Biological Psychiatry: CNNI

Archival Report

Shared Neuroanatomical Substrates of Impaired Phonological Working Memory Across Reading Disability and Autism

Chunming Lu, Zhenghan Qi, Adrianne Harris, Lisa Wisman Weil, Michelle Han, Kelly Halverson, Tyler K. Perrachione, Margaret Kjelgaard, Kenneth Wexler, Helen Tager-Flusberg, and John D.E. Gabrieli

ABSTRACT

BACKGROUND: Individuals with reading disability and individuals with autism spectrum disorder (ASD) are characterized, respectively, by their difficulties in reading and social communication, but both groups often have impaired phonological working memory (PWM). It is not known whether the impaired PWM reflects distinct or shared neuroanatomical abnormalities in these two diagnostic groups.

METHODS: White-matter structural connectivity via diffusion weighted imaging was examined in 64 children, age 5 to 17 years, with reading disability, ASD, or typical development, who were matched on age, gender, intelligence, and diffusion data quality.

RESULTS: Children with reading disability and children with ASD exhibited reduced PWM compared with children with typical development. The two diagnostic groups showed altered white matter microstructure in the temporoparietal portion of the left arcuate fasciculus and in the occipitotemporal portion of the right inferior longitudinal fasciculus (ILF), as indexed by reduced fractional anisotropy and increased radial diffusivity. Moreover, the structural integrity of the right ILF was positively correlated with PWM ability in the two diagnostic groups but not in the typically developing group.

CONCLUSIONS: These findings suggest that impaired PWM is transdiagnostically associated with shared neuroanatomical abnormalities in ASD and reading disability. Microstructural characteristics in left arcuate fasciculus and right ILF may play important roles in the development of PWM. The right ILF may support a compensatory mechanism for children with impaired PWM.

Keywords: Autism spectrum disorder, Diffusion tensor imaging, Phonological working memory, Reading disability, Transdiagnostic, White matter

http://dx.doi.org/10.1016/j.bpsc.2015.11.001

Reading disability and autism spectrum disorder (ASD) are two neurodevelopmental disorders that affect millions of children's language and/or social communication abilities (1,2). Although reading disability and ASD are typically considered as two fundamentally different disorders, children with either diagnosis often exhibit impaired phonological working memory (PWM) (3–11). PWM is measured by auditory tests of phonological awareness and verbal short-term memory that require children to briefly maintain and manipulate auditory verbal or phonological information in words, nonwords, or digits (5,6). Such phenotypic similarity may reflect a shared neurobiological dimension as broadly conceptualized by the Research Domain Criteria approach to psychiatry (12). Here, we asked whether there is a shared transdiagnostic neuroanatomical correlate for impaired PWM across the diagnoses of reading disability and ASD or, alternatively, whether impaired PWM reflects different neuroanatomical correlates in these two different diagnostic disorders.

Deficits in PWM are closely associated with difficulty in learning to map the phonology of spoken language onto the orthography of print (13,14). Poor readers have shown impaired PWM reflected by impaired phonological awareness and verbal short-term memory (15). Children with ASD, particularly those with broader language impairments, have also shown impaired phonological awareness and verbal short-term memory (8–11). Moreover, atypical verbal short-term memory was found among unaffected first-degree relatives, which indicates that impaired PWM is a prominent feature of the broader autism phenotype (16).

PWM deficits have been associated with neuroanatomical differences in poor readers relative to typically developing (TD) children (17). One of the most consistent differences is observed in or near the left arcuate fasciculus (AF), which connects inferior frontal and posterior temporal regions crucial for PWM. For example, poor readers exhibited decreased fractional anisotropy (FA) as measured by diffusion tensor imaging (18). Although the precise location of the difference varied across studies, in most studies poor readers exhibited decreased FA in or near the left AF (18–23). Atypical white matter (WM) microstructure in poor readers has also been observed in the inferior longitudinal fasciculus (ILF), which connects anterior temporal cortex with occipital cortex, constituting a ventral pathway for visual and auditory processing (24,25).

Many studies report WM differences in ASD as measured by diffusion tensor imaging, but specific findings vary widely (26,27). Some reported increased radial diffusivity (RD) in the left AF, accompanied by decreased left-lateralized mean diffusivity (MD) and FA in children with ASD (28,29), but others have reported more widespread WM changes (30). Abnormalities in the left AF have also been found in children with ASD [(28–30), see review (31)] and with altered left AF measures (streamline length and MD) correlated with expressive language ability (32). In one study, when head movements were carefully controlled, the only difference in ASD was decreased FA in the right ILF (33). No study has examined the specific relation of WM microstructure to PWM or reading ability in ASD, despite the multiple reports of impaired PWM in ASD.

Here, we asked whether a common weakness in PWM reflects shared or disparate WM microstructural anomalies in reading disability and ASD. If common WM microstructural anomalies are found in relation to impaired PWM in reading disability and ASD, the PWM deficits can be interpreted transdiagnostically at the behavioral and the neuroanatomical level. We hypothesized that common WM microstructural anomalies might occur in the left AF and right ILF. On the other hand, if distinct WM microstructural anomalies are found in reading disability and ASD, then the PWM deficits more likely reflect shared behavioral manifestations of two distinct pathophysiological mechanisms.

METHODS AND MATERIALS

Participants

There were 29 children with reading disability (poor readers), 41 children with ASD, and 75 TD children recruited from the Boston area of the United States. After screening for data quality (see Image Data Acquisition and Image Data Analysis, below) and matching for demographic characteristics, 64 children (19 poor readers, 25 children with ASD, and 20 TD children) ages 5 to 17 years were included in this study (Table 1). All children were native speakers of American English, were right-handed, were born at 32 or more weeks gestational age, had normal hearing and nonverbal cognitive ability, and had no history of head injury or comorbid psychiatric or neurological conditions or any genetic disorders associated with autism (e.g., fragile X syndrome). The three groups of children did not differ significantly on age ($F_{2,61}$ = .91, p = .41), nonverbal IQ (Kaufman Brief Intelligence Test, Second Edition, $F_{2,61}$ = 1.86, p = .16) (34), or gender ratio (Kruskal–Wallis test, χ^2 = .20, df = 2, p = .90). This study was approved by the Committee on the Use of Humans as Experimental Subjects at the Massachusetts Institute of Technology.

Participant Groups

The three groups of children were defined by exclusionary and inclusionary criteria. Children in the poor reader group had standard scores below 90 (below 25th percentile) on at least two of the four subtests: word identification and word attack in the Woodcock Reading Mastery Test–Revised Normative Update (35) and sight word efficiency and phonemic decoding efficiency in the Test of Word Reading Efficiency (36). A composite reading score was derived by averaging the standard scores of the four subtests to provide an overall estimate of reading ability. In addition, sentence-level reading ability was assessed by administering the reading fluency subtest in the Woodcock-Johnson III Tests of Achievement (37). Children were included in the ASD group if they had a community-based clinical diagnosis of ASD that was confirmed by trained research staff using the Autism Diagnostic Observation Schedule (ADOS/ADOS-2) Module 3/4. To quantify the severity of the autism symptomatology, we converted participants' ADOS scores to autism severity scores by using the calibrated severity metrics (38,39). Participants in the TD group scored within normal limits on the above standardized assessments of reading and ADOS and had no first-degree relatives with reading disabilities or ASD (details in Supplement 1).

PWM Measures

Four subtests (elision, blending words, memory for digits, and nonword repetition) from the Comprehensive Test of Phonological Processing (40) and the Children's Test of Nonword Repetition (41) were used to measure participants' PWM (task details in Supplement 1). An intraclass correlation analysis showed high-level consistency among the five subtests (intraclass correlation = .694, $p < .001$, Table S1 in Supplement 1). Thus, a composite score was calculated for each participant by averaging the Z-transformed scores of the five tests to

Table 1. Group Characteristics

	Poor Readers	ASD	TD
Number	19	25	20
Age	11.8 (3.27)	11.3 (3.48)	10.3 (3.57)
Nonverbal IQ	101.8 (13.99)	108.9 (15.28)	110.1 (14.27)
Gender Ratio (F:M)	.36	.32	.43
Autism Severity	1.78 (1.52)	6.08 (2.48)[a]	1.33 (.69)
Word Reading	83.45 (9.90)[a]	99.33 (13.16)[b]	112.48 (10.25)
Sentence Reading	79.65 (11.54)[a]	100.04 (15.82)[a]	115.68 (9.67)
Language	92.47 (21.07)[a]	94.21 (18.87)[a]	113.15 (11.39)

Numbers outside and inside the parentheses indicate mean and standard deviation, respectively. Nonverbal IQ was measured by Kaufman Brief Intelligence Test Matrix subtest (34). Autism severity was measured with the standardized calibrated severity score, which ranges from 1 to 10 (38,39). Word reading was measured with the average of the standard scores across four reading tests: word identification, word attack, sight word efficiency, and phonemic decoding proficiency. Sentence reading was measured with the standard score of the sentence reading fluency subtest of the Woodcock-Johnson III Tests of Achievement (37). Language was measured with the core language score from Clinical Evaluation of Language Fundamentals, Fourth Edition (81) based on the sum of the scale scores of age-appropriate subtests, including concepts and following directions, recalling sentences, formulating sentences, word structure, word classes, and word definitions.

ASD, autism spectrum disorder; F, female; M, male; TD, typically developing.

