Citation: Marien, P., van Dun, K., Van Dormael, J., Vandenborre, D., Keulen, S., Manto, M., Verhoeven, J. & Abutalebi, J. (2017). Cerebellar induced differential polyglot aphasia: a neurolinguistic and fMRI study. Brain and Language, 175, pp. 18-28. doi: 10.1016/j.bandl.2017.09.001

Link to published version: https://doi.org/10.1016/j.bandl.2017.09.001

Title: CEREBELLAR INDUCED DIFFERENTIAL POLYGLOT APHASIA: A NEUROLINGUISTIC AND FMRI STUDY

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Abbreviated Title: Cerebellar induced polyglot aphasia

Funding: this study was supported by a research grant of the Fund for Scientific Research-Flanders (G035714N) and by a Strategic Research Program (SPR15) awarded by the Vrije Universiteit Brussel, Belgium.

ABSTRACT

Research has shown that linguistic functions in the bilingual brain are subserved by similar neural circuits as in monolinguals, but with extra-activity associated with cognitive and attentional control. Although a role for the right cerebellum in multilingual language processing has recently been acknowledged, a potential role of the left cerebellum remains largely unexplored.

This paper reports the clinical and fMRI findings in a strongly right-handed (late) multilingual patient who developed differential polyglot aphasia, ataxic dysarthria and a selective decrease in executive function due to an ischemic stroke in the left cerebellum. fMRI revealed that lexical-semantic retrieval in the unaffected L1 was predominantly associated with activations in the left cortical areas (left prefrontal area and left postcentral gyrus), while naming in two affected non-native languages recruited a significantly larger bilateral functional network, including the cerebellum. It is hypothesized that the left cerebellar insult resulted in decreased right prefrontal hemisphere functioning due to a loss of cerebellar impulses through the cerebello-cerebral pathways.

Key words: Cerebellum; Polyglot Aphasia; Bilingualism; fMRI; Differential recovery

Declaration of interest: The authors declare that they have no conflict of interest to declare.

1. **Introduction**

During the past decades a substantial amount of clinical and experimental research has been dedicated to the functional organization of the bilingual brain and the neural networks subserving language processing in bi- or multilinguals in comparison to monolinguals. Findings from these studies have reported that essentially monolinguals and bilinguals process languages in the same neural fashion with the exception that bilingual language processing is often paralleled by extra-activity in areas related to cognitive and attentional control (Abutalebi & Green, 2007; 2016). This extra-activity is usually associated with some specific factors related to second language (L2) processing. Indeed, much of the available literature on the neurobiology of multilingualism indicates that the neural representation and organization of language is the product of a complex process depending on various factors such as age of language acquisition, level of proficiency and level of exposure (Abutalebi, 2008; Perani & Abutalebi, 2005). A more divergent network is associated with late acquisition of the L2 language (Liu and Cao, 2016) and less proficiency (Kotz, 2009). As outlined by Abutalebi and Green (2007), a non-native language which is not processed with the same ease as L1 is less automatized in neurocognitive terms and as such in need of increased cognitive control (i.e., language control). These language control mechanisms allow multilinguals to adequately suppress one language while communicating in another and to flawlessly switch between several target languages.

Converging evidence from clinical and experimental neuroimaging studies shows that the neural system subserving language control and selection processes consists of a widely distributed general cognitive control system mainly involving the bilateral dorsolateral prefrontal areas (specifically the middle and inferior frontal gyri), the anterior cingulate cortex, the bilateral inferior parietal lobules, and subcortical structures such as the basal ganglia, the thalamus, and the cerebellum (Abutalebi & Green, 2016; Green & Abutalebi, 2013). Although crucial involvement of the basal ganglia (e.g. thalamus, left caudate, left putamen) in bilingual language processing has been convincingly demonstrated (Abutalebi, Della Rosa, Castro Gonzaga, et al., 2013; Abutalebi, Della Rosa, Ding, et al., 2013; Crinion et al., 2006; Zou, Ding, Abutalebi, Shu, & Peng, 2012), a possible role of the recently acknowledged linguistic and cognitive posterior cerebellum, specifically including lobule VII and Crus I, and part of the prefronto-cerebellar loop involved in language and executive control (Stoodley & Schmahmann, 2009) in bilingual language processing has been much less explored.

