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Increased White Matter Gyral Depth in Dyslexia: Implications for Corticocortical Connectivity

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Abstract

Recent studies provide credence to the minicolumnar origin of several developmental conditions, including dyslexia. Characteristics of minicolumnopathies include abnormalities in how the cortex expands and folds. This study examines the depth of the gyral white matter measured in an MRI series of 15 dyslexic adult men and eleven age-matched comparison subjects. Measurements were based upon the 3D Euclidean distance map inside the segmented cerebral white matter surface. Mean gyral white matter depth was 3.05 mm ($SD \pm 0.30$ mm) in dyslexic subjects and 1.63 mm ($SD \pm 0.15$ mm) in the controls. The results add credence to the growing literature suggesting that the attained reading circuit in dyslexia is abnormal because it is inefficient. Otherwise the anatomical substratum (i.e., corticocortical connectivity) underlying this inefficient circuit is normal. A deficit in very short-range connectivity (e.g., angular gyrus, striate cortex), consistent with results of a larger gyral window, could help explain reading difficulties in patients with dyslexia. The structural findings hereby reported are diametrically opposed to those reported for autism.

Keywords

Autistic disorder; Cerebrum; Corpus callosum; Dyslexia; Gyral window

Introduction

Dyslexia is characterized by substandard reading achievement when considering an individual's intelligence and education (DSM-IV-TR) (APA 2000). Perceptual problems in dyslexia seemingly result from an inability to retrieve correct verbal labels for phonemes (Vellutino and Scanlon 1987). The deficit makes it difficult to deconstruct words into

constituent sounds and match written words to spoken language. Consistent with this observation educational interventions that teach phoneme awareness have shown better results than other programs at dealing with reading disorders (Torgesen 2004). Although considerable progress has been made towards the identification of effective instructional practices (Tallal et al. 1998), our knowledge regarding underlying pathological changes and pathophysiological mechanisms remains fragmentary.

Case studies in dyslexia have variously suggested flaws in the circuitry of the visual cortex, connectivity/synchronicity between different brain regions, and the use of alternative circuits for reading (Wolf 2007). A significant number of these studies have focused their attention on the visual-auditory and visual-verbal systems (Birch and Belmont 1964; Blank and Bridger 1964). Evidence that the underlying lesion is developmental in origin derives from structural imaging and pathological examinations. These studies have revealed symmetry of the planum temporale, ectopias, and dysplastic cortical changes, i.e., loss of cytoarchitectural organization and micro- or polymicro-gyria (Heiervang et al. 2000; Casanova et al. 2004). Still, investigators argue whether dyslexia exists as a “condition” and whether previously described clinical and pathological findings are normal when considered from an evolutionary standpoint; namely, that the heterochronic development of the brain when paired with zygote selection culminates in a spectrum of neurological phenotypes (Geschwind and Galaburda 1987).

The evolutionary hypothesis of dyslexia offers an overarching explanation to observed phenomena (e.g., gender bias, abnormalities in cerebral dominance, and islands of cognitive strengths) in a number of childhood developmental disorders (Geschwind and Galaburda 1987). However, for scientists to accept this concept as theory it needs to be supported by a large body of observational data. Given the lack of fossil record for the microstructure of the cortex evidence suggestive of evolutionary antecedents to dyslexia may best be gleaned from gross observations such as anthropometric indices.

It has been hypothesized that many of the processes involved in neocorticalization, including brain parcellation, lateralization, and gyrification, result from the addition of supernumerary minicolumns within the isocortex (Casanova and Tillquist 2008). Investigators suggest that the cortex is made up of hundreds of millions of minicolumns (Calvin 1996; Mountcastle 1998). These units have been found in all areas of the isocortex (Buxhoeveden and Casanova 2005) and derive from the radial glia unit present in all mammals (Gressens and Evrard 1993; Casanova et al. 2007a). Because of the large number of modules and widespread distribution, abnormalities to the minicolumn’s basic ontogenetic pattern may provide for macroscopic alterations. It is therefore unsurprising that some of the gross changes observed in putative minicolumnopathies include variations in brain volume, gray/white matter ratio, and gyrification (Casanova et al. 2002a, 2004, 2005).