[a]Statistical significance compared with TD: $p < .001$.

[b]Statistical significance compared with TD: $p < .01$.

provide a more reliable measure of PWM ability than any individual test.

Image Data Acquisition

Participants were trained to lie still in a mock scanner 30 minutes before imaging. A person with expertise in image data analysis oversaw the scan sessions and inspected the raw diffusion-weighted image data for visible motion immediately after scanning. In cases of excessive motion (4.1% of the initial sample), the scan was repeated either in the same or a different session. This process ensured that all raw diffusion-weighted images were free of visible motion (details in Supplement 1).

Anatomical Imaging. A whole-head, high-resolution T1-weighted multiecho magnetization prepared rapid acquisition gradient-echo anatomical volume was acquired: repetition time = 2530 ms, echo time = 1640 ms, inversion time = 1400 ms, flip angle = 7°, field of view = 220 × 220, interleaved slice number = 176 slices, slice thickness = 1 mm, in-plane resolution = 1.0 mm^2.

Diffusion Tensor Imaging. Repetition time = 9300 ms, echo time = 84 ms, inversion time = 2500 ms, flip angle = 90°, field of view = 256 × 256, in-plane resolution = 2.0 mm^2, slice thickness = 2 mm, 10 baseline volumes (b = 0), and 30 diffusion-weighted volumes (b = 700 sec/mm^2) with 74 slices per volume.

Image Data Analysis

Individual data quality was screened by DTIprep, a quality-control software that allows automatic evaluation of the quality of diffusion images, b-values, and gradient directions (42). Poor data quality resulted in removal of 14.5% of the initial sample from further analysis. Then, TRActs Constrained by UnderLying Anatomy (TRACULA) (43) was used to quantitatively assess data quality by calculating two motion (frame-to-frame translation and rotation parameters) and two intensity (averaged signal dropout score and the percentage of slices with scores greater than 1) measures (44) (details in Supplement 1). The four measures captured global frame-to-frame motion and the frequency and severity of rapid slice-to-slice motion. The three groups did not show any significant differences on these data quality measures (translation: $F_{2,61}$ = .242, p = .786; rotation: $F_{2,61}$ = .593, p = .556; signal-dropout score: $F_{2,61}$ = .665, p = .518; percent of bad slices: $F_{2,61}$ = .686, p = .507).

Standard data processing was conducted in TRACULA. TRACULA performs automated global probabilistic tractography that estimates the posterior probability of each of 18 WM tracts. Segmented anatomical images of the same participants were used to facilitate the estimation. The default procedures can calculate either the posterior mean or maximum of a posteriori pathways for each participant. Here, the posterior means were used. FA, MD, RD, and axial diffusivity were calculated both over the whole pathway and along each measurement point over the arc of the pathway (43) (details in Supplement 1).

Based on prior reports of altered WM in the left AF in poor readers and right ILF in ASD, we examined these two tracts bilaterally as a priori tracts of interest and then also performed whole-brain analyses to examine whether any group differences were specific to these two tracts or extended more widely across tracts. Specifically, for the bilateral AF and ILF, analysis of covariance procedures were conducted point-by-point along each of the two tracts to examine the group differences (43). Age, IQ, and gender were included as potential covariates. Only age significantly contributed to the model, so IQ and gender were removed from the final models. Results were corrected for multiple comparisons (i.e., 4 measures × all points × 4 tracts) at $p < .05$ level by using a Monte Carlo simulation method (height, $p < .005$; extent, cluster > 6 points; 3dClustSim within AFNI, http://afni.nimh.nih.gov/afni/) (45). In addition, the relations between the diffusion measures and PWM were also examined (Supplement 1). To validate the point-to-point analysis method, we further compared groups on the diffusion measures averaged across the whole tract of interest, as reported in previous studies (33,46).

RESULTS

Shared PWM Deficits in Poor Readers and ASD

Both the poor reader group (mean [M] = −.26, SD = .83) and ASD group (M = −.11, SD = .66) had lower composite PWM scores than the TD group (M = .44, SD = .47) (t_{37} = −3.26, p = .002 for poor reader vs. TD; t_{43} = −3.14, p = .003 for ASD vs. TD) (Figure 1). The poor reader and ASD groups did not differ significantly from one another (t_{42} = .43, p = .51). These results were confirmed in a linear regression model controlling for age and using group as an independent variable (Table 2). Standard scores for each subtest are presented in Table S1 in Supplement 1.

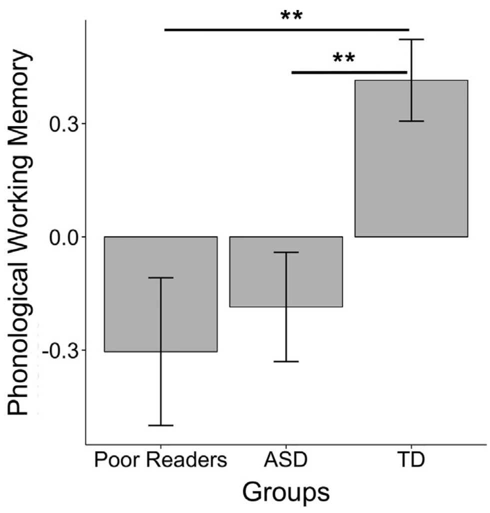

Figure 1. Group means of phonological working memory performance in poor reader group, autism spectrum disorder (ASD) group, and age-, IQ-, and gender-matched typically developing (TD) group. Phonological working memory composite scores were averaged across the Z-normed scores of five subtests. **$p < .01$.

Table 2. Group Comparison Statistics on PWM and White-Matter Structure

	Poor Reader Vs. TD	ASD Vs. TD	ASD Vs. Poor Reader
PWM	$F_{1,34} = 6.25$, $p = .017$	$F_{1,40} = 10.73$, $p = .002$	$F_{1,41} = .55$, $p = .463$
Left TP-AF (FA)	$F_{1,36} = 13.03$, $p < .001$	$F_{1,42} = 12.87$, $p < .001$	ns
Left TP-AF (RD)	$F_{1,36} = 26.85$, $p < .001$	$F_{1,42} = 12.15$, $p = .001$	ns
Right OT-ILF (FA)	ns	$F_{1,42} = 10.53$, $p = .002$	ns
Right OT-ILF (RD)	ns	$F_{1,42} = 15.86$, $p < .001$	ns

Age was included as a covariate in all analyses of covariance.

ASD, autism spectrum disorder; FA, fractional anisotropy; ns, not significant; OT-ILF, occipitotemporal portion of the inferior longitudinal fasciculus; PWM, phonological working memory; RD, radial diffusivity; TD, typically developing; TP-AF, temporoparietal portion of the arcuate fasciculus.

Shared WM Alterations in Poor Readers and ASD

Shared patterns of WM alterations were found in the left AF and right ILF for both the poor reader and ASD groups compared with the TD group (Figure 2A, uncorrected *p*). After correcting for multiple comparisons, the significant WM structural differences were found to share the same location for the poor reader and ASD groups (Figure 2A). Specifically, in the left temporoparietal portion of the AF (TP-AF; six points, peak position, x, y, z = −37, −45, 13; Figure 2A), the poor reader and ASD groups had significantly lower FA than the TD group (Figure 2B). In the same location (TP-AF, Figure 2A), the poor reader and ASD groups showed significantly higher RD than the TD group (Figure 2A, C). In the right occipitotemporal portion of the inferior longitudinal fasciculus (OT-ILF) (seven points, peak position, x, y, z = 33, −59, 0), the ASD group had significantly lower FA and higher RD (Figure 2A) than the TD group. Table 2 summarizes significant group differences. The diffusion measures of the right ILF in the poor reader group were between those found for TD and ASD but did not differ significantly from either group (Figure 2A–C). Direct comparisons between the poor reader and ASD groups did not reveal any significant differences on any diffusion measure in either tract after multiple comparison correction. There were no differences between any pairs of group in MD or axial diffusivity of either tract after correction. No group differences were found in any microstructural measures of either right AF or left ILF.

