NeuroImage 84 (2014) 495–504

Contents lists available at ScienceDirect

NeuroImage

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

Anatomical connectivity changes in the bilingual brain

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ARTICLE INFO

Article history:
Accepted 29 August 2013
Available online 7 September 2013

Keywords:
Bilingualism
Efficiency
Language
Network
Tractography

ABSTRACT

How the brain deals with more than one language and whether we need different or extra brain language sub-networks to support more than one language remain unanswered questions. Here, we investigate structural brain network differences between early bilinguals and monolinguals. Using diffusion-weighted MRI (DW-MRI) tractography techniques and a network-based statistic (NBS) procedure, we found two structural sub-networks more connected by white matter (WM) tracts in bilinguals than in monolinguals; confirming WM brain plasticity in bilinguals. One of these sub-networks comprises left frontal and parietal/temporal regions, while the other comprises left occipital and parietal/temporal regions and also the right superior frontal gyrus. Most of these regions have been related to language processing and monitoring; suggesting that bilinguals develop specialized language sub-networks to deal with the two languages. Additionally, a complex network analysis showed that these sub-networks are more graph-efficient in bilinguals than monolinguals and this increase seems to be at the expense of a whole-network graph-efficiency decrease.

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Introduction

Bilingualism is an extended phenomenon in the world and an interesting condition for investigating brain plasticity. Modern educational models often now include bilingual teaching from earliest childhood as societies become aware of the advantages of multilingualism for social communication and job opportunities. However, little is yet known about the brain implications of learning more than one language and so a key topic in recent brain research is the nature of the biological bases of bilingualism. It seems plausible that dealing with two languages instead of one should result in anatomical brain changes, especially when the languages concerned are typologically distant. Some previous studies have shown functional brain changes associated with bilingualism: i.e. the left inferior frontal gyrus (pars opercularis and triangularis), insula, anterior cingulate, dorsolateral prefrontal cortex, superior temporal cortex and the planum temporal (Kim et al., 1997; Parker Jones et al., 2012; Perani et al., 2003; Rodriguez-Fornells et al., 2002; Wartenburger et al., 2003). However, evidence for structural changes related to bilingualism is scarce and structural connectivity changes have not been documented so far. Here, we investigate whether the structural connectivity of the bilingual brain differs from that of the monolingual brain by using DTI (diffusion tensor imaging) and complex network analysis.

Several studies have shown specific brain changes related to experience and expertise in different cognitive skills (Carreiras et al., 2009; Draganski et al., 2004; Gaser and Schlaug, 2003; Lee et al., 2007; Maguire et al., 2012; Mechelli et al., 2004). Particularly in bilingualism, increased gray matter (GM) density has been reported in the left inferior parietal cortex in bilinguals as compared to monolinguals and this effect was stronger in early than in late bilinguals (Mechelli et al., 2004). In addition, Abutalebi et al. (2012) found a higher positive correlation for bilinguals as compared to monolinguals between GM volume in the anterior cingulated cortex (ACC) and the conflict effect that they found using an fMRI/behavioral paradigm in the same region. Stein et al. (2012), studied GM density changes in a group of second language (L2) learners after 5 months of L2 learning. They showed a correlation between the increase of L2 proficiency and increase of volume in the left inferior frontal gyrus and anterior temporal lobe. However, if bilingualism produces structural changes in GM, it is quite likely that these changes are also reflected in WM, due to changes in axonal characteristics such as myelination, density or caliber, axonal fiber wiring and synaptic connectivity during plasticity allowing faster and more efficient transmission of the information (Fields, 2008; Hursh, 1939; Tang et al., 2012; Thiebaut de Schotten et al., 2011; Waxman and Bennett, 1972). There are three prior studies showing higher WM density in the left parietal regions (Golestani et al., 2002) and in the left Heschl's gyrus (Golestani and Pallier, 2007) for faster learners as compared to slower

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http://dx.doi.org/10.1016/j.neuroimage.2013.08.064

learners of nonnative speech sounds, as well as in the left insula/prefrontal cortex and the bilateral inferior parietal cortex for people who accurately produce foreign sounds, compared to poorer producers (Golestani and Pallier, 2007; Golestani et al., 2007); suggesting that WM differences across individuals could predict behavioral differences in some aspects of language learning. More recently, Luk et al. (2011) compared the WM integrity in older bilinguals who regularly used both languages from childhood with their monolinguals peers. To do so, they used fractional anisotropy (FA), an index that can reflect variations in axonal density and myelination in WM tracts. Using a TBSS (tract-based spatial statistics) approach (Smith et al., 2006), they found higher FA values for older bilinguals as compared to those for monolinguals in the corpus callosum, in the superior longitudinal fasciculi, in the right inferior fronto-occipital fasciculus and uncinate fasciculus. Moreover, Mohades et al. (2012) extracted the mean FA values from 4 major tracks that are well known to connect language regions (i.e. the left arcuate fasciculus/superior longitudinal fasciculus, the left inferior fronto-occipital fasciculus and the bundles arising from the anterior and middle part of the corpus callosum) to compare children who were simultaneous bilinguals, sequential bilinguals and monolinguals. They found higher mean FA values in the left fronto-occipital fasciculus for simultaneous bilinguals as compared to those for other groups and lower values in the bundle arising from the anterior part of the corpus callosum in bilinguals as compared to those for monolinguals. Also, Schlegel et al. (2012) showed that brief linguistic immersion experience in L2 produced an increase in FA in the genu of the corpus callosum, in left tracts that connect language regions and in the right temporal regions for L2 learners as compared to that for non-learners.