The cerebellum is linked to all the key regions of the language control network and in their adaptive control model (Green & Abutalebi, 2013), Green and Abutalebi (2013) attribute a role in "opportunistic planning" to the cerebellum during multilingual language processing. This model attributes a prominent role to the cerebellar - left prefrontal connection in using more readily available L1 words/structures to convey meaning in a less proficient language (Green & Abutalebi, 2013). Functional imaging studies using sentence production and comprehension tasks have to elucidate this view but, as hypothesized (Abutalebi & Green, 2016), it is plausible that cerebellar activation mediates the prediction of future input (L2 processing) based on past knowledge (L1 structures/vocabulary) (Ito, 2008). The ability to make predictions entails maintaining an ongoing representation, which ensures resistance to interference (Abutalebi & Green, 2016). Several studies have reported changes in cerebellar grey matter density in bilingual speakers correlated to proficient performance (bilateral VIIa Crus I/II and right lobule V; Pliatsikas, Johnstone, & Marinis, 2014)[1] and the density in the right posterior vermis might predict the ease with which they resist interference from their first language (Filippi et al., 2011). These studies imply a cerebellar role in the multilingual control network, although the role of the cerebellum in prediction has been challenged (Argyropoulos, 2016).

Clinical findings might contribute to our knowledge about the cerebellar role in multilingualism, but bilingual or polyglot aphasia is a diverse and complex phenomenon that is still poorly understood (Paradis & Libben, 2014). A variety of aphasia symptoms and recovery patterns have been observed in bilinguals/multilinguals after stroke in language-critical regions (Lorenzen & Murray, 2008). Although parallel recovery typically occurs in most of the multilingual cases, a number of non-parallel recovery patterns have been documented in the literature (Fabbro, 2001). Green and Abutalebi (2008) argued that non-parallel recovery in multilingual aphasia is due to disruption of the language control network. One such pattern of non-parallel recovery is involuntary and uncontrolled ‘pathological language mixing and switching' (Mariën, Abutalebi, Engelborghs, & De Deyn, 2005; Kong, Abutalebi, Lam, & Weekes, 2014). Damage to the fronto(-parieto)-subcortical circuit can lead to pathological language switching and mixing, and even to fixation on one single language (Green & Abutalebi, 2008). Kong et al. (2014) related pathological language mixing and switching to an impairment of executive functions, suggesting a shared fronto-basal ganglia network between the domain-general executive system and language control.

We report the clinical and functional neuroimaging findings in a strongly right-handed multilingual patient who following a left cerebellar stroke developed aphasia in

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[1] All cerebellar anatomy terminology is in accordance with Schmahmann, Doyon, Petrides, Evans, and Toga (2000).

each of the six languages he acquired as a late polyglot, while his mother tongue (L1) remained largely unaffected (differential polyglot aphasia). Pathological fixation on one language has been previously reported after subcortical damage (Aglioti, Beltramello, Girardi, & Fabbro, 1996; Aglioti & Fabbro, 1993), and after damage to the language-dominant temporal lobe (Ku, Lachmann, & Nagler, 1996). After a stroke affecting the left basal ganglia, a 68-year-old right-handed woman developed bilingual aphasia affecting expression in her mother tongue (Venetian) more than in her second language (Italian) while comprehension was preserved in both languages (Aglioti et al., 1996; Aglioti & Fabbro, 1993). Left temporal lobe damage, on the other hand, resulted in a loss of all expressive and receptive second language skills, leaving his mother tongue fully intact (Ku et al., 1996). In our case, the pathological fixation on his mother tongue was linked to damage to the left cerebellum. A hypothesis is put forward to explain the selective disruption of the non-native languages due to left cerebellar stroke.