To validate the specificity of our a priori hypothesis, analyses of group differences across all 18 tracts were conducted on FA and RD. The left TP-AF and right OT-ILF were the only two areas that differentiated the disordered groups from the TD group (*p*s $< .05$, corrected), with the

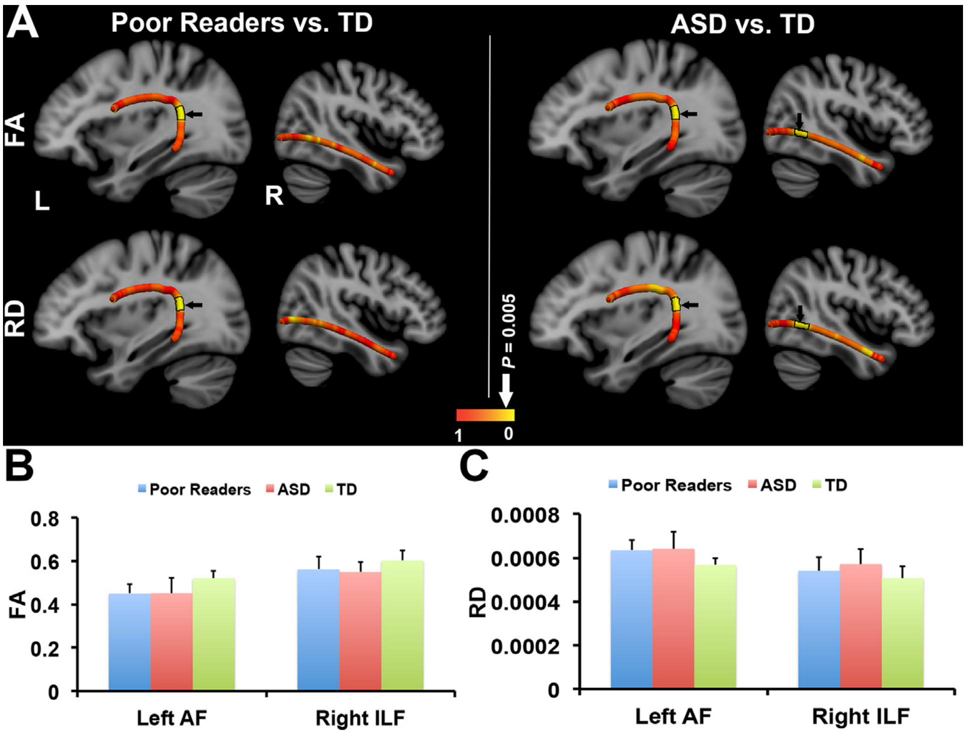

Figure 2. White-matter structural differences in poor reader group or autism spectrum disorder (ASD) group vs. age-, IQ-, and gender-matched typically developing (TD) group. **(A)** The poor reader (left panel) and ASD (right panel) groups exhibited decreased fractional anisotropy (FA) (top row) and increased radial diffusivity (RD) (bottom row) in the left (L) arcuate fasciculus (AF) (left column in each panel) and in the right (R) inferior longitudinal fasciculus (ILF) (right column in each panel). For visualization purposes, the diameter of each measurement point was increased to form a continuous fiber tract in both Figure 2 and Figure 3. Coloration along the tracts represents the uncorrected continuous *p*, from higher *p* in red through lower *p* in yellow. Portions of each tract that were significantly different between groups after correction for multiple comparisons are outlined in black; a black arrow next to the black outline indicates the position of peak group difference. The white arrow above the color bar indicates the color range for height threshold ($p < .005$). **(B)** Average FA and **(C)** RD extracted from the portion or tracts outlined in black in each group. Error bars represent standard deviation. The bar graphs were used to demonstrate the pattern of group difference, and no statistical tests were conducted.

clinical groups exhibiting decreased FA and increased RD relative to the TD group. We also compared groups on the tract averages of FA and RD for the left AF and right ILF. Largely consistent with the point-by-point analysis, the poor reader and ASD groups exhibited significantly decreased FA and increased RD in the left AF. The ASD group showed significantly decreased FA and increased RD in the right ILF, with the poor reader group falling in between the ASD and the TD groups (Supplement 1).

Association Between Structural Connectivity and PWM

We examined the relation of PWM ability to the left AF and the right ILF first by combining all three groups in a linear regression. There was a significant positive relation between the PWM scores and FA (*Z*-normed) in both the left TP-AF (6 points, peak position, x, y, z = −35, −45, 17, $\beta = .392$, $R^2 = .154$, $p = .001$) and right OT-ILF (15 points, peak position, x, y, z = 32, −61, 0, $\beta = .474$, $R^2 = .225$, $p < .001$) (Figure 3A). The relation remained significant while controlling for the effects of age (Table 3). The FA in the left TP-AF and right OT-ILF together explained 34% of the variance in PWM scores ($F_{3,61} = 10.467$, $p < .001$). Patterns of association between PWM and FA were replicated in the analysis on RD (Supplement 1). No significant results or similar patterns were found in axial diffusivity or MD, and no significant results were found in other parts of either the left AF or the right ILF.

The relations between PWM scores and WM diffusion measures were further examined with linear regression models within each participant group. PWM scores and FA in the right OT-ILF were significantly correlated in both the poor reader group ($\beta = .509$, R^2 change = .318, $p = .007$) and the ASD group ($\beta = .351$, R^2 change = .253, $p = .006$) but not in the TD group ($\beta = .040$, R^2 change = .048, $p = .731$, Figure 3B). The relation between PWM score and FA of the right OT-ILF for the poor reader and ASD groups remained significant after controlling for age (Table 3). No significant relationship was found between PWM scores and FA in the left TP-AF for any group (poor readers: $\beta = .200$, R^2 change = .0008, $p = .335$; ASD: $\beta = .191$, R^2 change = .044, $p = .16$; TD: $\beta = 1.676$, R^2 change = .067, $p = .560$). We observed similar patterns using RD as the dependent variable (Supplement 1).

Because the right ILF was found previously to be specifically atypical in children with ASD (33), we examined the relations between FA of the right OT-ILF and autism severity defined by the standardized severity score on the ADOS (38,39). There was no significant association within any group (poor readers: $\beta = .005$, R^2 change = .059, $p = .813$; ASD: $\beta = -.013$, R^2 change = .015, $p = .258$; TD: $\beta = .012$, R^2 change = .059, $p = .815$).

DISCUSSION

In this study, both children who were poor readers and children with ASD exhibited impaired PWM and shared WM microstructure anomalies in left AF and right ILF relative to TD children. For both tracts, the poor reader and ASD groups exhibited decreased FA and increased RD, consistent with the idea that these tracts were less developed relative to the TD

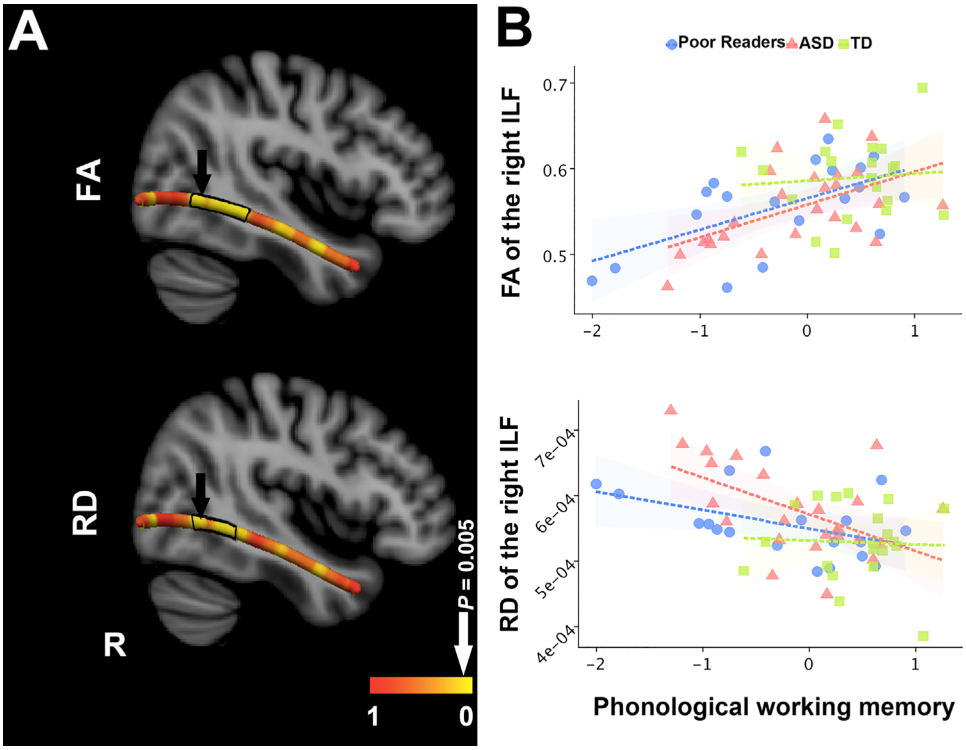

Figure 3. Correlations between diffusion measures of the right (R) inferior longitudinal fasciculus (ILF) and phonological working memory. **(A)** Coloration along the tracts represents uncorrected continuous *p* in the correlation. This is used to demonstrate the overall pattern of the relation between structural connectivity and phonological working memory. Note that significant results were only found in the left arcuate fasciculus and right ILF at $p < .05$ level (corrected). The portions of tract that were significantly correlated with phonological working memory after correction for multiple comparisons are outlined in black; a black arrow next to the black outline indicates the position of peak correlation. The white arrow above the color bar indicates the color range for height threshold ($p < .005$). **(B)** Relations between fractional anisotropy (FA) (upper) and radial diffusivity (RD) (lower) extracted from significant clusters in right ILF and phonological working memory within each individual group. The colors and shapes of the dots indicate group membership. The straight lines represent the linear correlation within each group. ASD, autism spectrum disorder; TD, typically developing.

Table 3. Correlation Between PWM and White-Matter Structure

	Poor Reader	ASD	TD	All
Left TP-AF (FA)	β = .194	β = .113	β = .028	β = .413
	R^2 change = .053	R^2 change = .026	R^2 change = .003	R^2 change = .171
	p = .353	p = .414	p = .801	p = .001[a]
Left TP-AF (RD)	β = −.209	β = −.073	β = −.002	β = −.356
	R^2 change = .063	R^2 change = .009	R^2 change = 2×10^{-5}	R^2 change = .127
	p = .310	p = .625	p = .985	p = .005[a]
Right OT-ILF (FA)	β = .499	β = .303	β = .157	β = .511
	R^2 change = .361	R^2 change = .198	R^2 change = .086	R^2 change = .262
	p = .008[a]	p = .016[b]	p = .192	p < .001[c]
Right OT-ILF (RD)	β = −.374	β = −.294	β = −.200	β = −.446
	R^2 change = .203	R^2 change = .165	R^2 change = .113	R^2 change = .194
	p = .058[d]	p = .030[b]	p = .130	p < .001[c]

Age was controlled for in all correlation analyses.