A recent neuropathological case report suggested the presence of a minicolumnopathy in dyslexia (Casanova et al. 2002b). Consistent with this observation some structural Magnetic Resonance Imaging (MRI) studies have shown that dyslexic patients have reduced brain volume, decreased gyrification, and abnormal lateralization (Rumsey et al. 1997a; Casanova et al. 2004, 2005). We now expand on these findings by measuring the depth of white matter gyrifications (as a proxy measurement of the gyral window) in a series of dyslexic men and controls. The gyral window is the aperture for fibers entering and leaving the cortex (Prothero and Sundsten 1984). Variations in the width of the gyral window may bias intra- and interhemispheric connectivity and thus provide a correlate to recent findings suggesting altered circuitry in the brains of dyslexic patients (Horwitz et al. 1998; Simos et al. 2000).

Methods

Patient Sample

We studied 15 right-handed dyslexic men aged 18–40 years and 11 controls matched for sex, age, educational level, handedness, socioeconomic background, and general intelligence (Table 1). All gave informed consent before participation. All were physically healthy and free of any history of neurologic disease, head injury, significant uncorrected sensory deficit, severe psychiatric disorder, and chronic substance abuse. These traits were determined with a medical history, a physical examination, laboratory testing, and a structured psychiatric interview (Schedule for Affective Disorders and Schizophrenia-Lifetime version). Subjects currently undergoing treatment for attention deficit disorders were excluded. A semi-structured interview was used to collect additional developmental history and demographic information. Handedness was measured as a continuous variable with a self-report questionnaire (the Edinburgh Handedness Questionnaire) and with pantomimed responses to verbal commands using handedness items from the Physical and Neurological Examination for Subtle Signs (PANESS).

Dyslexic patients presented with a childhood history of significant impairment that necessitated special help, ranging from tutoring to full-time special education. Despite their significant reading disability, these patients had all graduated from high school, several were in college, and three had completed advanced degrees. All met Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition, criteria for developmental reading disorder. All these patients had at least average intelligence and good spoken language skills (Wechsler full-scale, verbal, and performance IQ all >90) but showed a persistent reading disorder. Passage (decoding) scores, reflecting a combination of reading rate and accuracy, on the Gray Oral reading test 3rd edition (GORT-3), were 8 or lower using norms for the ceiling of the tests—a 12.8 grade level and age of 18 years 11 months. This cutoff score is 0.67 of an SD below average for high school seniors. Single word recognition scores (Wide Range Achievement Test-3rd edition [WRAT-3]) were less sensitive to their reading deficits. Ten of 16 men scored within an average range on a test of single word recognition (WRAT-3 reading, 90–110), whereas the other 6 were deficient on this measure as well (range, 73–88). All but one dyslexic patient read at a level that was, at the time of study, at least 1 SD (15 points) lower than his full-scale IQ. Thus, this group generally met both absolute and discrepancy-based criteria for dyslexia. Based on interviews with patients and reviews of childhood records, only one patient had a history of a clinically significant delay in the acquisition of spoken language suggestive of a developmental language disorder. This subject spoke well by the time he entered school. At the time of the study, he showed good spoken language skills, an average verbal IQ, and excellent reading comprehension, much like our other patients. Thus, he was not excluded.

Control subjects were free of any history of developmental disorder, attention deficit disorder, special education, and reading decoding or spelling deficits. All scored well within an average range or above on the GORT-3 passage scores and the WRAT-3 reading and spelling subtests. They were matched to the dyslexic group by age, handedness, and estimation of IQ, obtained with a short form of the Wechsler Adult Intelligence Scale-Revised. They were also evaluated with the GFW and LAC tests, but these tests were not used in their selection.