2. Case report

2.1. History

A 72-year-old right-handed man was admitted to hospital after acute onset of language disturbances, balance problems, vertigo, and vomiting. On admission, the clinical neurological examination revealed left-sided ataxia with a strong tendency to fall over to the right side. He could stand up straddled. He was not able to understand or express himself in any other but his maternal language (English (L1)) that was unaffected, apart from mild word-finding difficulties for low-frequency words and mild ataxic dysarthria (slurred speech):

"I was watching television at my apartment in Antwerp when suddenly the room seemed to spin around violently. I tried to stand but was unable to do so. I felt a need to vomit and managed to crawl to the bathroom to take a plastic bowl. My next instinct was to call the emergency services, but the leaflet I have outlining the services was in Dutch and for some

> reason, I was unable to think (or speak) in any other language than my native English. I have lived in Antwerp for many years and use Dutch (Flemish) on a day-to-day basis. I called my son-in-law, who speaks fluent English and he drove me to Middelheim Hospital. We normally speak English when together. I understood none of the questions asked of me in Dutch by hospital staff and they had to be translated back to me in English. My speech was slurred. I had lost some words, I was aware of that, but I cannot recall which words. I made no attempt to speak any of the other languages I know, and in the first hours of my mishap happening, I do not think I realized that I had other languages."

Medical history consisted of arterial hypertension, type 2 diabetes mellitus and a right occipital infarction 10 years before the current stroke. He had an educational level of 12 years (grammar school) and had worked as a war and political correspondent for British, US and Australian newspapers in several countries for more than 40 years. He mastered seven languages: English (maternal language; L1), French (learned at school from age 11 onwards, L2), German (learned at school from age 13 onwards, L3), Slovene (L4) and Serbo-Croat (L5) (learned by means of a crash course at age 24), Hebrew (Ivrit, learned during an intensive course at age 28, L6), and Dutch (moved to live in Belgium from age 35 onwards, L7). He used English (L1), Dutch (L7) and French (L2) on a nearly daily basis. He was in regular contact with friends in Belgrade and Berlin with whom he communicated in Serbo-Croat (L5) and German (L3). He read the Serbian and German press on line and followed several forums that talk of the old Yugoslavia, its politics and economics.

T2-weighted axial FLAIR MRI of the brain showed an inhomogeneous hyperintense lesion in the territory of the medial branch of the left PICA slightly encroaching upon the posterior portion of the lower medulla at the left (gracile and cuneate nuclei) consistent with a recent infarction in the vascular territory of the left PICA (Figure 1 A-C). An old vascular lesion in the left occipital lobe (Figure 1 D-E) and some periventricular white matter lesions were found as well (Figure 1 F). Diffusion-weighted MRI (axial images) confirmed a hyperintense signal in the territory of the medial branch of left PICA (Figure 2 A-C) with involvement of the medial portion of left dentate nucleus. Based on the type of the stroke and the MRI, part of lobules VIIIa/VIIIb and IX were likely affected, together with VIIa Crus I/II. MR angiography (axial image) showed a hyperintense area in the lumen of left vertebral artery instead of a flow void (Figure 2 D). The angiogram revealed an absence of opacification of left vertebral artery (Figure 2 E). Anticoagulant therapy was started.

[INSERT FIGURE 1 NEAR HERE]

[INSERT FIGURE 2 NEAR HERE]

By the end of the first day remission of ataxic dysarthria was noted. The patient indicated that Dutch gradually began to return from the second day poststroke onwards and that a reversion to a previously learnt accent (Antwerp dialect and Estuary English) had taken place in both his mother tongue and in Dutch:

> "My Dutch began to return in the mid-day, by no means perfect, but enough to converse with the nursing staff. When speaking Dutch, there is a ‘’voice in my head” telling me that I am not speaking with good grammar, but I am pleased I can converse and be understood. I was still struggling for some everyday words and grammar. There appears to be more Antwerp accent (local) when speaking, though not at all times. (...) My English is no longer impaired in any way, though I still have trouble in finding certain words, words that I know, but do not use every day. I then find the word I was looking for in the morning popping into my mind for no apparent reason in the middle of the afternoon. In several years of commuting between Europe and Australia (five or six times a year for more than 12 years) as editor of a magazine, I had adopted a bit of an Australian accent, and the tendency to put the stress on certain words, sometimes making a sentence sound more like a question. That has gone. I am speaking in a more Estuary English, the English of my younger days (southern England)."

On the third day poststroke the patient noted that the other languages also started to return:

> "I find my other languages starting to return, in varying degrees of fluency. I carry out a simple test: counting to 20 in each language, and trying to form easy sentences. I felt inwardly pleased with my progress."

