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Structural correlates of spoken language abilities: A surface-based region-of interest morphometry study

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A B S T R A C T

Brain structure can predict many aspects of human behavior, though the extent of this relationship in healthy adults, particularly for language-related skills, remains largely unknown. The objective of the present study was to explore this relation using magnetic resonance imaging (MRI) on a group of 21 healthy young adults who completed two language tasks: (1) semantic fluency and (2) sentence generation. For each region of interest, cortical thickness, surface area, and volume were calculated. The results show that verbal fluency scores correlated mainly with measures of brain morphology in the left inferior frontal cortex and bilateral insula. Sentence generation scores correlated with structure of the left inferior parietal and right inferior frontal regions. These results reveal that the anatomy of several structures in frontal and parietal lobes is associated with spoken language performance. The presence of both negative and positive correlations highlights the complex relation between brain and language.

1. Introduction

Language is a multifaceted faculty that we use every day to comprehend and communicate complex ideas and emotions. Functional magnetic resonance imaging (fMRI) studies have shown that a distributed network of cortical and subcortical regions is used to accomplish even the simplest language tasks, which demonstrates that the complexity of the language system translates into a complex neural architecture (for a review, see for example Indefrey & Levelt, 2004; Price, 2010). While the relation between brain functioning and language processes has been studied in some detail, little is known about the relation between brain anatomy and language skills. Interestingly, if the results of functional and structural imaging are sometimes convergent, suggesting a close relationship between brain structure and function (Maguire et al., 2000; Richardson, Thomas, Filippi, Harth, & Price, 2010), structural imaging studies can also offer novel insights by identifying regions not typically identified using fMRI.

One of the most widely studied aspects of human brain anatomy is cortical thickness (CT), which can be assessed using magnetic resonance imaging (MRI). The human cerebral cortex is composed of highly folded horizontal layers of neurons; the thickness of this neuronal sheet varies across brain regions and individuals, and ranges from 1 to 4.5 mm, with an average of approximately 2.5 mm (Zilles, 1990). Changes in CT are of great interest in both normal brain maturation and aging as well as in a variety of neurodegenerative and psychiatric disorders (Fischl & Dale, 2000). Recent neuroimaging studies have revealed that differences in gray matter architecture are also associated with differences in performance in healthy adults in a number of cognitive and motor tasks (Kanai & Rees, 2011; May & Gaser, 2006; Tomassini et al., 2011). For example, positive correlations have been found between GM architecture and proficiency in sports, in regions involved in motor planning, execution and learning including the bilateral inferior frontal (IFG) and mid-temporal gyrus, left precentral and middle frontal gyri (MFG), cerebellum, as well as regions involved in visual and spatial association processes such as the left inferior parietal (IPL), left superior temporal sulcus and right parahippocampal gyrus (Di Paola, Caltagirone, &

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Petrosini, 2013; Draganski et al., 2004; Jacini et al., 2009; Wei, Zhang, Jiang, & Luo, 2011).

However, only a limited number of studies have used structural MRI to study language skills, including vocabulary acquisition (Lee et al., 2007), second language proficiency (Hosoda, Tanaka, Nariai, Honda, & Hanakawa, 2013; Mechelli et al., 2004), and speech perception and production (Bilodeau-Mercure, Lortie, Sato, Guitton, & Tremblay, 2014; Grogan, Green, Ali, Crinion, & Price, 2009; Tremblay, Dick, & Small, 2013). The study of spoken language production is complex because it depends upon a very large number of sensorimotor and cognitive processes. To express conceptual ideas, word forms must first be retrieved, converted into a phonological code, sequenced and articulated, while unintended words need to be suppressed and the output need to be monitored (see for example Guenther, Ghosh, & Tourville, 2006; Price, 2010 for a review). Commensurate with this complex picture, fMRI studies of speech production have identified a large number of regions involved in producing language including the cerebellum, M1, the basal ganglia, IFG and MFG, the inferior parietal lobe, the prefrontal cortex, and the superior and middle temporal gyri (e.g. Adank, 2012; Blank, Scott, Murphy, Warburton, & Wise, 2002; Bohland, Bullock, & Guenther, 2010; Bohland & Guenther, 2006; Ghosh, Tourville, & Guenther, 2008; Peeva et al., 2010; Riecker, Wildgruber, Dogil, Grodd, & Ackermann, 2002; Riecker et al., 2005; Tremblay & Gracco, 2009; Tremblay & Gracco, 2010; Tremblay & Small, 2011b; Turkeltaub, Eden, Jones, & Zeffiro, 2002; Whitney et al., 2009; Wildgruber, Ackermann, & Grodd, 2001; Wise, Greene, Büchel, & Scott, 1999). The functional importance of anatomical variations within these regions, however, is largely unknown, and so is their importance for the different cognitive and motor stages of spoken language production.