Image Acquisition

All images were acquired with the same 1.5 T Signa MRI scanner (General Electric, Milwaukee, Wisconsin) using a 3-D spoiled gradient recall acquisition in the steady state (time to echo, 5 milliseconds; time to repeat, 24 milliseconds; flip angle, 45°; repetition, 1; field of view, 24 cm²). Contiguous axial slices, 1.5 mm thickness (124 per brain), were obtained. The images were collected in a 192 × 256 acquisition matrix and were 0-filled in k space to yield

an image of 256×256 pixels, resulting in an effective voxel resolution of approximately $0.94 \text{ mm} \times 0.94 \text{ mm} \times 1.5 \text{ mm}$. These scans are a subset of the data used for the prior study of Rumsey et al. (1997b) (q.v. Table 1). Additional details of the scanning protocol (e.g., standardized head alignment) are described by Giedd et al. (1996).

Image Processing

Each image was preprocessed to reduce scanner noise, using a Gibbs-Markov Random Field model (Bouman and Sauer 1993; El-Baz et al. 2006). Segmentation of cerebral white matter proceeds via an a priori learned visual appearance model. Control points on a deformable surface ∂V were introduced, removed, or shifted to minimize the boundary energy, i.e. the surface integral of internal force ξ_{int} and external force ξ_{ext} (Kass et al. 1988):

$$E = \int_{\partial V} (\xi_{\text{int}} + \xi_{\text{ext}}) ds,$$

The functional form of ξ_{ext} was based on two recently derived probability models for the prior and current visual appearance (El-Baz et al. 2006, 2007). The boundary of the cerebral white matter W is then $\partial W = \arg \min_{\partial V} E$. More specifically, ∂W is the outer surface of the white matter, ignoring the medial gray/white boundary, which is of no importance to this study of cerebral white matter gyrification.

Cerebral white matter is subsequently divided into gyral and deep white matter components as follows: we calculated the Euclidean distance map inside the three dimensional region W using a fast marching level set method (Adalsteinsson and Sethian 1995) (Fig. 1). The distance map at any given point $p = (x_p, y_p, z_p) \in W$ is defined as the Euclidean distance from point to the nearest point on the boundary surface, i.e.

$$s(p) = \min_{\partial W} \sqrt{(x - x_p)^2 + (y - y_p)^2 + (z - z_p)^2}.$$

Denote the volume of a region R by μR . Then cumulative distribution function F , $F(t) = \mu\{p \in W | s(p) \leq t\} / \mu W$ called the spherical is the basis of subsequent measurements. Modeling F as a Gaussian mixture distribution (El-Baz and Gimel'farb 2007), we estimated the marginal densities within superficial white matter (class I) and deep white matter (class II). From this, we selected a threshold d that discriminates between the two classes (Fig. 2). Note that class I comprises white matter not only within gyri but also near to sulcal fundi. Therefore, we applied the Gaussian mixture modeling a second time to the spherical contact distribution of class II white matter W_{II} and once again selected a threshold d' . Then, W_{II} was dilated by the distance d' and the result was subtracted from the original segmented white matter, leaving only gyral white matter $W_{\text{G}} = W - (W_{\text{II}} \oplus d')$ (Fig. 3).

We used the average depth $\langle g \rangle$ of gyral white matter, viz. the mean of the marginal spherical contact distribution F_{G} , as a proxy measurement for gyral window. The relationship between the two quantities can be calculated for simple, model cases. We present two such cases, omitting the details of computing $\langle g \rangle$. First consider a hemispherical “gyrus” of radius r . The gyral window is a circle of radius r , while $\langle g \rangle = 25r$. Consider also cubical model “gyri” with side length a . The gyral window is a square with side a , while $\langle g \rangle = \frac{7\sqrt{3}}{48}a$. If the square gyral window is expressed as a circle of equal area, then the equivalent radius is $r = a / \sqrt{\pi}$, so $\langle g \rangle = \frac{7\sqrt{3}}{48}r \approx 0.258r$. The advantage of $\langle g \rangle$ over white matter volume as a proxy for gyral window, not obvious from these examples because of their symmetry, is that the spherical

contact distribution of a gyrus is primarily a function of its smallest dimension. To wit, a long, narrow gyrus has smaller $\langle g \rangle$ than a wide gyrus with the same volume.