In-depth neuropsychological and neurolinguistic investigations were performed one week after stroke (see 2.2) and language therapy as well as an intensive locomotor rehabilitation programme were started which substantially improved gait and balance. During the next four weeks language skills gradually improved but apart from his mother tongue, all non-native languages remained affected at the lexical and syntactic level. In addition, non-native speech was characterized by the phenomenon of language mixing and switching:

> “Words in all my languages are coming back to me. Many are words that I have learned over the years, but rarely have use for -- words that do not fit into my everyday life. My Dutch is often ‘local’ – but when reading Gazet van Antwerpen *[Flemish newspaper]* and De Telegraaf *[Hollandic newspaper]*, I recognize instantly the different styles of language. (...) I have tried to recall my Slovene, but it gets mingled badly with Serbo-Croat. The same goes for German, which reverts to Dutch (mixed up). Dutch and German have considerable similarity (my opinion) and Serbo-Croat and Slovene both are Slavic languages with many similarities.”

2.2. Neuropsychological and Neurolinguistic Investigations

In-depth neurocognitive assessments were performed in the patient's maternal language one week poststroke on the basis of standardised clinical test batteries. Neuropsychological assessments consisted of the Mini Mental State Examination (MMSE; Folstein, Folstein, & McHugh, 1987), the revised version of the Repeatable Battery for the Assessment of Neuropsychological Status (RBANS; Randolph, 1998), Raven’s Colored Progressive Matrices (Raven, 1965), the Stroop Color Word Test (Golden, 1978), and the Wisconsin Card Sorting Test (WCST; Heaton, Chelune, Talley, Kay, & Curtis, 1993).

Formal investigation of language was performed in both English and Dutch by means of the English and Dutch version of the Comprehensive Aphasia Test (CAT; Howard, Swinburn, & Porter, 2004; CAT-NL; Visch-Brink, De Smet, Vandenborre & Mariën, 2013), the Boston Naming Test (BNT) (English: Kaplan, Goodglass, & Weintraub, 1983; Dutch: Mariën, Mampaey, Vervaet, Saerens, & De Deyn, 1998), and semantic verbal fluency tasks consisting of the production of as many names as possible of animals, means of transport, vegetables and clothes during one minute (unpublished norms). Neuropsychological and neurolinguistic test results are shown in Table 1 and 2.

A z-score of -1.5 was considered clinically abnormal. A z-score of more than -2 was considered pathological.

[INSERT TABLE 1 NEAR HERE]

[INSERT TABLE 2 NEAR HERE]

A strong and consistent right hand preference was objectified by means of the Edinburgh Handedness Inventory (Oldfield, 1971) demonstrating a laterality quotient of +100. General cognitive screening was normal (MMSE: 27/30, z: -0,6). The RBANS showed a superior visuospatial/constructive skill index (= 121, z: +1,40) and a very superior immediate recall index (= 136, z: +2,40). Language (= 96, z: -0,27), attention (= 94, z: -0,4), and delayed recall (= 101, z: +0,07) were within the normal range, although a clinically abnormal score was found for figure recall. Raven's Colored Progressive Matrices revealed a high average spatial intelligence level (pct. 90). The ability to form abstract concepts, to shift and maintain goal-oriented cognitive strategies in response to changing environmental contingencies as measured by means of the WCST was normal as well (4 categories within 64 trials). The Stroop Color Word test (pct. 15) showed a depressed, low average ability to inhibit a competing and more automatic response set.

Assessment of native language functions by means of the CAT revealed maximum scores for all subtests. By contrast, the CAT-NL disclosed a profile (Table 2) in which reading at both the comprehension and production (reading aloud) level was better preserved than oral and written language production. Oral language comprehension was severely affected at the word (24/30; z: -2.6), sentence (24/32; z: -4.0) and paragraph level (2/4; z: -2.1) while written language comprehension only scored in the defective range at the word level (24/30; z: -5.5). Repetition was only preserved for complex words. By contrast, pathological scores were obtained for word (16/32; z: -11.0), nonword (2/10; z: -3.8) and sentence repetition (4/6; z: -4.5). Digit string repetition was depressed and scored in the clinical defective range (4/7; z: -1.6). As reflected by a total score of 24/58 naming was severely disrupted. Object (18/48; z: -5.7) and action naming (6/10; z: -4.4) scored in the severely pathological range. Examination of reading skills only disclosed a pathological result for word reading (44/48; z: -2.2). The reading of complex words, function words and nonwords was normal. Writing skills were severely disrupted. The patient scored within the severely pathological range for written picture naming (10/23; z: -5.8) and writing to dictation (22/28; z: -4.5). Agrammatism was found in oral as well as written language production. Paraphasias (phonematic and semantic) only exceptionally occurred but speech and written language output was characterised by the intrusion of foreign words (English).

