, R., Barker, R.A., Sahakian, B.J., Robbins, T.W., 2001. Mechanisms of cognitive set flexibility in Parkinson's disease. Brain: J. Neurol. 124 (12), 2503–2512.
Costa, A., Santesteban, M., 2004. Lexical access in bilingual speech production: evidence from language switching in highly proficient bilinguals and L2 learners. J. Mem. Lang. 50, 491–511.
Costa, A., Santesteban, M., 2006. The control of speech production by bilingual speakers: introductory remarks. Bilingualism: Lang. Cogn. 9, 115–117.
Cotelli, M., Borroni, B., Manenti, R., Zanetti, M., Arévalo, A., Cappa, S.F., Padovani, A., 2007. Action and object naming in Parkinson's disease without dementia. Eur. J. Neurol. 14 (6), 632–637.
Dirnberger, G., Jahanshahi, M., 2013. Executive dysfunction in Parkinson's disease: a review. J. Neuropsychol. 7 (2), 193–224.
Fahn, S., Elton, R., Members of the UPDRS Development Committee. In: Fahn, S., Marsden, C.D., Calne, D.B., Goldstein, M., (1987). eds. Recent Developments in Parkinson's Disease, Vol 2. Florham Park, NJ. Macmillan Health Care Information, pp. 153-163, 293-304.
Folstein, M.F., Folstein, S.E., McHugh, P.R., 1975. “Mini-mental state”. A practical method for grading the cognitive state of patients for the clinician. J. Psychiatr. Res. 12 (3), 189–198.
Forster, K.I., Forster, J.C., 2003. DMDX: a windows display program with millisecond accuracy. Behav. Res. Methods Instrum. Comput. 35 (1), 116–124.
Gollan, T.H., Ferreira, V.S., 2009. Should I stay or should I switch? A cost-benefit analysis of voluntary language switching in young and aging bilinguals. J. Exp. Psychol. Learn. Mem. Cogn. 35 (3), 640–665.
Gollan, T.H., Sandoval, T., Salmon, D.P., 2011. Cross-language intrusion errors in aging bilinguals reveal the link between executive control and language selection. Psychol. Sci. 22 (9), 1155–1164.
Green, D.W., Grogan, A., Crinion, J., Ali, N., Sutton, C., Price, C.J., 2010. Language control and parallel recovery of language in individuals with aphasia. Aphasiology 24 (2), 188–209.
Grossman, M., Carvell, S., Stern, M.B., Gollomp, S., Hurtig, H.I., 1992. Sentence comprehension in Parkinson's disease: the role of attention and memory. Brain Lang. 42 (4), 347–384.
Guo, T., Liu, H., Misra, M., Kroll, J.F., 2011. Local and global inhibition in bilingual word production: fMRI evidence from Chinese–English bilinguals. NeuroImage 56 (4), 2300–2309.
Hayes, A.E., Davidson, M.C., Keele, S.W., Rafal, R.D., 1998. Toward a functional analysis of the basal ganglia. J. Cogn. Neurosci. 10 (2), 178–198.
Henry, J.D., Crawford, J.R., 2004. Verbal fluency deficits in Parkinson's disease: a meta-analysis. J. Int. Neuropsychol. Soc. 10 (4), 608–622.
Hoehn, M.M., Yahr, M.D., 1967. Parkinsonism: onset, progression and mortality. Neurology 17 (5), 427–442.

Hughes, A.J., Daniel, S.E., Kilford, L., Lees, A.J., 1992. Accuracy of clinical diagnosis of idiopathic Parkinson's disease: a clinico-pathological study of 100 cases. J. Neurol. Neurosurg. Psychiatry 55 (3), 181–184.
Johari, K., Ashrafi, F., Zali, A., Ashayeri, H., Fabbro, F., Zanini, S., 2013. Grammatical deficits in bilingual Azari – Farsi patients with Parkinson's disease. J. Neuroling. 26 (1), 22–30.
Koch, I., Prinz, W., Allport, A., 2005. Involuntary retrieval in alphabet-arithmetic tasks: task-mixing and task-switching costs. Psychol. Res. 69 (4), 252–261.
Kohnert, K.J., Bates, E., Hernandez, A.E., 1999. Balancing bilinguals: lexical-semantic production and cognitive processing in children learning Spanish and English. J. Speech Lang. Hear. Res. 42 (6), 1400–1413.
Kong, A.P.-H., Abutalebi, J., Lam, K.S.-Y., Weekes, B., 2014. Executive and language control in the multilingual brain. Behav. Neurol. 2014, 527951.
Kray, J., Lindenberger, U., 2000. Adult age differences in task switching. Psychol. Aging 15 (1), 126–147.
Lieberman, P., Kako, E., Friedman, J., Tajchman, G., Feldman, L.S., Jiminez, E.B., 1992. Speech production, syntax comprehension, and cognitive deficits in Parkinson's disease. Brain Lang. 43 (2), 169–189.
Los, S.A., 1996. On the origin of mixing costs: exploring information processing in pure and mixed blocks of trials. Acta Psychol. 94 (2), 145–188.
Luk, G., Green, D.W., Abutalebi, J., Grady, C., 2012. Cognitive control for language switching in bilinguals: a quantitative meta-analysis of functional neuroimaging studies. Lang. Cogn. Processes 27 (10), 1479–1488.
Marí-Beffa, P., Cooper, S., Houghton, G., 2012. Unmixing the mixing cost: contributions from dimensional relevance and stimulus-response suppression. J. Exp. Psychol.. Hum. Percept. Perform. 38 (2), 478–488.
Marié, R.M., Barré, L., Dupuy, B., Viader, F., Defer, G., Baron, J.C., 1999. Relationships between striatal dopamine denervation and frontal executive tests in Parkinson's disease. Neurosci. Lett. 260 (2), 77–80.