ASD, autism spectrum disorder; FA, fractional anisotropy; OT-ILF, occipitotemporal portion of the inferior longitudinal fasciculus; PWM, phonological working memory; RD, radial diffusivity; TD, typically developing; TP-AF, temporoparietal portion of the arcuate fasciculus.

[a] $p < .01$.

[b] $p < .05$.

[c] $p < .001$.

[d] $p < .06$.

group. RD may be especially sensitive to myelination differences as opposed to axon fibers [(47,48) but see (49)]. Further, increased FA and decreased RD in the right ILF correlated with better PWM among the poor reader and ASD groups, consistent with the hypothesis that the right hemisphere plays a more prominent role in language processing in these groups of children than in typically developing children. The striking similarities of altered WM organization in both clinical groups provide strong evidence for a transdiagnostic neuroanatomical basis of reduced PWM.

PWM in Poor Readers and ASD

In this study, PWM ability was measured with a composite score combining children's performance on tests of phonological awareness (elision and blending words) and verbal short-term memory (nonword repetition and memory for digits). Performance on all these tasks reflects the ability to maintain and manipulate auditory verbal or phonological information in short-term memory [e.g., (50)]. Such PWM deficits have been well documented in separate studies of children with reading disability (6,51–53) or ASD (8,11,16). Our results show directly that a similar impairment of PWM is shared across poor readers and the age-, IQ-, and gender-matched children with ASD.

The present study included children with ASD with both intact and impaired language skills to avoid an arbitrarily categorical definition of language deficit. Thus, analyses were based on a continuous range of language performance within the ASD group. Although the poor reader and ASD groups were similarly impaired on PWM tasks, the ASD group performed significantly better than the poor reader group on reading tasks. The reading scores of children with ASD were near the standardized mean of 100 but significantly lower than the scores of the TD group. The different relation between PWM scores and reading scores in the ASD and poor reader groups is consistent with previous reports that difficulties in PWM and reading are variable despite the prominent role of phonological abilities in reading acquisition (51,54).

Atypical White Matter of the Left AF

We found shared WM abnormalities in the left AF across the poor reader and ASD groups. This finding is consistent with prior studies examining either poor readers (55) or ASD (31). The shared WM anomaly for the two groups was striking in that it occurred at the same location of the left TP-AF. Anatomically, for a large pathway like the AF, different subgroups of fibers join the pathway for part of its trajectory, merging on or off at different points along the AF (43,47,56–59). Compared with other portions of the left AF, these fibers arch around the TP region and line up temporarily in parallel before fanning out toward dorsal parietal and frontal areas. It is unknown whether this anatomical feature of the TP region is related to pathological susceptibility and which subgroups of fibers are affected in poor readers and children with ASD.

The left AF connects critical nodes of the language and reading network, including the posterior superior temporal gyrus and the inferior frontal gyrus, by passing through the left TP region. The left AF constitutes a dorsal phonological stream involved in phonological processing and sound-to-word mapping (60,61). In this pathway, the left TP region supports phonological processing and reading acquisition in typical readers (62,63). The altered WM microstructure of the left TP-AF reported here could therefore be related to the PWM impairment exhibited by both the poor reader and ASD groups.

Despite evidence linking the left AF to PWM, we did not find a significant correlation between PWM and left AF properties within any single participant group. Thus, the significant correlation between PWM and FA of the left TP-AF across all groups was driven by group differences and not related to variability within any group. The lack of such a relation may reflect the large age range of the present study (5 to 17 years).

There is evidence that in children ages 7 to 11 years, lower FA in the left AF is associated with better phonological awareness (59) but that in older children and adults, the relationship reverses (64). Thus, our age range may have straddled this period of reversal. Other possibilities are that our sample is not powered adequately to observe the degree of association within each group or that the wide age range of participants obscured associations. Future studies may clarify this developmental variation by including a larger sample or using a longitudinal design.

Atypical White Matter of the Right ILF

The ASD group exhibited reduced FA and elevated RD of the right ILF compared with the TD group, and the poor reader group had FA and RD that were intermediate between the ASD and TD groups (albeit not significantly different from either group). Because there is evidence that people with congenital face recognition deficits have reduced FA in the right ILF (65) and ASD children show a selective deficit in face recognition (66), the reduced WM connectivity in the right ILF of ASD was interpreted in the context of impaired social communication skills, including face recognition (33). However, there is no reported relation between variation in right ILF microstructure and either ASD severity or face recognition ability among ASD participants.

In this study, the magnitude of FA and RD in the right ILF significantly correlated with PWM ability in both the poor reader and ASD groups. This is consistent with previous evidence that the right ILF, which carries information from right occipitotemporal cortex, is implicated in some aspects of language, including the perception of speech prosody (67) and atypical language development (23,24). Moreover, in this study, the FA of the right ILF did not differ significantly between the ASD and poor reader groups, even though the poor readers did not have impaired social communication scores as assessed by the ADOS. The lack of correlation between autism severity and the WM coherence in the right ILF further suggests variation in the right ILF microstructure was not related to a broad measure of social communication like the ADOS. Future studies using more sensitive or specific measures of social communication in ASD may find a relation with microstructural properties of the right ILF.

In general, phonological processes are most associated with the left hemisphere language network, so the relation between PWM and the right ILF observed within the poor reader and ASD groups (but not the TD group) may reflect atypical right lateralization of language processes in these groups (68–74). For example, both children (75) and adults (69) with reading disability showed reduced left lateralization of either brain function (75) or WM characteristics (69) around the TP region. Moreover, greater FA in the right superior longitudinal fasciculus/AF predicted greater reading improvement in children with dyslexia but not in TD children (76). Children with ASD have also shown greater right hemispheric activation than control subjects in language tasks ranging from passive speech perception to semantic processing (71,77). Interestingly, the increased rightward asymmetry has been associated with better language skills in both toddlers and school-age children with ASD (78,79). Taken together, these findings suggest that the atypical right hemispheric involvement might contribute to a compensatory mechanism of phonological processing in children with reading disability or those with ASD.

These findings have important implications for understanding neurodevelopmental disorders. The National Institute of Mental Health Research Domain Criteria approach to psychiatry (12) has emphasized a dimensional approach to relating behaviors to neural circuits across traditional diagnostic disease categories, including neurodevelopmental disorders [e.g., (80)]. Deficits in PWM cut across several diagnostic categories, including dyslexia, specific language impairment, and ASD, although the idea that the neurocognitive underpinnings of this impairment may be shared across disorders has been debated [e.g., (9,10)]. Here, we showed, for the first time, that the dimension of impaired PWM is related to shared neuroanatomical abnormalities of WM microstructure in two different diagnostic groups, reading disability and autism spectrum disorder.

ACKNOWLEDGMENTS AND DISCLOSURES

This work was funded by National Institutes of Health Grant No. R01DC011339.

We thank the participating families for their contribution to our study; Satrajit Ghosh for advice on data analysis; Sara Beach, Abigail Cyr, Clara Baron-Hyppolite, Colleen Buckless, Katalina Sher, Calvin Goetz, Irina Ostrovskaya, and Mengyuan Xu for help on data collection; and Atsushi Takahashi, Sheeba Arnold Anteraper, and Steven Shannon at the Athinoula A. Martinos Imaging Center at the McGovern Institute for Brain Research, Massachusetts Institute of Technology, for technical support.

The authors reported no biomedical financial interests or potential conflicts of interest.

ARTICLE INFORMATION

From the State Key Laboratory of Cognitive Neuroscience and Learning and IDG/McGovern Institute for Brain Research (CL) and Center for Collaboration and Innovation in Brain and Learning Sciences (CL), Beijing Normal University, Beijing, China; McGovern Institute for Brain Research (CL, ZQ, MH, KH, JDEG) and Department of Linguistics and Philosophy (KW), Massachusetts Institute of Technology, Cambridge; Departments of Psychological & Brain Sciences (AH, LWW, HT-F) and Speech, Language & Hearing Sciences (TKP), Boston University, Boston; Department of Brain and Cognitive Sciences (TKP, MK, KW, JDEG), Massachusetts Institute of Technology, Cambridge; and MGH Institute of Health Professions (MK), Boston, Massachusetts.

CL and ZQ contributed equally to this work.

Address correspondence to Zhenghan Qi, M.D., Ph.D., Massachusetts Institute of Technology, McGovern Institute for Brain Research, 43 Vassar Street, Cambridge, MA 02139; E-mail: zqi@mit.edu.

Received Aug 7, 2015; revised Nov 3, 2015; accepted Nov 3, 2015.

Supplementary material cited in this article is available online at http://dx.doi.org/10.1016/j.bpsc.2015.11.001.

REFERENCES

1. Peterson RL, Pennington BF (2012): Developmental dyslexia. Lancet 379:1997–2007.
2. Elsabbagh M, Divan G, Koh YJ, Kim YS, Kauchali S, Marcín C, *et al*. (2012): Global prevalence of autism and other pervasive developmental disorders. Autism Res 5:160–179.
3. Wagner RK, Torgesen JK (1987): The nature of phonological processing and its causal role in the acquisition of reading skills. Psychol Bull 101:192–212.