Visual confrontation naming was normal for English (BNT: 57/60, z: +0.3) but scored in the severely defective range for Dutch (BNT: 25/60, z: -10,6) (Table 1). The majority of errors consisted of 'don't know responses' (n=18/35 errors) and intrusions of foreign (English) words (n=11/35 errors). Controlled oral word association (semantic word fluency) scored within the low average range (38 items, z: -1.2).

2.3. Functional Magnetic Resonance Imaging (fMRI)

2.3.1. Stimuli and Tasks

To build a set of items for fMRI purposes, an experimental visual confrontation naming task was constructed that consisted of a selection of 50 black and white drawings (Snodgrass & Vanderwart, 1980), of high-frequency words in English (L1) (Snodgrass & Vanderwart, 1980), French (L2) (Alario & Ferrand, 1999), German (L3) (Bates et al., 2003), Serbo-Croat (L4) (Kostíc, 1999), Slovenian (L5) (Erjavec & Dzeroski, 2004), Hebrew (L6) (Frost & Plaut, 2001), and Dutch (L7) (Keuleers, Brysbaert, & New, 2010).

Administration of the naming tests one month post stroke showed that the patient named less than 20 percent of the high-frequency items correctly in German, Hebrew, Serbo-Croat and Slovenian and more than 80 percent in English (L1), French (L2) and Dutch (L7). Only the sets in which he scored above 80 percent correct were retained for fMRI purposes. Three sets consisting of 40 high-frequency items that were all named correctly in English (L1), French (L2) and Dutch (L7) were included in the fMRI paradigm.

Four blocks of ten images were generated for each language, and four blocks of control line drawings without meaning (scribbles) for a total of 16 blocks. Each of the 40 black and white drawings were presented to the patient just before the actual scanning to make sure he could still name the object or animal in the requested language. The blocks were presented randomly during the scan with nine seconds rest between the blocks to avoid switching effects. Each image was shown for three seconds, resulting in blocks of 30 seconds. To indicate in which language the patient had to name the depicted item, the flag of the country (United Kingdom (L1), Belgium (L7), France (L2)) was added in the upper left corner of the images. The patient named the pictures covertly to avoid movement artefacts. Therefore the entire block of 30 seconds was used in the analysis to identify naming activations.

2.3.2. Acquisition

Functional MRI was conducted five months poststroke on a 3T Siemens scanner (TrioTim) equipped with a standard 32-channel head coil. A BOLD sensitive T2*-weighted single shot gradient recalled (GR) echo planar imaging (EPI) sequence (TE/TR: 50/3000ms; FA: 90º) was used resulting in voxel dimensions of 3 x 3 x 3 mm3 (interleaved), FOV = 1344 x 1344, matrix = 64 x 64. Functional images were acquired in the axial orientation.

2.3.3. Analysis

fMRI data were analysed using SPM12 software (www.fil.ion.ucl.ac.uk/spm). After motion and slice timing correction, the unwarped functional images were registered to the T1 weighted anatomical data set. The anatomical image was then segmented and the forward deformation field was used to normalize the functional images to MNI (Montreal Neurological Institute) space. The registered functional data were smoothed spatially with a Gaussian kernel with a full width at half maximum (FWHM) of 6 x 6 x 6 mm3. Activations during the control condition were subtracted from the activations during naming in the three languages to assess language-specific activations (EN > CTRL; FR > CTRL; DU > CTRL). A conjunction analysis of these three contrasts was performed to identify the common regions. In addition, differences between the languages were investigated by contrasting French and Dutch with English (FR > EN; DU > EN). A conjunction analysis of these two contrasts revealed the activations specific for L2 languages. The clusters specific for Dutch naming were identified by masking the contrast DU > EN with the contrast FR > EN. Clusters with a peak with an uncorrected p-value smaller than 0.001 and a minimal cluster size of 20 voxels were detected. Only clusters with a family-wise error (FWE)-corrected p-value ≤ 0.05 or with a cluster peak with an FWE-corrected p-value ≤ 0.01 are reported. All clusters are listed in Table 3.