Statistical Analysis

Differences in $\langle g \rangle$ were tested using a linear model with diagnosis (dyslexic or control) as the sole factor and age as a covariate. The sample was matched for age but not for brain volume. To gauge the effect of this difference we used a simple power law $S_{cw} = AV_{cw}^\alpha$ where both parameters A and α were potentially dependent on diagnosis. White matter surface area, rather than gyral window, was taken for the dependent variable in the nonlinear model for theoretical reasons addressed in the Discussion, below.

Results

Statistical analysis of the white matter distance distribution, restricted to gyri, showed that mean $\langle g \rangle$ was 3.05 mm (SD 0.30 mm) in dyslexic subjects and 1.63 mm (SD 0.15 mm) in the controls ($F_{1,22} = 5.83$; $P = 0.0246$). There was no overlap between the groups, as the full range of $\langle g \rangle$ was 1.46–1.97 mm across the control group and 2.67–3.76 mm across the dyslexic group. There was no significant age dependence ($F_{1,22} = 0.299$; $P = 0.59$) or age/diagnosis interaction ($F_{1,22} = 0.942$; $P = 0.34$) in gyral white matter depth. The full spherical contact distributions show the two groups to be even better separated than their means alone indicate (Fig. 4).

The scaling exponent $\alpha = 0.57$ (95% confidence interval [0.29,0.85]), with no evidence for different α in the dyslexic and control groups ($F_{1,22} = 0.453$; $P = 0.508$). Differences in A were, however, statistically significant ($t_{23} = -15.75$; $P < 0.0001$) (Fig. 5). S_{cw} in dyslexia was $1190 \text{ cm}^2 \pm 108 \text{ cm}^2$, or about three-fifths (95 % confidence interval [0.53,0.62]) that of the control group. Dyslexics' mean V_{cw} was $406 \text{ cm}^3 \pm 41.9 \text{ cm}^3$, or 0.86 (95% confidence interval [0.78,0.93]) that of controls.

Discussion

Our results indicate that the gyral window (or white matter depth) of patients with dyslexia is wider than normal. The resultant phenotype may be the product of broader gyri or may reflect changes in the thickness of the cortex, involution of sulci, and/or complexity of cortical folding. A previous study showing a reduction in the gyrification index (GI, i.e. the ratio of the contour of the pial surface in cross-section to the length of its convex hull) of dyslexic patients suggests that any given gyral abnormality resides in the folding of the cortex rather than its thickness (Casanova et al. 2004). Differences in GI were not so pronounced as the differences in $\langle g \rangle$ reported here, however. In the recently published companion article on autism (Casanova et al. 2009), gyral window was significantly reduced in autistic patients as compared to a control group, while a corresponding difference in GI was not in evidence. As a quantitative measure of cortical folding, GI is less sensitive than the techniques described here and in Casanova et al. (2009).

Since absolute brain size has long been considered an important determinant of gyrification (Brodmann 1913; Pillay and Manger 2007), our results complement previous studies suggesting that, on average, dyslexic patients have reduced brain volume (Eliez et al. 2000; Casanova et al. 2004). It should be noted that brain volume in dyslexia—as reported by Eliez et al. (2000) using almost the same sample as in this study and hence not duplicated here—was 92% that of controls (1263 vs. 1368 cm^3). This stands in contrast to the pronounced difference, almost a factor of two, in gyral white matter depth.