4. Hulme C, Snowling MJ (2014): The interface between spoken and written language: Developmental disorders. Philos Trans R Soc Lond B Biol Sci 369:20120395.
5. Ramus F, Rosen S, Dakin SC, Day BL, Castellote JM, White S, Frith U (2003): Theories of developmental dyslexia: Insights from a multiple case study of dyslexic adults. Brain 126:841–865.
6. Szenkovits G, Ramus F (2005): Exploring dyslexics' phonological deficit I: Lexical vs sub-lexical and input vs output processes. Dyslexia 11:253–268.
7. Gerdts J, Bernier R (2011): The broader autism phenotype and its implications on the etiology and treatment of autism spectrum disorders. Autism Res Treat 2011:545901.
8. Lindgren KA, Folstein SE, Tomblin JB, Tager-Flusberg H (2009): Language and reading abilities of children with autism spectrum disorders and specific language impairment and their first-degree relatives. Autism Res 2:22–38.
9. Williams D, Payne H, Marshall C (2013): Non-word repetition impairment in autism and specific language impairment: Evidence for distinct underlying cognitive causes. J Autism Dev Disord 43:404–417.
10. Riches NG, Loucas T, Baird G, Charman T, Simonoff E (2011): Non-word repetition in adolescents with specific language impairment and autism plus language impairments: A qualitative analysis. J Commun Disord 44:23–36.
11. Whitehouse AJO, Barry JG, Bishop DVM (2008): Further defining the language impairment of autism: Is there a specific language impairment subtype? J Commun Disord 41:319–336.
12. Insel TR (2014): The NIMH Research Domain Criteria (RDoC) Project: Precision medicine for psychiatry. Am J Psychiatry 171:395–397.
13. Melby-Lervag M, Lyster SA, Hulme C (2012): Phonological skills and their role in learning to read: A meta-analytic review. Psychol Bull 138: 322–352.
14. Hulme C, Bowyer-Crane C, Carroll JM, Duff FJ, Snowling MJ (2012): The causal role of phoneme awareness and letter-sound knowledge in learning to read: Combining intervention studies with mediation analyses. Psychol Sci 23:572–577.
15. Dandache S, Wouters J, Ghesquiere P (2014): Development of reading and phonological skills of children at family risk for dyslexia: A longitudinal analysis from kindergarten to sixth grade. Dyslexia 20:305–329.
16. Wilson LB, Tregellas JR, Slason E, Pasko BE, Hepburn S, Rojas DC (2013): Phonological processing in first-degree relatives of individuals with autism: An fMRI study. Hum Brain Mapp 34:1447–1463.
17. Gabrieli JD (2009): Dyslexia: A new synergy between education and cognitive neuroscience. Science 325:280–283.
18. Klingberg T, Hedehus M, Temple E, Salz T, Gabrieli JD, Moseley ME, Poldrack RA (2000): Microstructure of temporo-parietal white matter as a basis for reading ability: Evidence from diffusion tensor magnetic resonance imaging. Neuron 25:493–500.
19. Boets B, Op de Beeck HP, Vandermosten M, Scott SK, Gillebert CR, Mantini D, *et al*. (2013): Intact but less accessible phonetic representations in adults with dyslexia. Science 342:1251–1254.
20. Rimrodt SL, Peterson DJ, Denckla MB, Kaufmann WE, Cutting LE (2010): White matter microstructural differences linked to left perisylvian language network in children with dyslexia. Cortex 46:739–749.
21. Niogi SN, McCandliss BD (2006): Left lateralized white matter microstructure accounts for individual differences in reading ability and disability. Neuropsychologia 44:2178–2188.
22. Deutsch GK, Dougherty RF, Bammer R, Siok WT, Gabrieli JDE, Wandell B (2005): Children's reading performance is correlated with white matter structure measured by diffusion tensor imaging. Cortex 41:354–363.
23. Steinbrink C, Vogt K, Kastrup A, Müller HP, Juengling FD, Kassubek J, Riecker A (2008): The contribution of white and gray matter differences to developmental dyslexia: Insights from DTI and VBM at 3.0 T. Neuropsychologia 46:3170–3178.
24. Rollins NK, Vachha B, Srinivasan P, Chia J, Pickering J, Hughes CW, Gimi B (2009): Simple developmental dyslexia in children: Alterations in diffusion-tensor metrics of white matter tracts at 3 T. Radiology 251:882–891.
25. Yeatman JD, Dougherty RF, Ben-Shachar M, Wandell BA (2012): Development of white matter and reading skills. Proc Natl Acad Sci U S A 109:E3045–E3053.
26. Travers BG, Adluru N, Ennis C, Tromp do PM, Destiche D, Doran S, *et al*. (2012): Diffusion tensor imaging in autism spectrum disorder: A review. Autism Res 5:289–313.
27. Ameis SH, Catani M (2015): Altered white matter connectivity as a neural substrate for social impairment in autism spectrum disorder. Cortex 62:158–181.
28. Lai G, Pantazatos SP, Schneider H, Hirsch J (2012): Neural systems for speech and song in autism. Brain 135:961–975.
29. Fletcher PT, Whitaker RT, Tao R, DuBray MB, Froehlich A, Ravichandran C, *et al*. (2010): Microstructural connectivity of the arcuate fasciculus in adolescents with high-functioning autism. Neuroimage 51:1117–1125.
30. Kumar A, Sundaram SK, Sivaswamy L, Behen ME, Makki MI, Ager J, *et al*. (2010): Alterations in frontal lobe tracts and corpus callosum in young children with autism spectrum disorder. Cereb Cortex 20: 2103–2113.
31. Hoppenbrouwers M, Vandermosten M, Boets B (2014): Autism as a disconnection syndrome: A qualitative and quantitative review of diffusion tensor imaging studies. Res Autism Spectr Disord 8: 387–412.
32. Billeci L, Calderoni S, Tosetti M, Catani M, Muratori F (2012): White matter connectivity in children with autism spectrum disorders: A tract-based spatial statistics study. BMC Neurol 12:148.
33. Koldewyn K, Yendiki A, Weigelt S, Gweon H, Julian J, Richardson H, *et al*. (2014): Differences in the right inferior longitudinal fasciculus but no general disruption of white matter tracts in children with autism spectrum disorder. Proc Natl Acad Sci U S A 111:1981–1986.
34. Kaufman AS, Kaufman NL (2004): Kaufman Brief Intelligence Test, *Second Edition (KBIT-2)*. Bloomington, MN: Pearson, Inc.
35. Woodcock RW (1998): Woodcock Reading Mastery Tests–Revised/ Normative Update. Circle Pines, MN: American Guidance Service.
36. Torgesen JK, Wagner RK, Rashotte CA (1999): Test of Word Reading Efficiency. Austin, TX: Pro-Ed Publishing, Inc.
37. Woodcock RW, McGrew KS, Mather N (2001): Woodcock-Johnson III Tests of Achievement. Itaska, IL: Riverside Publishing.
38. Gotham K, Pickles A, Lord C (2009): Standardizing ADOS scores for a measure of severity in autism spectrum disorders. J Autism Dev Disord 39:693–705.
39. Hus V, Lord C (2014): The Autism Diagnostic Observation Schedule, Module 4: Revised algorithm and standardized severity scores. J Autism Dev Disord 44:1996–2012.
40. Wagner R, Torgesen J, Rashotte CA (1999): Comprehensive test of phonological processes (CTOPP). Austin, TX: Pro-Ed Publishing, Inc.
41. Gathercole SE, Baddeley AD (1996): The Children's Test of Nonword Repetition. London: Psychological Corporation.
42. Oguz I, Farzinfar M, Matsui J, Budin F, Liu Z, Gerig G, *et al*. (2014): DTIPrep: Quality control of diffusion-weighted images. Front Neuroinform 8:4.
43. Yendiki A, Panneck P, Srinivasan P, Stevens A, Zollei L, Augustinack J, *et al*. (2011): Automated probabilistic reconstruction of white-matter pathways in health and disease using an atlas of the underlying anatomy. Front Neuroinform 5:23.
44. Yendiki A, Koldewyn K, Kakunoori S, Kanwisher N, Fischl B (2013): Spurious group differences due to head motion in a diffusion MRI study. Neuroimage 88C:79–90.
45. Cox RW (1996): AFNI: Software for analysis and visualization of functional magnetic resonance neuroimages. Comput Biomed Res 29: 162–173.
46. Saygin ZM, Norton ES, Osher DE, Beach SD, Cyr AB, Ozernov-Palchik O, *et al*. (2013): Tracking the roots of reading ability: White matter volume and integrity correlate with phonological awareness in prereading and early-reading kindergarten children. J Neurosci 33:13251–13258.
47. Song SK, Sun SW, Ramsbottom MJ, Chang C, Russell J, Cross AH (2002): Dysmyelination revealed through MRI as increased radial (but unchanged axial) diffusion of water. Neuroimage 17:1429–1436.
48. Song SK, Yoshino J, Le TQ, Lin S-J, Sun SW, Cross AH, Armstrong RC (2005): Demyelination increases radial diffusivity in corpus callosum of mouse brain. Neuroimage 26:132–140.