Mariën, P., Abutalebi, J., Engelborghs, S., De Deyn, P.P., 2005. Pathophysiology of language switching and mixing in an early bilingual child with subcortical aphasia. Neurocase 11, 385–398.
Meuter, R.F.I., Allport, A., 1999. Bilingual language switching in naming: asymmetrical costs of language selection. J. Mem. Lang. 40, 25–40.
Morris, J.C., Heyman, A., Mohs, R.C., Hughes, J.P., van Belle, G., Fillenbaum, G., Mellits, E.D., et al., 1989. The Consortium to Establish a Registry for Alzheimer's Disease (CERAD). Part I. Clinical and neuropsychological assessment of Alzheimer's Disease.Neurology 39 (9), 1159–1165.
Narayanan, N.S., Rodnitzky, R.L., Uc, E.Y., 2013. Prefrontal dopamine signaling and cognitive symptoms of Parkinson's disease. Rev. Neurosci. 24 (3), 267–278.
Owen, A.M., Doyon, J., Dagher, A., Sadikot, A., Evans, A.C., 1998. Abnormal basal ganglia outflow in Parkinson's disease identified with PET. Implications for higher cortical functions. Brain: J. Neurol. 121 (5), 949–965.
Peña-Casanova, J., Quinones-Ubeda, S., Quintana-Aparicio, M., Aguilar, M., Badenes, D., Molinuevo, J.L., NEURONORMA Study Team, et al., 2009a. Spanish Multicenter Normative Studies (NEURONORMA Project): norms for verbal span, visuospatial span, letter and number sequencing, trail making test, and symbol digit modalities test. Arch. Clin. Neuropsychol. 24 (4), 321–341.
Peña-Casanova, J., 2005. Test Barcelona. Masson, Spain.
Peña-Casanova, J., Quiñones-Ubeda, S., Gramunt-Fombuena, N., Quintana-Aparicio, M., Aguilar , M., Badenes, D., NEURONORMA Study Team, et al., 2009b. Spanish Multicenter Normative Studies (NEURONORMA Project): norms for verbal fluency tests. Arch. Clin. Neuropsychol. 24 (4), 395–411.
Polito, C., Berti, V., Ramat, S., Vanzi, E., De Cristofaro, M.T., Pellicanò, G., Mungai, F., et al., 2012. Interaction of caudate dopamine depletion and brain metabolic changes with cognitive dysfunction in early Parkinson's disease. Neurobiol. Aging. 33 (1), 29– 39.
Prior, A., Gollan, T.H., 2013. The elusive link between language control and executive control: a case of limited transfer. J. Cogn. Psychol. 25 (5), 622–645.
Protopapas, A., 2007. CheckVocal: a program to facilitate checking the accuracy and response time of vocal responses from DMDX. Behav. Res. Methods 39 (4), 859–862.
Reitan, R.M., Wolfson, D., 1985. The Halstead–Reitan Neuropsycholgical Test Battery: Therapy and Clinical Interpretation. Neuropsychological Press, Tucson, AZ.
Roelofs, A., Piai, V., 2011. Attention demands of spoken word planning: a review. Front. Psychol. 2, 307.
Rogers, R.D., Sahakian, B.J., Hodges, J.R., Polkey, C.E., Kennard, C., Robbins, T.W., 1998. Dissociating executive mechanisms of task control following frontal lobe damage and Parkinson's disease. Brain: J. Neurol. 121 (5), 815–842.
Rubin, O., Meiran, N., 2005. On the origins of the task mixing cost in the cuing task-switching paradigm. J. Exp. Psychol. Learn. Mem. Cogn. 31 (6), 1477–1491.
Snodgrass, J.G., Vanderwart, M., 1980. A standardized set of 260 pictures: norms for name agreement, image agreement, familiarity, and visual complexity. J. Exp. Psychol. Hum. Learn. Mem. 6 (2), 174–215.
Ullman, M.T., Corkin, S., Coppola, M., Hickok, G., Growdon, J.H., Koroshetz, W.J., Pinker, S., 1997. A neural dissociation within language: evidence that the mental dictionary is part of declarative memory, and that grammatical rules are processed by the procedural system. J. Cogn. Neurosci. 9 (2), 266–276.
Weissberger, G.H., Wierenga, C.E., Bondi, M.W., Gollan, T.H., 2012. Partially overlapping mechanisms of language and task control in young and older bilinguals. Psychol. Aging 27 (4), 959–974.
Witt, K., Daniels, C., Schmitt-Eliassen, J., Kernbichler, J., Rehm, S., Volkmann, J., Deuschl, G., 2006. The impact of normal aging and Parkinson's disease on response preparation in task-switching behavior. Brain Res. 1114 (1), 173–182.
Ye, Z., Zhou, X., 2009. Executive control in language processing. Neurosci. Biobehav. Rev. 33 (8), 1168–1177.
Zanini, S., Tavano, A., Fabbro, F., 2010. Spontaneous language production in bilingual Parkinson's disease patients: evidence of greater phonological, morphological and syntactic impairments in native language. Brain Lang. 113 (2), 84–89.
Zanini, S., Tavano, A., Vorano, L., Schiavo, F., Gigli, G.L., Aglioti, S.M., Fabbro, F., 2004. Greater syntactic impairments in native language in bilingual Parkinsonian patients. J. Neurol. Neurosurg. Psychiatry 75 (12), 1678–1681.
Zou, L., Ding, G., Abutalebi, J., Shu, H., Peng, D., 2012. Structural plasticity of the left caudate in bimodal bilinguals. Cortex 48 (9), 1197–1206.