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Brain and Language 89 (2004) 69–75
Brain and Language
www.elsevier.com/locate/b&l

Bilingual corpus callosum variability

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Accepted 21 July 2003

Abstract

Magnetic resonance imaging was used to produce midsagittal images of the corpus callosum of 19 right-handed adult male and female subjects. The preliminary findings of this study indicate that significant adaptation in the anterior midbody of the corpus callosum has occurred to accommodate multiple language capacity in bilingual individuals compared to monolingual individuals. The main interpretation of this finding is that the precentral gyrus is involved in bilingual faculty adaptation assuming a role consistent with the somatotopical input to areas dedicated to the mouth, and input to association tracts connecting the premotor and supplementary motor cortices. This paper discusses possible implications to neuroscientists, second language educators, and their students.

Keywords: Corpus callosum; Neurolinguistics; Bilingual; Language; Second language education

1. Introduction

In response to second language (L2) acquisition and use, the human brain undergoes cortical adaptation to accommodate multiple languages either by recruiting existing regions used for the native language (L1) (e.g., Chee, Tan, & Thiel, 1999; Hasegawa, Carpenter, & Just, 2002; Hernandez, Dapretto, Mazziotta, & Bookheimer, 2001; Illes et al., 1999; Kim, Relkin, Lee, & Hirsch, 1997; Simos et al., 2001), or by creating new cortical networks in distinct adjacent areas of the cortex to handle certain functional aspects of L2 (e.g., Dehaene et al., 1997; Gomez-Tortosa, Martin, Gaviria, Charbel, & Ausman, 1995; Kim et al., 1997; Paulesu et al., 2000; Perani et al., 1996; Rodriguez-Fornells, Rotte, Heinze, Nösselt, & Münte, 2002; Simos et al., 2001). However, regardless of how the cortex organizes the circuitry required to handle multiple languages, all non-reflexive behavior, including cognition and communication, is normally the result of unconscious and seamless coordination of activity between both hemispheres via the cerebral commissures.

The corpus callosum is the major commissure, or bundle of axons, connecting the two cerebral hemispheres. Callosal axon size and number have been studied by light and electron microscopy (Aboitiz, Scheibel, Fisher, & Zaidel, 1992a; Aboitiz, Scheibel, Fisher, & Zaidel, 1992b; Tomasch, 1954), and consists of between 200 million and 300 million axons (Aboitiz et al., 1992a; Nolte, 1998; Tomasch, 1954). Variability in corpus callosum morphology has been associated with a wide range of clinical pathological conditions including Attention Deficit Hyperactive Disorder (ADHD), autism, deep head injuries, dyslexia, epilepsy, learning disabilities, multiple sclerosis, neurofibromatosis, obsessive-compulsive disorder, prenatal alcohol exposure,

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doi:10.1016/S0093-934X(03)00299-2

schizophrenia, and Tourette syndrome (e.g., Benavidez et al., 1999; Egaas, Courchesne, & Saitoh, 1995; Gean-Marton et al., 1991; Georgy, Hesselink, & Jernigan, 1993; Hynd et al., 1991; Hynd et al., 1995; Jacobsen et al., 1997; Mostofsky, Wendlandt, Cutting, Denckla, & Singer, 1999; Njiokiktjien, de Sonneville, & Vaal, 1994; Peterson et al., 1994; Riley et al., 1995; Rosenberg et al., 1997; Semrud-Clikeman et al., 1994; Woodruff, Pearlson, Geer, Barta, & Chilcoat, 1993). A glance at corpus callosum tracings from Byne, Bleier, and Houston (1988) and Peterson, Feineigle, Staib, and Gore (2001), for example, illustrate the extreme variability of the structure in normal populations. Both animal and human studies have shown that the cerebral cortex is malleable under environmental factors (Diamond, 2001; Raichle et al., 1994). With respect to language, Raichle, et al. examined the effects of practice of linguistic tasks on cortical activation. The corpus callosum has been shown to be plastic under influencing factors in combination of experience (enriched, impoverished, educational opportunities, etc.), environment (nutrition, exposure to toxins, etc.), and genetics (Armstrong, Kennedy, & Coggins, 2002; Coggins, 2002; Innocenti & Frost, 1979; Juraska & Kopcik, 1988; Schlaug, 2001; Schlaug, Jäncke, Huang, Staiger, & Steinmetz, 1995). Such results naturally beg the question of the functional significance of corpus callosum variability with respect to bilingual faculty. Modern investigators have proposed that the corpus callosum is intimately connected with cognition. Gazzaniga (2000, p. 1294) noted "It may turn out that the oft-ignored corpus callosum, ..., was the great enabler for establishing the human condition", Lassonde (1986, p. 387) conjectured that "... the corpus callosum may not be solely involved in interhemispheric transfer, but may also play an important role in the activation of each cerebral hemisphere", and Witelson (1990, p. 176) hypothesized that the corpus callosum "may prove to be a window to the study of the cortex and a guide for specific further investigations" with respect to behavioral laterality. Although language is lateralized to the left hemisphere in over 90% of the normal population, as mentioned above, language (subsumed under cognition and communication) normally involves information processing between both hemispheres.