49. Wheeler-Kingshott CAM, Cercignani M (2009): About “axial” and “radial” diffusivities. Magn Reson Med 61:1255–1260.
50. Ramus F, Marshall CR, Rosen S, Van Der Lely HK (2013): Phonological deficits in specific language impairment and developmental dyslexia: Towards a multidimensional model. Brain 136:630–645.
51. Catts HW, Adlof SM, Hogan TP, Weismer SE (2005): Are specific language impairment and dyslexia distinct disorders? J Speech Lang Hear Res 48:1378–1396.
52. Castro-Caldas A, Petersson KM, Reis A, Stone-Elander S, Ingvar M (1998): The illiterate brain. Learning to read and write during childhood influences the functional organization of the adult brain. Brain 121: 1053–1063.
53. Petersson KM, Reis A, Askelöf S, Castro-Caldas A, Ingvar M (2000): Language processing modulated by literacy: A network analysis of verbal repetition in literate and illiterate subjects. J Cogn Neurosci 12:364–382.
54. Joanisse MF, Manis FR, Keating P, Seidenberg MS (2000): Language deficits in dyslexic children: Speech perception, phonology, and morphology. J Exp Child Psychol 77:30–60.
55. Vandermosten M, Boets B, Wouters J, Ghesquière P (2012): A qualitative and quantitative review of diffusion tensor imaging studies in reading and dyslexia. Neurosci Biobehav Rev 36:1532–1552.
56. Behrens TEJ, Berg HJ, Jbabdi S, Rushworth MFS, Woolrich MW (2007): Probabilistic diffusion tractography with multiple fibre orientations: What can we gain? Neuroimage 34:144–155.
57. Catani M, Jones DK, Ffytche DH (2005): Perisylvian language networks of the human brain. Ann Neurol 57:8–16.
58. Catani M, Mesulam M (2008): The arcuate fasciculus and the disconnection theme in language and aphasia: History and current state. Cortex 44:953–961.
59. Yeatman JD, Dougherty RF, Rykhlevskaia E, Sherbondy AJ, Deutsch GK, Wandell BA, Ben-Shachar M (2011): Anatomical properties of the arcuate fasciculus predict phonological and reading skills in children. J Cogn Neurosci 23:3304–3317.
60. Schlaggar BL, McCandliss BD (2007): Development of neural systems for reading. Annu Rev Neurosci 30:475–503.
61. Hickok G, Poeppel D (2007): The cortical organization of speech processing. Nat Rev Neurosci 8:393–402.
62. Pugh KR, Landi N, Preston JL, Mencl WE, Austin AC, Sibley D, *et al.* (2013): The relationship between phonological and auditory processing and brain organization in beginning readers. Brain Lang 125:173–183.
63. Yamada Y, Stevens C, Dow M, Harn BA, Chard DJ, Neville HJ (2011): Emergence of the neural network for reading in five-year-old beginning readers of different levels of pre-literacy abilities: An fMRI study. Neuroimage 57:704–713.
64. Vandermosten M, Boets B, Poelmans H, Sunaert S, Wouters J, Ghesquiere P (2012): A tractography study in dyslexia: Neuroanatomic correlates of orthographic, phonological and speech processing. Brain 135:935–948.
65. Thomas C, Avidan G, Humphreys K, Jung KJ, Gao F, Behrmann M (2009): Reduced structural connectivity in ventral visual cortex in congenital prosopagnosia. Nat Neurosci 12:29–31.
66. Weigelt S, Koldewyn K, Kanwisher N (2012): Face identity recognition in autism spectrum disorders: A review of behavioral studies. Neurosci Biobehav Rev 36:1060–1084.
67. Gandour J, Tong Y, Wong D, Talavage T, Dzemidzic M, Xu Y, *et al.* (2004): Hemispheric roles in the perception of speech prosody. Neuroimage 23:344–357.
68. Altarelli I, Leroy F, Monzalvo K, Fluss J, Billard C, Dehaene-Lambertz G, *et al.* (2014): Planum temporale asymmetry in developmental dyslexia: Revisiting an old question. Hum Brain Mapp 35: 5717–5735.
69. Vandermosten M, Poelmans H, Sunaert S, Ghesquière P, Wouters J (2013): White matter lateralization and interhemispheric coherence to auditory modulations in normal reading and dyslexic adults. Neuropsychologia 51:2087–2099.
70. Tailby C, Weintrob DL, Saling MM, Fitzgerald C, Jackson GD (2014): Reading difficulty is associated with failure to lateralize temporooccipital function. Epilepsia 55:746–753.
71. Yoshimura Y, Kikuchi M, Shitamichi K, Ueno S, Munesue T, Ono Y, *et al.* (2013): Atypical brain lateralisation in the auditory cortex and language performance in 3- to 7-year-old children with high-functioning autism spectrum disorder: A child-customised magnetoencephalography (MEG) study. Mol Autism 4:38.
72. Roberts TPL, Khan SY, Rey M, Monroe JF, Cannon K, Blaskey L, *et al.* (2010): MEG detection of delayed auditory evoked responses in autism spectrum disorders: Towards an imaging biomarker for autism. Autism Res 3:8–18.
73. Knaus TA, Silver AM, Lindgren KA, Hadjikhani N, Tager-Flusberg H (2008): fMRI activation during a language task in adolescents with ASD. J Int Neuropsychol Soc 14:967–979.
74. Cardinale RC, Shih P, Fishman I, Ford LM, Müller RA (2013): Pervasive rightward asymmetry shifts of functional networks in autism spectrum disorder. JAMA Psychiatry 70:975–982.
75. Shaywitz Ba Shaywitz SE, Pugh KR, Mencl WE, Fulbright RK, Skudlarski P, *et al.* (2002): Disruption of posterior brain systems for reading in children with developmental dyslexia. Biol Psychiatry 52: 101–110.
76. Hoeft F, McCandliss BD, Black JM, Gantman A, Zakerani N, Hulme C, *et al.* (2011): Neural systems predicting long-term outcome in dyslexia. Proc Natl Acad Sci U S A 108:361–366.
77. Knaus TA, Silver AM, Kennedy M, Lindgren KA, Dominick KC, Siegel J, Tager-Flusberg H (2010): Language laterality in autism spectrum disorder and typical controls: A functional, volumetric, and diffusion tensor MRI study. Brain Lang 112:113–120.
78. Redcay E, Courchesne E (2008): Deviant functional magnetic resonance imaging patterns of brain activity to speech in 2-3-year-old children with autism spectrum disorder. Biol Psychiatry 64:589–598.
79. Joseph RM, Fricker Z, Fenoglio A, Lindgren Ka, Knaus Ta, Tager-Flusberg H (2014): Structural asymmetries of language-related gray and white matter and their relationship to language function in young children with ASD. Brain Imaging Behav 8:60–72.
80. Casey BJ, Oliveri ME, Insel T (2014): A neurodevelopmental perspective on the research domain criteria (RDoC) framework. Biol Psychiatry 76:350–353.
81. Semel E, Wiig EH, Secord WA (2003): Clinical Evaluation of Language Fundamentals, Fourth Edition—Screening Test (CELF-4 Screening Test). Toronto: The Psychological Corporation/A Harcourt Assessment Company.

Shared Neuroanatomical Substrates of Impaired Phonological Working Memory Across Reading Disability and Autism

Supplemental Information

Supplemental Methods and Materials

Participant Groups

Three groups of children were included in the study: poor readers, ASD, and TD children. Participant groups were defined according to a set of exclusionary and inclusionary criteria (Table 1). 1) Children were included in the Poor Reader group based on performance on standardized assessments of real and non-word reading abilities. Children in this group had standard scores of 90 or below on at least two of the following four reading measures: Word Identification and Word Attack in the Woodcock Reading Mastery Test – Revised Normative Update (1), Sight Word Efficiency and Phonemic Decoding Efficiency in the Test of Word Reading Efficiency (2). A composite reading score was derived by averaging the standard scores of the four subtests in order to provide an overall estimate of reading ability. Four children with ASD also met criteria as poor readers. We examined these four children separately in both the PWM and related neural measures. Their behavioral and neural profiles were similar to the other children with ASD and therefore they were included in the ASD group. 2) Children were included in the ASD group if they had a community-based clinical diagnosis of ASD that was then confirmed by trained and reliable research staff using the Autism Diagnostic Observation Schedule (ADOS or ADOS-2) Module 3 or 4 (3). The ADOS was also administered to the Poor Reader and TD groups to rule out autism in these groups. In the few cases where children without clinical ASD diagnoses met ASD criteria on the ADOS (two in the Poor Reader group) or where children with existing ASD diagnoses did not meet ASD criteria on the ADOS (one child), the ADOS videos were reviewed by a licensed neuropsychiatrist for final clinical judgment and group assignment. In each case the original diagnostic classification was confirmed. 3) In addition to the inclusionary criteria for all participants, participants in the TD group scored within normal limits on standardized assessments of reading, demonstrated no developmental delays or confounding diagnoses (e.g., ADHD), and had no first-degree relatives with ASD, reading disabilities, or other genetic disorders.

One child in the ASD group did not complete the reading tests and was therefore excluded from the group comparisons that utilized reading scores. In addition, ADOS scores were not available for four children (one poor reader, one child with ASD, and two TD children). Parents of these children had completed a Social Communication Questionnaire (SCQ, 4), which was used to confirm group assignment. Among these children, the SCQ total score of the one in the ASD group was greater than 15, confirming her autism diagnosis; the two in the TD group and one in the Poor Reader group had SCQ total scores lower than 15, confirming their non-autism status. These four children were excluded from the group comparisons that utilized ADOS scores.