It is interesting to consider the relationship between brain volume and gyrification in humans as compared with the relationship across species. From Prothero and Sundsten (1984) we find

that $S_{cx} \propto V_{Br}^{0.91}$ across 44 mammalian species, and $V_{cx} \propto V_{Br}^{1.04}$ over 96 mammalian species. More recent work by Bush and Allman (2003), using data from 45 species, has shown that $V_{cw} \propto V_{cx}^{1.28}$. Then if the white matter surface, i.e. the inner surface of the cerebral cortex, scales like the outer surface of the cerebral cortex, one would expect to find that $S_{cw} \propto V_{cx}^{0.68}$. The apparent relation of white matter surface to volume in our sample $S_{cw} \propto V_{cw}^{0.57 \pm 0.28}$ is broadly consistent with this estimate *within* diagnostic categories. The difference between dyslexic and control groups' mean white matter surface areas, however, is much greater than this model would predict given their difference in mean white matter volume (Fig. 5). The mechanism underlying differences in cortical folding in dyslexia is distinct from that accounting for encephalization, e.g., alteration in the total number of minicolumns. The findings are in opposition to those predicted by the evolutionary theory of dyslexia (Geschwind and Galaburda 1987).

Comparable diminution in brain volume and cortical folding has now been reported in patients with attention deficit hyperactivity disorder (ADHD) (Wolosin et al. 2009); the most frequent comorbidity to reading disorders (Jensen and Brieger 2005). Studies suggest that between 15 and 26% of patients with reading disability experience ADHD, whereas 25–40% of individuals with ADHD meet criteria for reading disorder. The presence of similar neuroanatomical features in both ADHD and dyslexia gives credence to the reported findings and to the possibility of a common etiopathologic mechanism.

There are several ways by which gyral window relates to altered corticocortical connectivity. A larger gyral window, as in dyslexia, may remove the space constraint for longer corticocortical fibers which themselves are bigger in width, i.e., combined axon and myelin diameter. This is the same mechanism by which compression may preferentially eliminate larger axons in some neuropathies. Alternatively, causality may run in the opposite direction and a genetically pre-programmed bias in the development of long distance axons may cause changes in the gyral window and gyrification of the cortex. The latter mechanism stems from Van Essen's (1997) tension-based theory of cortical folding. Regardless of the means, the end result for dyslexic patients is a bias in connectivity which favors longer connections at the expense of shorter ones. In dyslexia this is manifested as increased size of the corpus callosum (long commissural fibers) (Hynd et al. 1995; Robichon et al. 2000) despite a smaller than average brain size (Eliez et al. 2000; Casanova et al. 2004). The overall increase in longer fibers comes at the expense of a diminution in short, arcuate (μ) connections (El-Zehiry et al. 2006; Abd El Munim et al. 2007).

Previous studies on dyslexic and control subjects used signed distance maps and front propagation to parcel the white matter into inner and outer compartments (El-Zehiry et al. 2006; Abd El Munim et al. 2007). The parcellated images were then used to compute and compare the white matter volumes across the comparison series. Dyslexic subjects had a significant reduction of the outer white matter compartment. Most of the fibers populating the outer radiate compartment of white matter are late myelinating and, by contrast, found to be increased in other conditions, e.g., autism (Herbert et al. 2004). A deficit in very short-range connectivity (e.g., angular gyrus, striate cortex), consistent with results of a larger gyral window, could help explain reading difficulties in patients with dyslexia.

Reading does not result from the expression of a singular gene or the activity of a given brain center; rather, reading is a postnatally acquired process that varies according to cultural norms (Wolf 2007). Neuroimaging studies suggest that changes in reading patterns may be the result of remodeling of exuberant corticocortical connections throughout the first few years of life (see below). The size of the gyral window biases connections for optimal conduction and metabolic efficiency based on the relative amounts of short and long corticocortical fibers. As

an example, the striate cortex has a small gyral window and short connections (e.g., V1 → V2, V2 → V3), whereas by contrast, the motor cortex has a large gyral window and long connections (e.g., M1 → spinal cord). These retractive events extend into the postnatal period as typified by areal changes of the corpus callosum in response to cortical development (Moses et al. 2000). Experience with hemi-spherectomies suggests that this remodeling is framed during the first 4 years of life, during which time the hemispheres are equipotent with regards to linguistic abilities (Mariotti et al. 1998; Devlin et al. 2003). This time frame coincides with the critical period for language acquisition (Almli and Finger 1987; Frith 2003).