Nonetheless, modifications in the axonal connectivity of the whole brain associated with bilingualism are still unknown. In particular, the relationship between bilingualism and topological properties of the brain anatomical network has never been investigated. There are many studies modeling the human brain as a complex network (Bassett et al., 2009; Iturria-Medina et al., 2007, 2008; Li et al., 2009; Zalesky et al., 2010a). From this perspective, the brain is modeled as a graph whose nodes (structural/functional brain regions) are interconnected by edges (structural/functional connections) (Bullmore and Bassett, 2011). This brain graph has complex network topological properties that are important for its performance. Conversely, functional performance can impact these topological properties (Sporns et al., 2000). As structural changes have been associated with increased language demands (Abutalebi and Green, 2007), we investigate whether, when two languages are acquired simultaneously early in life as compared with only one: a) whether brain structural network connections between GM regions are modified and b) if the network's capacity of management and integration of information differ or not. Taking into account the convergences between previous functional and structural findings, we expect structural connectivity in bilinguals to show higher axonal connection density among regions that have previously shown increased GM density and/or different functional demands in bilinguals or between regions that are connected by bundles of fibers with higher FA values, as previously demonstrated in bilinguals. These regions may have required a different configuration to increase their processing capacity in order to fulfill the increased language demands, thus we expect changes in some topological properties of the brain structural network in bilinguals.

We investigate the brain network structural changes associated with early bilingualism by using DTI-based anatomical connectivity analysis, where the connection density between pairs of GM regions is estimated by a tractography algorithm (Gong et al., 2009; Hagmann et al., 2008; Iturria-Medina et al., 2007, 2008). More specifically, we investigate brain network connectivity differences in 13 early Basque–Spanish bilinguals as compared to those in 13 Spanish monolingual participants, using a probabilistic fiber tractography algorithm. To determine differences in connectivity patterns between both groups we employ a network-based statistic (NBS) approach (Zalesky et al., 2010a, 2010b). The NBS identifies differences between groups; isolating sets of more highly interconnected regions (i.e. sub-networks) instead of just pairs of regions, thus providing information about whole-brain structural organization. Previous studies have used this methodology to identify impaired connectivity in subjects with different disease conditions as compared to that in healthy subjects (Bai et al., 2012; Verstraete et al., 2011; Zalesky et al., 2010b; Zang et al., 2011). To assess for the spatial configuration properties of the whole brain network and possible differential sub-networks we use a graph theoretical approach (Costa et al., 2007; Latora and Marchiori, 2001; Watts and Strogatz, 1998). This allows us to explore differences between networks in terms of quantitative parameters that can be structurally and, by inference, functionally interpreted. So, we also use here a graph theory approach in order to investigate differences in the topological parameters associated with the structural networks of bilinguals and monolinguals. In particular, we focus on graph network efficiency, a measure of the intrinsic capability of the network to guarantee high information exchange between nodes/regions. In general, we expect to detect the presence of more interconnected and graph-efficient sub-networks to accomplish the processing of two languages. Our results will provide new evidence of how the brain deals with physical constraints in adapting to a challenging functional behavior (Bullmore and Sporns, 2012), something that could have advantages and/or disadvantages for the functioning of the brain network.

Methods

Participants

13 native Spanish monolinguals (7 females, age range from 20 to 40 years, mean age, 29.07 years, 6.60 std) and 13 early Spanish–Basque bilinguals (9 females, age range from 20 to 36, mean age, 24.08 years, 4.62 std) took part in the experiment. Mean age was not statistically significantly different between groups (Z-value = −1.77, P-value = 0.076). Eleven of the bilinguals acquired Spanish and Basque simultaneously from birth and 2 of them started to acquire the second language before or at age three. Thus, all bilingual participants had acquired both languages before preschool. They used both languages everyday and rated themselves as very highly proficient in both languages (mean rates: 9.86, 0.26 std for Spanish and 9.38, 0.71 std for Basque) on a scale from 1 (very poor level) to 10 (perfectly fluent). The ratings were based on reading, writing, listening and speaking skills. The monolinguals used only Spanish for daily life and had no/little knowledge of any other language. Only 5 monolinguals had been in contact with Basque but they had received little exposure and rated themselves as very poorly proficient in Basque (mean rate: 1.20, 1.78 std) or any other language (see Table 1 for participants' language profile). Information about language profile was obtained by means of a questionnaire before the experiment. Because handedness can influence language laterality, the study contained only right-handed participants as assessed by the Edinburgh Handedness Inventory (Oldfield,

Table 1
Language profile of monolingual and bilingual groups.

Variables	Mean (±SD)	
	Monolinguals (N = 13)	Bilinguals (N = 13)
AoA of Spanish	0	0.23 (±0.44)
AoA of Basque		0.46 (±0.96)
% daily exposure to Spanish	97.13 (±3.44)	61.8 (±17.41)
% daily exposure to Basque	2.40 (±3.30)	29.58 (±14.42)
% daily exposure to other language		3.75 (±8.76)
Spanish proficiency	9.92 (±0.24)	9.86 (±0.26)
Basque proficiency	1.20 (±1.78)	9.38 (±0.71)
Other language proficiency	0.53 (±1.66)	1.35 (±3.16)

AoA, age of acquisition (the age at which participants started to learn these languages). SD, standard deviation. Proficiency measures are means on a scale from 1 (very poor level) to 10 (perfectly fluent) of ratings based on reading, writing, listening and speaking skills.

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