[INSERT TABLE 3 NEAR HERE]

2.3.4. Results

English (L1) compared to control task

Silent naming of pictures in the patient's mother tongue (English, L1) activated three brain regions. The strongest activation was found in the right frontal lobe, including the middle and superior frontal gyrus. A smaller cluster was detected in the contralateral left frontal homologue region. A third cluster was marginally activated in the left postcentral gyrus, near Wernicke's area. These clusters are visualized in Figure 3.

[INSERT FIGURE 3 NEAR HERE]

French (L2) compared to control task

During French picture naming (Figure 4), a large bilateral frontal network was recruited including the bilateral anterior insular regions, the middle and superior frontal gyri, the left cingulate gyrus, and a small part of the right superior temporal gyrus. Besides a large activation in the left superior temporal gyrus, a smaller (and less activated) contralateral right cluster was found in the homologue region. A right fronto-parietal cluster was also observed including the cingulate gyrus. In addition, the left posterior cerebellum (primarily lobule VI/VIIb) was activated.

[INSERT FIGURE 4 NEAR HERE]

Dutch (L7) compared to control task

Dutch picture naming resulted in largely the same clusters of activation as in French picture naming (Figure 5). At the supratentorial level, a large bilateral frontal network including the middle and superior frontal gyri was found as well as activation of the insular regions and the left and right temporal regions. No activation was found in the cingulate gyri. At the infratentorial level bilateral activation of the right (primarily VIIa Crus I-II) and left posterior cerebellum (primarily lobule VI/VIIb) were found.

[INSERT FIGURE 5 NEAR HERE]

Regions common to all languages

The three regions activated during English picture naming (the right and left middle and superior frontal gyrus and the left postcentral gyrus) were common to naming in all languages, but only the shared right frontal cluster reached significance.

Dutch (L7) and French (L2) compared to English (L1)

Regions that were more activated in the languages learned at a later age (Dutch and French) than the native language (English) were primarily situated in the left and right fronto-temporal areas (Figure 6). In the left hemisphere, a large cluster in the precentral gyrus in the vicinity of the insular region and a more anterior region in the middle frontal gyrus were actively recruited, while in the right hemisphere a fronto-temporal region in the rolandic operculum was activated together with the insula. During Dutch naming, however, the areas that were stronger activated than during English naming were more diffuse and widespread. In addition to larger activation of left and right fronto-temporal areas, both cerebellar hemispheres (left posterior cerebellum, and a more anterior cluster involving primarily the right cerebellar hemisphere), the left fusiform gyrus, the cingulate gyrus, and the bilateral dorsolateral prefrontal regions were significantly stronger activated compared to English (Figure 7).

[INSERT FIGURE 6 NEAR HERE]

[INSERT FIGURE 7 NEAR HERE]

3. Discussion

Following a left cerebellar ischemic stroke this strongly right-handed multilingual patient acutely developed a transient mild ataxic dysarthria and differential polyglot aphasia initially characterized by a complete loss of all six non-native languages while his maternal language was only very mildly affected by word-finding difficulties for low-frequency words. Within the course of a few days, remission of polyglot aphasia started to take place but apart from full recovery of the mother tongue, all non-native languages remained affected to a different degree at the lexical and syntactic level. In addition, non-native speech was characterized by the phenomenon of pathological language mixing and switching and reversion to a previously learned accent occurred as well (see Keulen et al., 2017).

To assess cerebral language lateralization, an fMRI visual confrontation naming study consisting of 40 high-frequency objects and animals versus 40 simple meaningless line drawings was performed in English (L1), French (L2) and Dutch (L7). Since aphasia still substantially affected lexical-semantic retrieval in German, Hebrew, Serbian and Slovenian one month after stroke these languages could not be reliably tested in the scanner. As evidenced by fMRI results, naming in the maternal language (L1) was predominantly associated with left hemisphere activations (left postcentral gyrus) and a bilaterally distributed dorsolateral prefrontal activation pattern (right more than left). Naming in the non-native languages French (L2) and Dutch (L7) recruited a significantly larger neuronal network consisting of extensive bilateral frontal activations, left parieto-temporal activations extending towards the temporal lobe and activation of the right temporal homologue. In addition, an activated cluster was found in the left posterior cerebellum (lobule VI/VIIb) for L2 naming, and in the right cerebellum (more anteriorly in the VIIa Crus I-II) for Dutch naming.