The corpus callosum has been studied extensively in relation to disease and injury. Postmortem, in vivo, and pre-surgical studies in humans have shown that language is susceptible to various impairments due to lesions of certain structures of the brain, but surprisingly, the relationship between corpus callosum variability and language has not been an extensive topic of neurolinguistic research. Further, this is the first known study to address the relationship between the corpus callosum and bilingual capacity. Concerning general linguistic functionality and corpus callosum variation, Beaton (1997) and Hynd et al. (1995) both have reported on corpus callosum variation with respect to dyslexia, Castro-Caldas et al. (1999) found that literate women had a significantly larger posterior midbody midsagittal area compared to illiterate women, Funnell, Corballis, and Gazzaniga (2000) reported that the splenium (posterior fifth of the corpus callosum) carries word information (defined by visual orthographic representation, rhymes, and whole word), and Hines, Chiu, McAdams, Bentler, and Lipcamon (1992) found that the midsagittal splenium area exhibited a significant positive correlation with verbal fluency (based on the Thurstone Fluency Test, the Controlled Associates Test, and the Sentence Making Test) in a sample of women. Considering the integrative function that the corpus callosum plays in cognition, differences in corpus callosum morphology between monolingual and bilingual individuals may also provide some insights into issues of cytoarchitectural development, organization, and plasticity. While this study will be unable to completely resolve these open questions, the results may indicate directions of future research that may more specifically address such questions.

The purpose of this small sample study was to investigate midsagittal corpus callosum variability in bilingual individuals compared to monolingual individuals. Specifically, we hypothesized that the corpus callosum of bilingual individuals will differ from the corpus callosum of monolingual individuals in the midsagittal plane.

Magnetic resonance imaging (MRI) was the procedure used in this study to produce images of the corpus callosum. A midsagittal section of the corpus callosum was imaged and used for this study. Using a modification of Witelson (1989), the midsagittal corpus callosum image was partitioned plane into five subregions (Fig. 1). Researchers investigating corpus callosum

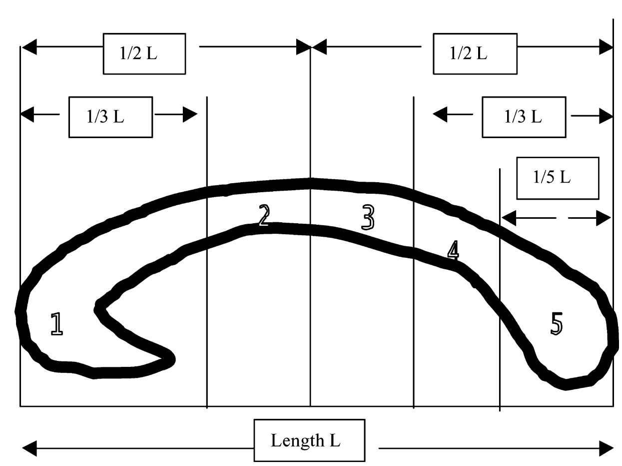

Fig. 1. Regional subdivision of the midsagittal corpus callosum. Region 1, anterior third; Region 2, anterior midbody; Region 3, posterior midbody; Region 4, isthmus; Region 5, splenium. Adapted from Witelson (1989).

