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Synergistic effects of age on patterns of white and gray matter volume across childhood and adolescence

White and gray matter volume networks in childhood

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Abstract

The human brain develops with a non-linear contraction of gray matter across late childhood and adolescence, and a concomitant increase in white matter volume. Across the adult population, properties of cortical gray matter co-vary within networks that may represent organizational units for development and degeneration. Although gray matter covariance may be strongest within structurally connected networks, the relationship to volume changes in white matter remains poorly characterized. In the present study we examined age-related trends in white and gray matter volume using T1-weighted MR images from 360 human participants from the NIH MRI study of Normal Brain Development. Images were processed through a voxel-based morphometry pipeline. Linear effects of age on white and gray matter volume were modeled within four age bins, spanning 4-18 years, each including 90 participants (45 male). White and gray matter age-slope maps were separately entered into k-means clustering, to identify regions with similar age-related variability across the four age bins. Four white matter clusters were identified, each with a dominant direction of underlying fibers: anterior-posterior, left-right, and two clusters with superior-inferior directions. Corresponding, spatially proximal, gray matter clusters encompassed largely cerebellar, fronto-insular, posterior and sensorimotor regions, respectively. Pairs of gray and white matter clusters followed parallel slope trajectories, with white matter changes generally positive from 8 years onward (indicating volume increases) and gray matter negative (decreases). As developmental disorders likely target networks rather than individual regions, characterizing typical coordination of white and gray matter development can provide a normative benchmark for understanding atypical development.

Significance statement

The structure of the brain changes across late childhood and adolescence: gray matter volume decreases and white matter volume increases. Gray matter changes occur within networks that may be targets for neurodegenerative, developmental and psychiatric disorders. This study demonstrates that changes in white matter volume are also coordinated across regions, and that changes in these clusters parallel corresponding gray matter clusters. While gray matter clusters show a posterior to anterior organization, we observe here that white matter volume groups into regions with similar fiber orientation. This work adds to our understanding of typical gray and white matter development, which ultimately can help to understand how the brain may be developing abnormally in neurodevelopmental disorders.

Introduction

As the brain develops across late childhood and adolescence, a pattern of white matter expansion (Giedd et al., 1999; Paus et al., 1999; Sowell et al., 2002; Taki et al., 2013) and gray matter contraction (Gogtay et al., 2004a; Shaw et al., 2008; Sowell et al., 2003; 2004) has been observed. These co-occurring phenomena are widely considered to be the product of developmental exuberance (Innocenti and Price, 2005), through which an overproduction of connections is followed by a selection process. White matter volume expansion is thought to reflect both an increase in myelination and axonal diameter (Benes, 1989; Benes et al., 1994; Paus, 2010; Rademacher et al., 1999; Yakovlev and Lecours, 1967). Observed patterns of gray matter thinning may reflect synaptic pruning (Huttenlocher, 1979), changes in size and number of glia or size of neurons (Cotter et al., 2002; Drevets et al., 1998; Elgeti et al., 1976), vasculature (Vaidya et al., 2007), or changes in myelination of superficial white matter (Shaw et al., 2008; Sowell et al., 2004) (though see (Wu et al., 2014)).

Distributed cortical regions show correlated anatomical features across the population (Alexander-Bloch et al., 2013; Chen et al., 2008; Evans, 2013; Lerch et al., 2006; Mechelli et al., 2005; Tijms et al., 2012) in networks similar to those defined by resting state functional connectivity (Alexander-Bloch et al., 2013; Segall et al., 2012) and white matter tractography (Gong et al., 2012). These findings have been extended to describe coordinated cortical development across childhood and adolescence (Alexander-Bloch et al., 2013; Alexander-Bloch et al., 2014; Khundrakpam et al., 2013; Raznahan et al., 2011; Zielinski et al., 2010). The importance of these findings is underscored by the suggestion that neurodegenerative, psychiatric and neurodevelopmental disorders may target cortical networks rather than specific regions (Alexander-Bloch et al., 2014; Raznahan et al., 2010; Reid et al., 2010; Seeley et al., 2009; Zielinski et al., 2012).

White matter tracts also show developmental changes in structural properties (Barnea-Goraly et al., 2005; Ben Bashat et al., 2005; Giorgio et al., 2008; Lebel and Beaulieu, 2011). Fractional anisotropy (FA), a measure of coherent fiber orientation linked to myelination and axon packing (Beaulieu, 2002), increases in most tracts (Barnea-Goraly et al., 2005; Lebel et al., 2008) and peaks in early adulthood before declining (Lebel et al., 2012). Mean diffusivity (MD), a measure reflecting water content and density, shows an opposite pattern, declining across adolescence and increasing in adulthood (Lebel and Beaulieu, 2011). The volume of white matter tracts also typically increases across childhood, though the relationship between tract-volume and microstructural parameters is complex (Lebel and Beaulieu, 2011).

Although gray matter developmental networks are increasingly well characterized, the relationship between white matter structural changes and network-level gray matter development remains unclear. In the present study, we tested the hypothesis that clusters of white matter regions would show coordinated volume development, in parallel to gray matter clusters. That is, clusters of white matter regions showing coordinated variability with age (e.g. volume expansion) would be inversely associated with changes in gray matter volume (e.g. contraction), in related regions, across childhood and adolescence.