The reading scores in the Poor Reader and ASD groups were significantly lower than the TD group (Poor Reader: $t_{(37)} = 8.99$, $P < 0.001$; ASD: $t_{(42)} = 3.64$, $P < 0.001$). The reading scores of the ASD group were close to the normal range and significantly higher than the scores of the Poor Reader group ($t_{(41)} = 4.37$, $P < 0.001$). In order to compare the severity of the autism symptomatology, we converted participants' ADOS scores to severity score (5, 6) (Table 1). The severity score in the ASD group were significantly higher than both the TD group ($t_{(40)} = 7.87$, $P < 0.001$) and the Poor Reader group ($t_{(40)} = 6.49$, $P < 0.001$), and there was no significant difference between the Poor Reader and TD groups ($t_{(34)} = 1.13$, $P = 0.27$).

In addition, children's receptive and expressive language skills were assessed by combining the age-appropriate subtests in Clinical Evaluation of Language Fundamentals –

Revised – Fourth Edition (7). One child in the ASD group did not complete all the subtests and therefore was excluded from the group comparison. The language scores in both the Poor Reader and ASD groups were significantly lower than the TD group (Poor Reader: $t_{(37)} = 3.84$, $P < 0.001$; ASD: $t_{(42)} = 3.77$, $P < 0.001$), but there was no significant difference between the Poor Reader and ASD groups ($t_{(41)} = 0.28$, $P = 0.77$). All of these assessments further confirmed the group assignment.

In addition, we also reported children's sentence reading ability in company with children's single-word reading ability to examine the severity of reading impairment in higher-level comprehension (Table 1). This was measured by the reading fluency subtest in Woodcock-Johnson 3 Test of Achievement (8). There were five children who did not complete the test (2 ASD, 2 poor readers and 1 TD). As expected, performance of the Poor Reader group (mean standard score: 79.6, SD = 11.5) is significantly lower than both the TD (mean standard score: 115.7, SD = 9.7, $t_{(34)} = -10.2$, $P < 0.001$) and the ASD groups (mean standard score: 100.0, SD = 15.8, $t_{(38)} = -4.50$, $P < 0.001$). Children with ASD performed in the normal range, but also significantly worse than the TD group ($t_{(40)} = -3.8$, $P < 0.001$).

Phonological Working Memory Measures

Four subtests from the Comprehensive Test of Phonological Processing (CTOPP, 9) was used to measure participants' phonological working memory: 1) Elision: The child repeats a word after removing a given sound. 2) Blending Words: The child listens to a recorded series of sounds and blends them together to derive a real word. 3) Memory for Digits: The child is given a string of increasingly longer numbers and asked to repeat them in the same order as they hear them. 4) Nonword Repetition: The child listens to a nonsense word and is asked to repeat it. The syllable length increases as the child progresses through the task.

The Children's Test of Non-word Repetition (CNRep, 10) was administered as a second measure of nonword repetition performance, because features of stimuli (such as word-likeness, phonotactic frequency, and prosodic structure) have been found to significantly influence children's performance (11). Compared to the CTOPP, the CNRep stimuli are more like English words and contain English lexical components, morphemes, and prosodic patterns similar to English (e.g., "pennel"). Thus, the CNRep provides a complementary measure of children's phonological ability in an English-like context.

Image-Data Analysis

DTI Data Quality Control. The data quality assessment also went through two steps. First, data quality was assessed immediately after scanning. Specifically, the visual inspection step was taken at an earlier stage before the TRActs Constrained by UnderLying Anatomy (TRACULA) analysis. That is, 1) all participants were trained to lie still in the mock scanner 30 minutes before data acquisition by people with expertise in pediatric data acquisition, and 2) A person with expertise in imaging data analysis, who oversaw the scan sessions, inspected the raw DWI data immediately after the scanning for visible motions. If excessive motions were detected, the DWI acquisition would be repeated either in the same session or a different session. If visible motion remained in the second scan, the child's data were discarded. Initially 29 poor readers, 41 children with ASD and 75 children with TD were scanned. Among them, 6 children (3 in the ASD group, 2 in the Poor Reader group and 1 in the TD group) were scanned twice and 2 children (1 poor reader and 1 TD) were excluded from the analysis for visible motion. This process ensured that all raw DWI images were free of visible motion.

During the earliest stage of data analysis, we further screened the overall quality of the DWI images in the current study by using DTIprep, a quality-control software that allows automatic evaluation of the quality of diffusion images, b-values and gradient directions (12, 13). This procedure removed an additional 5 poor readers, 7 children with ASD, and 9 TD children from the analysis. Thus, 23 poor readers (21% removed), 34 children with ASD (17% removed) and 65 TD children (13% removed) were included for further group matching based on their demographic information. After matching for age, IQ, and gender among the three groups, 19 poor readers, 25 children with ASD, and 20 TD children were included in this study. The difference of the rejection rate due to data quality between our study and Koldewyn *et al.* can also be attributed to the age difference between our samples. The average age in our sample (11.1 yo) is almost two years older than that of Koldewyn *et al.* (14) (average age 9.2 yo). Our sample included 23 children who were older than 12, while the oldest child in Kolewyn *et al.* (14) was only 11 years old. Therefore it is expected that the data quality in an older cohort is much improved.

Then, standardized data quality assessment was accomplished during the process of TRACULA analysis. Two motion and two intensity measures were calculated for data quality assessment (12). First, frame-to-frame translation and rotation parameters were computed from the affine registration matrix of each frame to the first frame. The translation and rotation parameters were averaged over all frames within a scan, and the mean translation and rotation parameters were defined as the two motion measures. Second, the intensity dropout scores were computed by comparing the image intensities in each slice to the corresponding slice in the reference ($b = 0$) volume, as proposed by Benner *et al.* (15). Slices with a score greater than 1 were considered to have suspect signal dropout. The first intensity measure was obtained by calculating the averaged signal dropout score for those slices with scores greater than 1, and the second intensity measure was obtained by calculating the percentage of those slices across the scan. Taken together, the four measures capture global frame-to-frame motion as well as the frequency and severity of rapid slice-to-slice motion. Statistical tests on the four measures did not show any significant differences among the three participant groups (Translation: $F_{(2,61)} = 0.242$, $P = 0.786$; Rotation: $F_{(2,61)} = 0.593$, $P = 0.556$; Signal-dropout score: $F_{(2,61)} = 0.665$, $P = 0.518$; Percent of bad slices: $F_{(2,61)} = 0.686$, $P = 0.507$).

DTI Preprocessing and Tract Reconstruction. TRACULA was used to delineate 18 major WM fascicles (13). This is an algorithm for automated global probabilistic tractography that estimates the posterior probability of each of 18 WM tracts. The posterior probability is decomposed into a data likelihood term, which uses the "ball-and-stick" model of diffusion (16), and a pathway prior term, which incorporates prior anatomical knowledge on the tracts from a set of training subjects. The information extracted from the training subjects is the probability of each tract passing through (or next to) each anatomical segmentation label. This probability is calculated separately for every measurement point along the trajectory of the tract. Thus, there is no assumption that the tracts have the same shape in the study subjects and training subjects, only that the tracts traverse the same regions relative to the surrounding anatomy. The anatomical segmentation labels required by TRACULA were obtained by processing the T1-weighted images of the study subjects with the automated cortical parcellation and subcortical segmentation tools in FreeSurfer (17-19). More details on the tractography method, as well as an evaluation of its accuracy on healthy subjects and patients, can be found in Yendiki *et al.* (13).

For preprocessing, images were registered to the b = 0 images to compensate for motion and eddy-current distortions. A registration transform was computed using FreeSurfer's bbregister (20) for mapping each participant's b = 0 image to the native structural scan. Images were checked for registration errors and corrections were made manually when necessary. Cortical parcellations and subcortical segmentations from each individual's FreeSurfer reconstruction were mapped to his/her DTIs using the above transform. FSL's DTIFIT estimated the tensor fits at each voxel. Mean values of the fractional anisotropy (FA), mean diffusivity (MD), radial diffusivity (RD), and axial diffusivity (AD) in each of the 18 WM tracts were reconstructed by TRACULA for each subject. To compute these mean values, the tract distributions were thresholded at 20% of their maximum value, and the FA, MD, RD, and AD values at each voxel were weighted by the tract probability at that voxel. For this purpose, a WM mask was generated from the subject's anatomical segmentation and mapped from the space of the T1-weighted image to the space of the diffusion-weighted images. The tensor model was fit to the data only to extract these anisotropy and diffusivity measures, and not to perform the tractography in TRACULA, which relies on the ball-and-stick model of diffusion instead. The default procedures can calculate both the posterior mean and maximum of *a posteriori* pathways for each participant. Here, the posterior means were used.

Association of the Structural Connectivity Pattern With Phonological Working Memory. To investigate whether the potential group differences in diffusion measures were associated with the phonological working memory, the following analyses were conducted. First, a linear regression modeling analysis was conducted between FA/AD/RD/MD at each point of the left AF and right ILF and the phonological composite score across all participants. The results were thresholded at $P < 0.05$ level (Height, $P < 0.005$; Extent, cluster > 6 points). Second, mean FA/AD/RD/MD values within each cluster that survived the threshold were extracted. A hierarchical linear regression was conducted by using the composite phonological working memory score as a dependent variable, diffusion measures as independent variables, and age, IQ, and gender as control variables. In our analyses, only age significantly contributed to the model, so IQ and gender were removed from the final models.