morphology in the midsagittal plane have developed numerous methods to analyze variability of the structure. Witelson developed a scheme of partitioning the corpus callosum into seven sections based on hemispheric cortical innervation. In that scheme, the anterior third of the corpus callosum was further divided into three subsections. In the present study, the anterior third was not subdivided into the three subsections, but considered as a whole region. Based on current understanding of callosal projections, there was no principled reason to expect that subdividing the anterior third into smaller regions as in the Witelson scheme would shed any additional light on the role of the corpus callosum in bilingual language processing. Perhaps future research could provide a more definitive answer to the question of possible functionality of specific anterior third subregions in this respect. All other regions of the Witelson scheme for partitioning the corpus callosum were used for measurements in this study.

2. Method

2.1. Subjects

Nineteen ($N = 19$) right-handed language and science teachers participated in the study. All participants are presently teaching at either the secondary or university level and were recruited for the study. Participants were required to give informed consent to participate which included allowing their midsagittal MRI brain images to be taken at a local hospital, answering a short survey regarding their past educational experiences, as well as providing additional personal information relevant to the study. The subjects included twelve bilingual and seven monolingual teachers.

All of the bilingual teachers reported studying their second language for more than 7 years, with 7 of the 12 bilingual teachers beginning their L2 study early in life, during their elementary education. However, none of the participated reported being raised in a bilingual environment since early childhood. The average age of the bilingual teachers is 38 years (range 25–57), 7 female and 5 male. All teachers reported to possess advanced to superior levels of proficiency in the L2 according to the established ACTFL Proficiency Guidelines (American Council for the Teaching of Foreign Languages, 1983).

The seven monolingual teachers who participated reported no previous study of a second language and all are presently teaching in science content areas. The average age of the monolingual teachers is 45 years (range 29–59), 5 males and 2 females.

2.2. Imaging protocol

Midsagittal images were taken on a Philips 1.0 T Gyroscan T10 NT scanner (Philips Medical Systems, North America, La Palma, CA) with the following imaging parameters: T1 sagittal image with slice thickness 5 mm, 192×256, 4 excitations, field of view 20 cm, TE 15, TR 324. Corpus callosum anterior to posterior length was measured from film on a HiPad digitizer using BIOQUANT II software (R&M Biometrics, Nashville, TN) and calibrated using the 10 cm scale marked on the films. Images were also transferred to compact disk and loaded onto a Windows 98 workstation. Image analysis measurements reported in Table 1 below were performed using MetaMorph image analysis software (Universal Imaging, Downingtown, PA). The MRI film and a 100% digital image were consulted regularly to determine reference points of corpus callosum contour, concave bend in the genu, rostrum tip, and the point where the fornix passes inferior to the isthmus and splenium. Once these points were located on the film and digital image, the image was enlarged to 800%. The corpus callosum was then divided into five sections as per Witelson (1989) (see Fig. 1) and traced with a computer mouse. Each subregion was measured three times using thresholding. The arithmetic mean of the three measures of each subregion was calculated and used as the average for that subregion.

3. Results

Table 1 below presents summary values of corpus callosum regional to total area ratio means, standard deviations, t test results (t), degrees of freedom, and p

Table 1
Midsagittal corpus callosum regional area differences between bilingual and monolingual individuals

Region	Ratio of regional to total corpus callosum area M (*SD*)			
	Monolinguals $n = 7$	Bilinguals $n = 12$	t (*df*)	p value
Anterior third	.41693 (.032949)	.39523 (.042827)	1.237(15.432)	.235
Anterior midbody	.11496 (.010686)	.12811 (.013921)	−2.309(15.484)	.035
Posterior midbody	.10533 (.013834)	.11462 (.010512)	−1.536(10.098)	.155
Isthmus	.08040 (.008761)	.08765 (.015051)	−1.327(16.984)	.202
Splenium	.28237 (.026750)	.27439 (.029314)	.605(13.687)	.555

