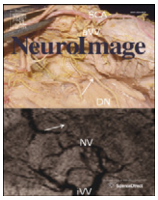
NeuroImage 66 (2013) 42–49

Contents lists available at SciVerse ScienceDirect

NeuroImage

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



Structural brain changes linked to delayed first language acquisition in congenitally deaf individuals

Sidonie Pénicaud [a], Denise Klein [a,*], Robert J. Zatorre [a], Jen-Kai Chen [a], Pamela Witcher [a], Krista Hyde [c], Rachel I. Mayberry [b]

[a] Cognitive Neuroscience Unit, Montreal Neurological Institute, McGill University, 3801 University Street, Montreal, Quebec, Canada H3A 2B4
[b] Department of Linguistics, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92093, USA
[c] McConnell Brain Imaging Centre, Montreal Neurological Institute, McGill University, Montreal, Quebec, Canada H3A 2B4

ARTICLE INFO

Article history:
Accepted 30 September 2012
Available online 11 October 2012

Keywords:
Anatomical brain imaging
Voxel-based morphometry (VBM)
Sign language
Age of language acquisition
Brain tissue concentration
Brain plasticity

ABSTRACT

Early language experience is essential for the development of a high level of linguistic proficiency in adulthood and in a recent functional Magnetic Resonance Imaging (fMRI) experiment, we showed that a delayed acquisition of a first language results in changes in the functional organization of the adult brain (Mayberry et al., 2011). The present study extends the question to explore if delayed acquisition of a first language also modulates the structural development of the brain. To this end, we carried out anatomical MRI in the same group of congenitally deaf individuals who varied in the age of acquisition of a first language, American Sign Language —ASL (Mayberry et al., 2011) and used a neuroanatomical technique, Voxel-Based Morphometry (VBM), to explore changes in gray and white matter concentrations across the brain related to the age of first language acquisition. The results show that delayed acquisition of a first language is associated with changes in tissue concentration in the occipital cortex close to the area that has been found to show functional recruitment during language processing in these deaf individuals with a late age of acquisition. These findings suggest that a lack of early language experience affects not only the functional but also the anatomical organization of the brain.

Introduction

Plasticity can be defined as the brain's ability to be shaped by experience at functional (Karni et al., 1998) and structural (Draganski et al., 2004; Maguire et al., 2000) levels. In this way, learning a new skill or acquiring a high level of proficiency at such varied tasks as juggling (Draganski et al., 2004), navigating a taxi through a city (Maguire et al., 2000), playing a musical instrument (Bermudez et al., 2009; Gaser and Schlaug, 2003; Hutchinson et al., 2003) or studying for an exam (Draganski et al., 2006) can be associated with structural changes in the adult brain.

Several aspects of language acquisition have also been associated with differences in brain structure (see Richardson and Price, 2009 for a review), be they present at birth or acquired through experience, such as differentiating or pronouncing novel phonemes (Golestani and Pallier, 2007; Golestani et al., 2002; Golestani et al., 2007), learning a tonal language (Wong et al., 2008), acquiring new vocabulary (Lee et al., 2007; Richardson and Price, 2009), learning Morse code (Schmidt-Wilcke et al., 2010) or acquiring a second language (Mechelli et al., 2004). While most studies have focused on structural changes following learning language in adulthood, to date no study has explored if a lack of language input early in life could alter brain development and result in lasting changes in the anatomical organization of the adult brain.

To address how early linguistic experience, and the lack of it, shapes the anatomical development of the brain, we studied a group of congenitally deaf individuals who varied in the age at which they acquired a first language, American Sign Language (ASL), and who were the same group of subjects who had shown functional Magnetic Resonance Imaging (fMRI) changes during language processing tasks related to the timing of language onset (Mayberry et al., 2011). In that fMRI study, Mayberry et al. (2011) observed a negative linear relationship between hemodynamic activity in the left frontal language regions and age of sign-language acquisition and a positive linear relationship between hemodynamic activity in the left visual cortex and age of sign-language acquisition. These activation patterns were found during both a phonemic hand-judgment and a grammatical-judgment task. Here, using Voxel-Based Morphometry (VBM), we asked if the same reciprocal relationship might be observed in the anatomical organization of the brain and whether we might observe local differences in

---

* Corresponding author at: Cognitive Neuroscience Unit, Montreal Neurological Institute, McGill University, 3801 University Street, Montreal, Quebec, Canada H3A 2B4. Fax: +1 514 398 1338.

E-mail addresses: sidonie.p@gmail.com (S. Pénicaud), denise.klein@mcgill.ca (D. Klein), robert.zatorre@mcgill.ca (R.J. Zatorre), jen-kai.chen@mcgill.ca (J.-K. Chen), krista.hyde@mail.mcgill.ca (K. Hyde), rmayberry@ucsd.edu (R.I. Mayberry).

1053-8119/$ – see front matter © 2012 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.neuroimage.2012.09.076

white matter (WM) and gray matter (GM) concentration across the whole brain related to age of language acquisition in these individuals.