Current knowledge about the neural organisation of the bilingual brain seems to indicate that irrespectively of considerable diversity due to age of L2 acquisition and level of L2 proficiency, native as well as non-native languages are computed by a highly similar neural circuitry located in the perisylvian cortical and subcortical regions of the language dominant hemisphere. Abutalebi and Green (2016) defined the bilingual language network on the basis of a close functional interplay between the dorsal anterior cingulate cortex/pre-SMA, the left prefrontal cortex, the left caudate nucleus, and the bilateral inferior parietal lobules, controlled by the right prefrontal cortex, the thalamus and putamen, and the cerebellum. Within this neural network a possible crucial role of the cerebellum seems to be gradually emerging (Filippi et al., 2011; Pillai et al., 2004). Damage to the left posterior cerebellum (involving VIIb Crus I/II, anatomically and functionally linked to the right dorsolateral prefrontal area) resulting in the loss of all L2 languages might indicate an important role for the functional language network subserved by crossed cerebellocerebral pathways between the left cerebellum and the cortical association areas of the right dorsolateral prefrontal cortex (which was strongly implicated in picture naming in all languages).

The constellation of anatomoclinical findings in this strongly right-handed multilingual patient deserves some further attention. Green and Abutalebi (2008) have argued that non-parallel recovery, such as pathological mixing and switching, is usually the result of an impairment of the language control network (Green & Abutalebi, 2008), supported by domain-general executive mechanisms (Kong et al., 2014). As a result, it might be hypothesized that due to the damage in the left cerebellar hemisphere, the dorsolateral prefrontal areas, responsible for inhibiting and selecting the correct responses, were functionally disrupted through cerebellocerebral diaschisis. The ability to inhibit the stronger L1 was impaired, causing a temporary loss of all non-native languages. This might explain why the two most used non-native languages (French and Dutch) recovered faster, and why pathological language mixing and switching persisted when using the other non-native languages. Selective disruption of the executive mechanisms was also apparent at the non-linguistic level. Neurocognitive investigations revealed no abnormalities except for a severely impaired ability to inhibit competing and more automatic responses (Stroop color-word test).

Functional MRI revealed that naming in French and Dutch, languages learned at a later age, relied heavily on an extensive control network primarily involving the bilateral dorsolateral prefrontal areas, and the insular regions/basal ganglia. A number of studies has shown that left dorsolateral prefrontal/inferior frontal gyrus activity may be related to response selection and right dorsolateral prefrontal/inferior frontal gyrus activity to response inhibition (Abutalebi & Green, 2016; Aron, Behrens, Smith, Frank, & Poldrack, 2007). Of note, we report activity of the cingular cortex only during naming of the second languages (as observed in the contrast second languages > L1) and we suggest that this may be due to increased monitoring demands for those languages in which the patient struggles. Conflict monitoring and error detection are two well known cognitive processes ascribed to the cingular cortex and these processed are key for correct language output in multilinguals. On the other hand, and interestingly, only one area seemed to "work more efficiently" (in terms of functional brain activity for L1), i.e., the right prefrontal cortex. This area is linked to response inhibition (Abutalebi & Green, 2016; Aron et al., 2007) and, indeed, during L1 production, the patient never had intrusions from the other languages. Pathological switching was more common when speaking the second languages but not when speaking in L1 underlining that response inhibition was impaired specifically for the second languages. In other words, the left cerebellar lesion lead to a functional deactivation of the right prefrontal cortex only for the later acquired languages, which may be less resistant to brain damage. The observed activation of the right cerebellar Crus I and II, known to be functionally and anatomically connected to the prefrontal areas involved in executive control and language (Stoodley & Schmahmann, 2009), in our patient during Dutch picture naming might reflect a compensatory mechanism for the damaged left cerebellar hemisphere to regain the proficiency of a language learned as a late bilingual through response selection by the left prefrontal area. These results indicate that not only the right cerebellum is involved in the language control system, but that the left cerebellum might also be implicated.