Note. Refer to Fig. 1.
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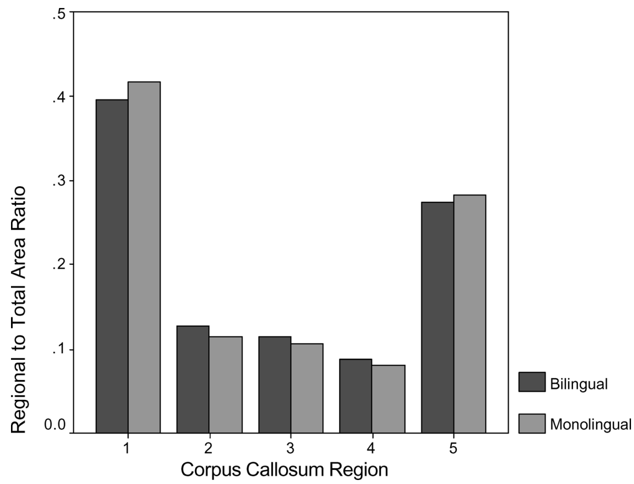

Fig. 2. Comparison of regional to total corpus callosum area ratios between the bilingual and monolingual groups. Region 1, anterior third; Region 2, anterior mid-body; Region 3, posterior midbody; Region 4, isthmus; Region 5, splenium (refer to Fig. 1).

values. The anterior midbody to total corpus callosum midsagittal area ratio was significantly larger in the bilingual individuals compared to the monolingual individuals at the 0.05 α level. Fig. 2 presents a bar graph of midsagittal regional to total area ratios for the two groups.

4. Discussion

In this study, the monolingual and bilingual groups exhibited significant differences in the corpus callosum midsagittal anterior midbody regional area. Although this significance should be interpreted cautiously due to small sample size, the results can be interpreted as an adaptive response to bilingual capacity. The methodology used in this study did not allow for any determination as to whether the increased regional area is due to an increase in axon number or an increase in myelination. In spite of this open question, it appears that processing demands of multiple language organization in the cortex requires an increase in communication from homotopic cortical regions served by the corpus callosum through this anterior midbody region. The area of the cortex associated with the anterior midbody has been shown to be primarily dedicated to primary motor, primary somatosentory function, and the insula, motor areas, some visuo-spatial and posterior superior frontal areas (De Lacoste, Kirkpatrick, & Ross, 1985; Dimond, Scammell, Brouwers, & Weeks, 1977; Nolte, 1998; Pandya & Seltzer, 1986; Witelson, 1989). Dimond and colleagues found that the body of the corpus callosum (which includes the anterior midbody) is also specifically involved in language processing. If the increase in midsagittal anterior midbody area in bilinguals is due to myelination, then conduction speed between the two cerebral hemispheres would be, for some as yet undetermined reason, the likely adaptive function of the processing load of maintaining multiple languages. On the other hand, if the increase in area is due to an increase in axon number, perhaps the corpus callosum is involved in the switching mechanism which keeps one language from interfering with another during speech. Due to the role of the frontal cortex in linguistic processing (e.g. Bhatnagar, Mandybur, Buckingham, & Andy, 2000; Dehaene et al., 1997; Embick, Marantz, Miyashita, O'Neil, & Sakai, 2000; Fabbro, Skrap, & Aglioti, 2000; Hernandez et al., 2001; Keller, Carpenter, & Just, 2001; Ojemann, 1992; Rodriguez-Fornells et al., 2002; Sakai, Hashimoto, & Homae, 2001), the lack of a significant area difference in the corpus callosum anterior third between the two groups was surprising. Most likely, the sample size was too small to detect differences that on principled accounts most likely exist. Similarly, that the two groups exhibited no significant differences in either the posterior midbody and isthmus considering the role of the left perisylvian region in language activity and the relationship of the posterior midbody and isthmus to the perisylvian cortex (Bhatnagar et al., 2000; Dehaene et al., 1997; Ojemann, 1991; Paulesu et al., 2000; Perani et al., 1996; Rodriguez-Fornells et al., 2002; Simos et al., 2001) was also surprising, but likely due to the small sample size.