The brain reorganizes itself postnatally according to environmental demands. This ability to make new connections is fostered by the modular organization of the cortex. It is suggested that minicolumns have the capacity to provide for “weak linkages” enabling the cortex to adapt to environmental demands without having to reconstruct a myriad of intracortical circuits (Casanova and Tillquist 2008). This ability of the cortex to retool itself explains changes in the receptive fields of musicians following extensive manual practice (Pantev et al. 2001). By analogy it also explains how the brain appropriates circuits, initially established for vision and language, into a reading system (Bolger et al. 2005; Wolf 2007). As novel connections are acquired, the conjoint activation of neurons propitiates the formation of new circuits or engrams (Hebb 1949). With maturation and increased fluency bihemispheric activation in children is superseded by the activation of a more efficient system within the left hemisphere (Sandak et al. 2004; for an opposing view see Vargha-Khadem et al. 1991). This reorganization changes the way we read and think. In effect, it has been argued that learning to read expands our thought process and stimulates novel conceptions (Vygotsky 1962; Olson 1977; Jackendoff 2002).

In dyslexia the shift towards a reading dominance by the left hemisphere is not normally established. Consistent with this idea early studies showed that dyslexic patients unusually relied on their right hemisphere for language related processes (Yeni-Komshian et al. 1975; Pirozzolo and Rayner 1977). More recent studies have refined this view in favor of a deficit in intrahemispheric “short” corticocortical connectivity targeting, among other structures, the left angular gyrus (Horwitz et al. 1998; Pugh et al. 2000; Shaywitz et al. 2003; Sandak et al. 2004). The resultant modifications in connectivity engenders in those so affected an alternate brain circuit for reading (Simos et al. 2000). The less efficient reading circuit provides for a decoding deficiency manifested as weak phonologic processing or awareness. Affected patients have difficulties in sounding out words despite normal or superior cognitive skills (Jensen and Brieger 2005). It is our contention that these changes are the result of a reorganization of the ratio of short and long corticocortical connections that occur during the early postnatal years (see above).

Computer modeling of columnar cortical features using a Kohonen map with Hebbian learning has shown that wide columns, as in dyslexia, provide for great variability in signal processing (Gustafsson 1997). Wide columns facilitate generalization and small columns provide for discrimination (Casanova et al. 2002a). Contrary to dyslexia, autistic individuals tend to have larger brains and a small gyral window (Lainhart et al. 2005; Casanova et al. 2007b, 2009). (Readers should note that a different proxy measurement of gyral window, the quantity labeled *d* in Methods, above, was used in the latter two articles). Furthermore, autistic patients’ radiate white matter compartment appears to be significantly increased at the expense of a smaller corpus callosum (Herbert et al. 2004; Lainhart et al. 2005). Not coincidentally autism seems to be characterized by smaller minicolumns (Casanova et al. 2002c, 2006) and a deficit of inhibition for which anticonvulsants appear to ameliorate selected behavioral traits (Plioplys 1994; Uvebrant and Bauzienne 1994; Childs and Blair 1997; Jambaqué et al. 2000; Casanova et al. 2003; Sokhadze et al. 2008). It may be that “minicolumns exist within a phenotypic spectrum that intertwines the inhibitory/excitatory flow of neocortical information with a

tweaking of the signal-to-noise ratio relevant to feature extraction” (Casanova et al. 2002b). Within this phenotypic spectrum autism and dyslexia appear to fall at opposite ends.

Modern neuroimaging techniques enable us to probe the microstructure of the white matter by defining the diffusion-driven displacement of molecules along axons. It is hoped that the application of these techniques in combination with functional MRI may better demonstrate the deficit in corticocortical connectivity suggested in our structural analysis. Thus far, preliminary studies using diffusion tensor imaging (DTI) support a disconnection syndrome involving multiple areas of the brain in patients with dyslexia (Klingberg et al. 2000; Niogi and McCandliss 2006; Richards et al. 2008; Steinbrink et al. 2008).