Supplemental Results

Common WM Structural Connectivity Differences in Poor Readers and ASD-Tract-Average Results

Analysis based on tract-average FA and RD of the left AF and right ILF revealed a similar pattern of group differences as the point-to-point analysis. Specifically, for the left AF, the Poor Reader and ASD groups showed lower FA values (Fig. S1A, Poor Reader vs. TD: $F_{(1,36)} = 4.44$, $P = 0.042$; ASD vs. TD: $F_{(1,42)} = 11.50$, $P = 0.002$) and increased RD values (Fig. S1B, Poor Reader vs. TD: $F_{(1,36)} = 4.34$, $P = 0.044$; ASD vs. TD: $F_{(1,42)} = 11.86$, $P = 0.001$) than the TD group. For the right ILF, the ASD group showed lower FA values (Fig. S1A, $F_{(1,42)} = 10.51$, $P = 0.002$) and increased RD values (Fig. S1B, $F_{(1,42)} = 12.32$, $P = 0.001$) than the TD group. One exception was that the Poor Reader group showed significantly lower tract-averaged RD of the right ILF than the ASD group (Fig. S1B, $F_{(1,41)} = 4.30$, $P = 0.04$).

Association Between Structural Connectivity and Phonological Working Memory

We examined the relation of phonological working memory ability to the left AF and the right ILF by combining all three groups in a linear regression. Similar patterns of association between phonological working memory and structural connectivity to the FA value were replicated in the analysis on RD value of the left AF (peak position, x, y, z = 32, -61, 0, β = -0.348, R^2 = 0.121, P = 0.005, not significant after cluster-wise correction) and right ILF (10 points, peak position, x, y, z = 32, -61, 0, β = -0.468, R^2 = 0.219, $P < 0.001$). After controlling for age, the relationship was the same (left AF: β = -0.356, R^2 change = 0.127, P = 0.005, not significant after correction; right ILF: β = -0.446, R^2 change = 0.194, $P < 0.001$).

The relations between WM diffusion measures and the phonological composite scores were further examined with linear regression models within each participant group. The relation between RD in the right ILF on phonological working memory was negative and marginally significant in the Poor Reader group (β = -0.381, R^2 change = 0.318, P = 0.055), significant in the ASD group (β = -0.351, R^2 change = 0.254, P = 0.006), but not significant in the TD group (β = -0.023, R^2 change = 0.048, P = 0.844, Figure 3B). No significant relation between RD values of the left AF was found on phonological working memory within any group.

Table S1. Standard scores for each CTOPP subtest and CNRep scores.

	Poor Readers	**ASD**	**TD**
Blending Words	10.00 (2.83)	9.44 (2.90)	10.00 (2.40)
Elision	7.42 (2.89) ***	9.88 (3.57)	11.45 (2.84)
Memory for Digits	8.37 (2.97) **	8.96 (2.60) **	11.35 (2.21)
Nonword Rep	7.79 (2.95) *	7.68 (2.27) **	10.05 (2.19)
CNRep	27.32 (8.21)	26.56 (8.17) *	30.45 (4.97)

Numbers outside and inside the bracket indicate mean and standard deviation, respectively. Statistical significance compared with the TD group: *P < 0.05, **P < 0.01, ***P < 0.001. The Poor Reader group performed marginally worse than the ASD group in the Elision task (β = -1.93, $F_{(1,39)}$ = 3.59, P = 0.065). The Poor Reader and ASD groups did not differ from one another in any of the other subtests (P's > 0.05).

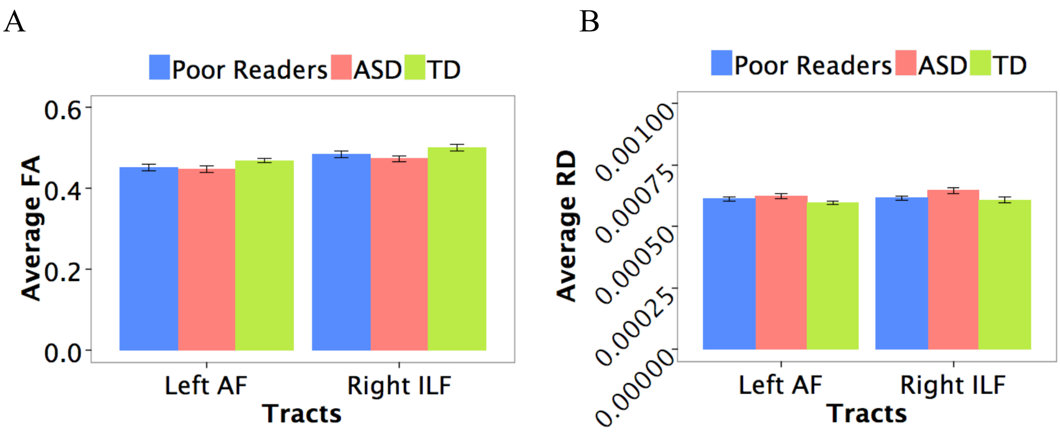

Figure S1. The average FA (**A**) and RD (**B**) values extracted from the whole tracts of left AF and right ILF. Error bars represent standard error.

Supplemental References

1. Woodcock RW (1998): *Woodcock reading mastery tests–Revised/Normative Update.* Circle Pines, MN: American Guidance Service.

2. Torgesen JK, Wagner RK, Rashotte CA (1999): *Test of Word Reading Efficiency*. Austin, TX: PRO-ED Publishing, Inc.

3. Lord C, Risi S, Lambrecht L, Cook EHJ, Leventhal BL, DiLavore PC, et al. (2000): The autism diagnostic observation schedule-generic: a standard measure of social and communication deficits associated with the spectrum of autism. *Journal of autism and developmental disorders*. 30:205-223.

4. Rutter M, Le Couteur A, Lord C (2003): *Social communication questionnaire*. Los Angeles, CA: Western Psychological Services.

5. Gotham K, Pickles A, Lord C (2009): Standardizing ADOS scores for a measure of severity in autism spectrum disorders. *Journal of autism and developmental disorders*. 39:693-705.

6. Hus V, Lord C (2014): The autism diagnostic observation schedule, module 4: revised algorithm and standardized severity scores. *Journal of autism and developmental disorders*. 44:1996-2012.

7. Semel E, Wiig EH, Secord WA (2003): *Clinical Evaluation of Language Fundamentals, Fourth Edition*. Toronto, Canada: The Psychological. (p. CELF-4) Corporation/A Harcourt: Assessment Company.

8. Woodcock RW, McGrew KS, Mather N (2001): *Woodcock-Johnson III Tests of Achievement*. Itaska, IL: Riverside Publishing.

9. Wagner R, Torgesen J, Rashotte CA (1999): *Comprehensive test of phonological processes (CTOPP)*. Austin, TX: Pro-Ed.

10. Gathercole SE, Baddeley AD (1996): *The Children's Test of Nonword Repetition*. London: Psychological Corporation.

11. Gallon N, Marshall C (2009): Using Non-word Repetition Tasks with Children with Dyslexia. *Dyslexia Review*. 21:4-9.

12. Yendiki A, Koldewyn K, Kakunoori S, Kanwisher N, Fischl B (2013): Spurious group differences due to head motion in a diffusion MRI study. *Neuroimage*. 88C:79-90.

13. Yendiki A, Panneck P, Srinivasan P, Stevens A, Zollei L, Augustinack J, et al. (2011): Automated probabilistic reconstruction of white-matter pathways in health and disease using an atlas of the underlying anatomy. *Frontiers in neuroinformatics*. 5:23.

14. Koldewyn K, Yendiki A, Weigelt S, Gweon H, Julian J, Richardson H, et al. (2014): Differences in the right inferior longitudinal fasciculus but no general disruption of white matter tracts in children with autism spectrum disorder. *Proceedings of the National Academy of Sciences of the United States of America*. 111:1981-1986.

15. Benner T, van der Kouwe AJW, Sorensen AG (2011): Diffusion imaging with prospective motion correction and reacquisition. *Magnetic resonance in medicine*. 66:154-167.

16. Behrens TEJ, Berg HJ, Jbabdi S, Rushworth MFS, Woolrich MW (2007): Probabilistic diffusion tractography with multiple fibre orientations: What can we gain? *NeuroImage*. 34:144-155.

17. Fischl B, Salat DH, Busa E, Albert M, Dieterich M, Haselgrove C, et al. (2002): Whole brain segmentation: automated labeling of neuroanatomical structures in the human brain. *Neuron*. 33:341-355.

18. Fischl B, van der Kouwe A, Destrieux C, Halgren E, Segonne F, Salat DH, et al. (2004): Automatically parcellating the human cerebral cortex. *Cereb Cortex*. 14:11-22.

19. Fischl B, Salat DH, van der Kouwe AJ, Makris N, Segonne F, Quinn BT, et al. (2004): Sequence-independent segmentation of magnetic resonance images. *Neuroimage*. 23 Suppl 1:S69-84.

20. Greve DN, Fischl B (2009): Accurate and robust brain image alignment using boundary-based registration. *Neuroimage*. 48:63-72.