We have presented data that indicate that the corpus callosum undergoes adaptation to accommodate multiple language facility. It is important to note that the age between the two adult groups would not affect the morphology of the corpus callosum between the adult groups since prior research (Hopper, Patel, Cann, Wilcox, & Schaeffer, 1994) indicates that age under 65 years does not significantly influence corpus callosum variability. Callosal adaptation might facilitate increased interhemispheric transfer by way of increased myelination, or by way of an increased number of fibers that provide greater cortical connectivity. It may be that callosal adaptation is related in some as yet undetermined way to the switching mechanism which keeps languages separated during conscious use (inhibiting the language(s) not in current use in order to prevent interference with the language that is currently in use). Fabbro et al. (2000) found switching related to the frontal lobe lesions, and Hernandez et al. (2001) reported dorsolateral perfrontal cortex activity during switching. Although we reported no significant difference between the mono- and bilingual groups for corpus callosum regions which connect frontal lobe areas, it is possible that the corpus callosum might well play a role in the switching mechanism either via association tracts or in due to regions of the corpus callosum which would be evident under a larger sample size. Price, Green, and von Studnitz (1999) failed to find evidence for frontal lobe activation in switching as reported in Fabbro et al. (2000), but did note activation in the supramarginal gyri, which is connected by the posterior midbody region of the corpus callosum (and perhaps in part by some of the splenium). Again, although posterior corpus callosum regions did not appear to differ significantly between the mono and bilingual groups, a larger sample size would help to clarify this issue.

The precentral gyrus is normally dedicated as the primary motor area with association tracts to both the premotor and supplementary motor areas. The primary and premotor areas have large patches dedicated to the mouth. An intriguing hypothesis is that the anterior midbody is significantly different due in part to an increase in phonetic capacity required for multiple language ability. The greater the phonetic capacity, the greater the need for mouth and lip adjustment. If this were true, considering the lateralization of language faculty, one wonders whether the increase in anterior midbody area in bilinguals is due to an increase in fiber numbers emanating from the left hemisphere traveling to the right hemisphere. That is, whether there is an asymmetry in the number of projections between the hemispheres through the anterior midbody region of the corpus callosum. Follow-up studies specifically designed to test this hypotheses would help settle this question.

What was not addressed in this study, but which may be of great importance, are the relationships of corpus callosum variation between mono and bilinguals to L2 acquisition age, and to L2 proficiency. For example, Dehaene et al. (1997), Kim et al. (1997), Simos et al. (2001), and Perani et al. (1998) report that age of L2 acquisition is related to variation in cortical activation under various linguistic tasks. It would be of significant interest if age of L2 acquisition has a similar affect on corpus callosum morphology. Perani et al. (1998) and Rodriguez-Fornells et al. (2002) report an L2 proficiency effect on cortical activation during linguistic activities. Proficiency, which normally is related to practice and experience, reasonably could be expected to affect corpus callosum morphology. Corpus callosum response to practice would further illuminate the role played by the corpus callosum in mediating cognition beyond just serving as a conduit of information passing between the hemispheres. With respect to second language education, the results of this study could suggest that bilingual learning and use can have a profound affect on brain structures in general and the corpus callosum in particular. Normal corpus callosum development suggests that the corpus callosum is involved in a developmental language learning critical period (Thompson et al., 2000). In that the present study was not designed to address age of acquisition, rate, and amount of corpus callosum adaptation to second language acquisition with respect to the critical period, these issues should be addressed in future studies due to enormous educational implications with respect to second language education funding, instruction, and curriculum decisions (see Gordon, 2000, for example, for a review of this issue). In any case, the role of the corpus callosum in bilingual processing should be further investigated for a more complete understanding of both its function in its own right, for its relation in bilingual processing, and for potential application to second language learning. For example, whether corpus callosum adaptation to L2 is a temporary or permanent response with important implications. If it turns out that the adaptation is permanent, then, one wonders whether the adaptation to L2 has secondary effects on other cognitive or behavioral tasks. Future research may hold the keys to these questions, and considering the potential of important implications, funding for such studies would be a wise investment.

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