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List of Symbols

S	Surface area
V	Volume
cx	Cerebral cortex (gray matter)
cw	Cerebral white matter
$\langle g \rangle$	Mean gyral depth (gyral window)

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Fig. 1.

A sagittal cross-section through segmented white matter, with its *interior shaded* according to the Euclidean distance map in two dimensions. At each point within the white matter, the Euclidean distance map is equal to the radius of a ball, or circle in two dimensions, centered on that point and tangent to the region's boundary

Fig. 2.

The spherical contact distribution is modeled as a Gaussian mixture in order to determine the optimal threshold d to classify a point within the white matter as deep or superficial. The histogram of the Euclidean distance map, binned at 1 mm (*points*), is approximated by the sum (*solid*) of two scaled normal densities (*dashed*). Then d is chosen to be the point at which the two components intersect, where a point is equally likely, given its depth, to lie within deep or superficial white matter

Fig. 3.

Segmentation of gyral white matter. The whole cerebral white matter, whose boundary is shown by the light contour on the left, is eroded to the threshold depth d sufficient to exclude gyri from the resulting volume (*dark contour*). That surface is then evolved outward a distance d' so as to include superficial white matter outside of gyri. The resulting surface (*left, middle contour*) serves to separate gyral white matter (*right*) from interior white matter

Fig. 4.

Left, the envelopes, i.e. the pointwise maxima and minima, of the spherical contact distributions for our sample of 15 dyslexic subjects and 11 controls. Gyri in dyslexia are clearly wider, having proportionally more white matter far from the surface than in individuals with normal reading ability. *Right*, the envelopes of P–P plots of observed spherical contact distributions versus a model distribution. For a given subject, the P–P plot is the locus of points $[F_o(r)]$ where

$F_o(r) = 1 - \frac{4}{3}\pi(R-r)^3/V_{cw}$ for a sphere of radius R such that its volume equals the subject's V_{cw} . Naturally, the shape of gyral white matter is far from spherical (the latter indicated by the diagonal line). Of greater interest is the fact that dyslexic and control groups remain distinct from each other on this scale. The structural difference between them is primarily one of brain shape rather than brain size

Fig. 5.

The dyslexic sample had somewhat smaller less white matter than the control sample, and significantly less white matter surface area. Within each group, volume and surface area appear to be related by power laws (*solid lines*) with the same exponent

Table 1

Summary of study participants

	Dyslexic	Control
<i>N</i>	15	11
Age (years)	28.2	25.1
Range	18.5–40.4	17.8–40.6
Education (years)	14 ± 3	14 ± 2
Social class	All middle to upper middle class	
WAIS-R IQ	113 ± 7	111 ± 12
GORT-3 passage	4 ± 2	13 ± 2
Comprehension	13 ± 2	11 ± 2
GFW reading	41 ± 4	51 ± 4
Spelling	43 ± 8	51 ± 8
WRAT-3 reading	91 ± 11	107 ± 7
Spelling	74 ± 14	106 ± 7
Arithmetic	97 ± 13	112 ± 11
LAC total	80 ± 12	96 ± 5

Cerebral white matter volume is the size of the interior of the segmented white matter surface, for which see Methods. All participants were right handed, male, and Caucasian. Values are given as mean ± SD. The age of each participant at MRI acquisition time was known, while the other data are abstracted from Rumsey et al. (1997b), with the caveat that a subset of the original sample of 14 control and 16 dyslexic men was used for the present study (11 control and 15 dyslexic)

Acronyms: *GFW* Goldman-Fristoe-Woodcock Sound Symbol Tests, *GORT-3* Gray Oral Reading Test, 3rd edition, *WAIS-R* Wechsler Adult Intelligence Scale, Revised, *WRAT-3* Wide Range Achievement Test, 3rd edition