VBM is a fully automated technique that searches for local differences in gray-matter and white-matter concentrations across the whole brain between two groups (Ashburner and Friston, 2000). While VBM has been used to study the deaf population in the past, these studies have focused on isolating structural differences between deaf and hearing individuals related to auditory deprivation (Li et al., 2012; Penhune et al., 2003; Shibata, 2007; Smith et al., 2011). The results have showed, for the most part, that deaf individuals have less white matter than hearing individuals in an area underlying the planum temporale and Heschl's gyrus (Li et al., 2012; Shibata, 2007; Smith et al., 2011), an expected finding given the plasticity which could accompany auditory deprivation. Such findings are consistent with the findings of an earlier anatomical study using regions of interest (ROI) (Emmorey et al., 2003). However, the behavioral sequelae of these structural differences in auditory cortex are currently unknown (Leonard et al., 2012). Plasticity-related differences have also been observed in other brain regions in deaf individuals, for example, several studies have examined differences in visual cortex associated with deafness (e.g. Bavelier et al., 2001), and Penhune et al. (2003) observed increased gray-matter density localized in the left motor cortex that they interpreted as being related to increased fine-motor control of the dominant hand during signing. Structural differences in the posterior insular cortex have been documented in deaf signers compared to hearing signers that have been interpreted to be related to lip-reading requirements for deaf individuals as compared to hearing signers (Allen et al., 2008). Although there is an emerging body of literature focusing on the consequences of deafness associated with brain morphological changes, to date no studies have yet capitalized on the age range at which congenitally deaf individuals acquire their first language to explore how brain structure may be shaped by language experience during development.

We predicted that delayed first-language acquisition would result in the modulation of tissue concentration in the left frontal lobe and in the left occipital cortex as previously reported in the fMRI study with these same subjects (Mayberry et al., 2011).

Material and methods

Subjects

Anatomical magnetic resonance images (MRI) from 23 congenitally deaf individuals (12 males; 11 females, average age ± SD = 39.2 ± 12.3 years, range = 25–61 years; 23 right handed; Table 1) were acquired as part of a larger study that also involved functional magnetic resonance imaging (fMRI) (Mayberry et al., 2011). Eighteen of the recruited deaf subjects were profoundly deaf (> 90 dB in both ears), 3 subjects had profound loss in one ear (> 90 dB) and severe loss (> 80 dB) in one ear, and 2 subjects who had severe loss in both ears (> 80 dB) — see Table 2 for details). All subjects had used ASL as their primary means of communication on a daily basis for an extended period of time of at least 18 years (ASL experience: mean ± SD = 33.5 ± 11.5 years, range = 18–55 years; see Fig. 1 for illustration of ASL signs). Subjects were unable to understand spoken language sufficiently to engage in it for functional communication with others. The deaf subjects varied in their age of ASL acquisition; age of acquisition being defined as the chronological age at which each deaf subject gained daily access to fully perceivable linguistic input. The subjects chosen represented three developmental epochs (infancy, early childhood and late childhood) related to the age at which they first started acquiring ASL: (1) *Infant signers* were first exposed to ASL before age 3 by a parent who signed to them. (2) *Early signers* were first exposed to ASL between the ages of 4–7 years and; (3) *Late signers* were first exposed to ASL between the ages of 11–14 years. Early and late signers were born to hearing parents who did not use sign language as a means of communication with their children during childhood and were initially enrolled in schools where only speech was used; they were subsequently transferred to schools where sign language was used. All the deaf subjects were tested on two non-verbal subtests of the Wechsler Adult Intelligence Scale III (WAIS) consisting of Picture Completion and Picture Arrangement (Weschler, 1981) and scored within the normal range. To assess language deprivation apart from auditory deprivation, a separate set of anatomical scans using the same scanner and imaging parameters was also acquired from a control group of right-handed hearing subjects matched for age and gender who had never been exposed to sign language (n = 43, 21 males; 22 females, average age ± SD = 37.3 ± 11.5 years, range = 25–62 years); these subjects had been

Table 2
Range of hearing levels for deaf participants.

Subject	R-PTA	L-PTA
Native group		
N01	> 95	> 95
N02	> 95	> 95
N03	> 95	> 95
N04	> 95	> 95
N05	> 95	> 95
N06	> 95	> 95
N07	> 95	> 95
N08	> 95	> 95
N09	80	85
Early group		
E01	88	93
E02	> 95	> 95
E03	> 95	> 95
E04	93	93
E05	81	90
E06	> 95	> 95
E07	> 95	> 95
E09	85	85
Late group		
L01	93	93
L02	> 95	> 95
L03	> 95	> 95
L04	> 95	> 95
L05	88	> 95
L06	> 95	> 95

Degree of hearing in dB HTL is taken at 500 Hz, 1000 Hz and 2000 Hz.
The average of these three frequencies is the Pure Tone Average or PTA. Severe Loss (71–90 dB) Profound Loss (> 90 dB) is given for L (left) and R (right) ear. 95 dB represents the limits of portable audiometric testing.

Table 1
Demographic information of deaf subjects.

Developmental epochs	N	Age (Years)	Gender		Age of ASL Acquisition (Years)			ASL Experience (Years)
		Mean (SD)	M	F	Mean (SD)	Min	Max	Mean (SD)
Infancy	9	31.8 (8.6)	2	7	0.6 (1.0)	0	3	31.2 (8.6)
Early childhood	8	44.0 (12.1)	5	3	6.3 (1.0)	4	7	37.8 (11.7)
Late childhood	6	40.2 (11.9)	4	2	12.3 (1.0)	11	14	27.8 (11.4)
Total deaf	23	38.2 (11.6)	11	12	5.6 (4.9)	0	14	32.6 (10.8)