4. Conclusion

This neuropsychological and neuroimaging study of a strongly right-handed multilingual patient seems to indicate a cardinal role of the left cerebellum in the neural mechanisms subserving linguistic non-native language processing and control in multilingual subjects.

5. Acknowledgments

We are grateful to JVD for setting up the fMRI naming tasks in the different languages, to WVH for performing the fMRI experiment, and to JB for lending his expertise in this case study.

6. References

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Legend to Figures

Figure 1: Structural MRI of the brain

Axial MR images showing a hyperintense signal in the territory of the medial branch of left posterior inferior cerebellar artery (PICA; white arrows in A, B, C), with a small extension to the posterior portion of the lower medulla on the left (gracile and cuneate nuclei; arrowhead in A). The inferior cerebellar peduncles (dotted arrows in B) and the middle cerebellar peduncles (dotted arrows in C) are spared, as well as the mesencephalon (dotted arrows in D). Hypersignals in left occipital lobe (D, E) and periventricular white matter (F) are detected.
Legend: R=right

Figure 2: Magnetic Resonance Angiography

Diffusion-weighted MRI (axial images) confirming a hyperintense signal in the territory of the medial branch of left posterior inferior cerebellar artery (PICA; white arrows in A, B, C). Note the involvement of the medial portion of left dentate nucleus. MR angiography (axial image) shows an area of hypersignal in the lumen of left vertebral artery instead of a flow void (white arrow in D). The angiogram reveals an absence of opacification of left vertebral artery (E).
Legend: R=right

Figure 3: fMRI visual confrontation naming (p = 0.0001)

fMRI of visual confrontation naming in English (L1) versus a visual control task shows strongest activation in the right frontal lobe (A), including the middle and superior frontal gyrus. In addition to a region of activation in the left postcentral gyrus (C) a much smaller cluster is found in the contralateral left frontal homologue region (not visualised).
Legend: R=right; L=left; A=anterior; P=posterior

Figure 4: fMRI visual confrontation naming (p = 0.0001)

fMRI of visual confrontation naming in French (L2) versus a visual control task recruited the bilateral dorsolateral prefrontal areas (right: A, left: B), and the cingulate gyri (right: E, left: F). Besides a large activation in the left superior temporal gyrus including the insular regions (C), a smaller contralateral right cluster was found in the homologue region (K). In addition, the left posterior cerebellum (D) was activated, and the left (I) and right (J) basal ganglia.
Legend: R=right; L=left; A=anterior; P=posterior

Figure 5: fMRI visual confrontation naming (p = 0.0001)

fMRI of visual confrontation naming in Dutch (L7) versus a visual control task disclosed activation of the bilateral dorsolateral prefrontal areas (right: A, left: B), and the left and right temporal regions including the anterior insula (right: K, left: C). Activations in the right (H) and left posterior cerebellum (D), and in the basal ganglia (right: J, left: I) were found as well.
Legend: R=right; L=left; A=anterior; P=posterior

Figure 6: fMRI visual confrontation naming

Conjunction analysis of visual confrontation naming in Dutch (L7) and French (L2) versus visual confrontation naming in English (L1). Regions more activated in L7 and L2 than in L1 included the left and right fronto-temporal areas. In the left hemisphere, a large cluster in the precentral gyrus in the vicinity of the insular region (B) and a more anterior region in the middle frontal gyrus (A) were actively recruited, while in the right hemisphere a fronto-temporal region in the rolandic operculum (C) was activated together with the anterior insula (D).
Legend: R=right; L=left; A=anterior; P=posterior

Figure 7: fMRI visual confrontation naming

fMRI of visual confrontation naming in Dutch (L7) versus visual confrontation naming in English (L1) after subtracting the activated areas in French (L2) (see Figure 6). The areas that were stronger activated in L7 than in L1 (and L2) were more diffusely distributed and widespread. In addition to larger activation of left and right fronto-temporal areas including the insula (right: K, left: C) and a cluster in the left inferior parietal lobule (M), both cerebellar hemispheres (left posterior cerebellum extending into the fusiform gyrus (D), right posterior and anterior cerebellum (H)), and the bilateral dorsolateral prefrontal regions (AB) were significantly stronger activated in L7 compared to L1/L2.
Legend: R=right; L=left; A=anterior; P=posterior