Because most studies of language production have relied preferentially on voxel-based morphometry (VBM) (Amici et al., 2007; Beal, Gracco, Brettschneider, Kroll, & De Nil, 2013; Golestani & Pallier, 2007; Grogan et al., 2009; Mechelli et al., 2004; Zhu, Zhang, & Qiu, 2013) and no study has examined how other morphometric measures (cortical volume (VOL) and surface area (SA)) are associated with language abilities in healthy adults, the main objective of this study was to explore the relation between brain morphometry and language performance using two classic language production tasks (sentence generation task and semantic fluency) in healthy adults using surface-based morphometry (SBM). In SBM, morphometric measures are derived from geometric models of the cortical surface from which different metrics like CT, VOL or SA of brain regions at a subvoxel level resolution can be extracted (Dale, Fischl, & Sereno, 1999; Fischl, Sereno, & Dale, 1999). In the present study, CT, VOL, and SA measures were computed and correlated with performance in these tasks, which involve different sets of processes. In the verbal fluency task, word retrieval is usually driven by association chains between clusters of words belonging to semantic subcategories. For example, for the category "animals", people often begin with animals considered as pets and when this subcategory is exhausted, they switch to a different subcategory (Katzev, Tuscher, Hennig, Weiller, & Kaller, 2013; Wechsler-Kashi, Schwartz, & Cleary, 2014). Sentence generation, in contrast, involves a different series of cognitive stages that include object recognition, lexical retrieval of the element presented in the picture, access to the phonological word form, syntactic planning (DeLeon et al., 2007; Wechsler-Kashi et al., 2014). Because of these differences, we hypothesized that performance on the two language tasks would be correlated with distinct brain regions. For example, damage to the anterior insula (AI) has been associated with fluency and articulatory impairments (Baldo, Wilkins, Ogar, Willock, & Dronkers, 2011; Dronkers, 1996). The structure of the AI could then correlate with the performance on the semantic fluency task. Because the sentence generation task relies on the recognition of object pictures, performance on this task should instead correlate with the structure of regions involved in visual processing located in the inferior parietal lobe (Culham & Kanwisher, 2001). Several fMRI studies have also shown that manipulating response selection during word production modulates the pre-SMA, the inferior fontal gyrus (IFG), and the ventral premotor (PM) cortex (Alario, Chainay, Lehericy, & Cohen, 2006; Crosson et al., 2001; Nagel, Schumacher, Goebel, & D'Esposito, 2008; Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997; Thompson-Schill, D'Esposito, & Kan, 1999; Thompson-Schill et al., 1998; Tremblay & Gracco, 2006; Tremblay & Gracco, 2009; Zhang, Feng, Fox, Gao, & Tan, 2004). In view of these results, we were interested in examining if the structure of these regions would show a stronger relation to verbal fluency than to sentence generation due to the high demand on selection imposed by the fluency task.

2. Methods

2.1. Participants

21 right-handed adults (10 males, mean 25 ± 4.4 years, range 20–36 years), with a mean education level of 15.4 years (range = 12–22 years) participated in the experiment. The study sample consisted of Caucasian (85.7%), African American (9.5%) and Hispanic participants (4.7%). All participants were native speakers of standard American English and had normal pure tone thresholds and normal speech recognition scores (92.3% accuracy on the Northwestern University auditory test number 6). Participants were recruited through the student email address list at The University of Chicago. The study was approved by the Institutional Review Board for the Division of Biological Sciences at The University of Chicago.

2.2. Image acquisition

T1-weighted brain images were acquired on a 3T General Electric (Milwaukee, WI) Signa HDx MRI scanner. The structural images included 166 slices (TR = 5.7 ms, TE = 2.036 ms, FoV = 240 mm, flip angle = 12°, matrix = 256 mm × 256 mm, 166 slices, 1 mm × 1 mm × 1 mm, no gap).

The images were acquired as part of a larger project that also included BOLD fMRI. The BOLD fMRI results have been reported elsewhere and will not be discussed in this article (Argyropoulos, Tremblay, & Small, 2013; Tremblay & Small, 2011a; Tremblay & Small, 2011c).

2.3. Image analysis

CT, SA, VOL and subcortical volumetric brain measures were computed with the FreeSurfer image analysis suite, which is well documented and freely available for download online (http://surfer.nmr.mgh.harvard.edu/) (Dale et al., 1999; Fischl et al., 1999; Fischl et al., 2004). First, a surface representation of each participant's anatomy was created by inflating each hemisphere of the anatomical volumes to a surface representation. The resulting surface representation was aligned to a template of average curvature. These surface representations were obtained by submitting each participant's MRI to a series of steps that included: (1) motion correction and affine transformation to Talairach space, (2) intensity normalization, (3) removal of non-brain voxels, (4) segmentation of GM, white matter (WM) and cerebrospinal fluid, and, finally (5) tessellation of the GM/WM boundary, and automated topology correction. At each step, the results were visually inspected and manual interventions were performed when required to correct