Materials and Methods

Participants and neuroimaging data

Neuroimaging data were obtained from the US National Institutes of Health (NIH) MRI study of Normal Brain Development's Pediatric MRI Data Repository (Evans and Brain Development Cooperative Group, 2006). The cohort includes 433 typically developing participants, male and female, aged 4:6 to 18:3 years. All subjects are purported to be normal and healthy, e.g., no history of brain disease or trauma, and IQ>70. Analyses reported here used T1-weighted images collected on 1.5T MRI scanners (GE or Siemens) at 6 sites (Boston Children's Hospital, Cincinnati Children's

Hospital Medical Center, University of Texas Houston Medical School, Neuropsychiatric Institute and Hospital, UCLA, Children's Hospital of Philadelphia and Washington University, St. Louis). Parameters for whole-brain T1-weighted acquisitions were standardized across sites: 3D RF-spoiled gradient echo, TR=22-25ms, TE=10-11ms, sagittal acquisition, FoV=AP 256 LR 160-180. Resolution was typically $1mm^3$, however on GE scanners on which thickness was increased up to 1.5mm and in some participants resolution was decreased to $3mm^3$ to enable more rapid imaging. For our sample we generated four evenly sized groups of participants (90) with an equal number of males and females (45), for a total sample including 360 high-quality scans. Age groups were 4-8, 8-10.5, 10.5-13.5 and 13.5-18.5 years; detailed information about participants is provided in Table 1.

VBM processing

T1-weighted MRI scans were processed through a voxel-based morphometry (VBM) pipeline in SPM12b. Steps included segmentation and normalization using a custom template generated with the DARTEL Toolbox (Ashburner, 2007). Normalized gray and white matter segmented images were modulated to 'preserve amounts' and smoothed using an 8mm Gaussian kernel. All segmentations were visually inspected prior to analysis. VBM tools were also used to identify potential outliers by calculating the squared distance to sample mean in each age bin; no outliers were identified in this step.

Linear age models

As developmental changes in gray matter volume across childhood and adolescence are known to be non-linear (Gogtay et al., 2004b; Raznahan et al., 2011; Shaw et al., 2008), our sample was divided into four age bins similar to Zielinski et al. (2010) and Khundrakpam et al. (2013). Two general linear models were estimated in each age group, modeling a linear effect of mean-centered age on gray and white matter volume separately. Models included effects of gender, site (one regressor per site), and a linear effect of image resolution. Explicit masks were used to spatially constrain the analyses; gray and white matter masks were created using the Masking Toolbox in SPM12b (Ridgway et al., 2009), and constrained to probabilities > 0.4 to ensure that there was no overlap in gray and white matter masks. Neither proportional scaling nor total brain volume regression were used in the main models reported here. However, both methods were tested in additional analyses, as described below.

Clustering based on gray and white matter age-slope

For each tissue type (white and gray matter), parameter estimates for the effect of age in each of the four age bins were obtained for each voxel. All parameter estimates (β values) were entered into a pair of matrices, one gray and one white matter, in which each row corresponded to a voxel and each column corresponded to an age-bin. Analyses were performed on all voxels independent of the significance of age effects, that is, voxel-level significance of age-effects was not assessed as part of this study. Matrices were entered into k-means clustering in MATLAB to identify clusters of voxels with similar age-slopes across these developmental stages. Clustering was seeded with random centers and repeated 10 times; 2-10 cluster solutions were tested, and peak silhouette values (Kaufman and Rousseeuw, 1990) were used to identify the optimal clustering solution for each tissue class.

Directional bias in white matter clusters

Visual inspection of white matter clusters indicated a potential directional bias. To test this, white matter clusters were compared against directional maps from the ICBM-DTI-81 Atlas (Mori et al., 2008) to determine the primary direction of white matter fibers in each cluster. This atlas includes estimated eigenvalues for eigenvectors corresponding to three principal directions (x:right-left, y:anterior-posterior, z:superior-inferior). To determine whether voxels assigned to each

white matter cluster had a preferred direction, the three eigenvalue maps were masked by each white matter cluster. For each cluster the subset of voxels with a dominant orientation along one of these principal directions was obtained by thresholding to include only voxels for which at least one eigenvalue ≥ 0.4. We then calculated the proportion of voxels for which the maximum eigenvalue was in each principal direction.

Effects of site and resolution on VBM segmentation

As previous studies have shown that VBM segmentations may be affected by data collection site and acquisition parameters (Focke et al., 2011; Pardoe et al., 2008; Pereira et al., 2008; Takao et al., 2013), additional analyses were run to investigate effects of data collection site and image resolution. We note that participant age did not significantly vary by site ($F(1, 360)=0.02$, $p=0.88$). Resolution did show a significant negative trend with age as the youngest participants were more likely to have larger voxel size ($F(1, 360)=12.6$, $p<0.001$). However, resolution did not significantly vary with age in individual age bins, though a trend remained in the youngest bin ($p=0.051$, $p=0.73$, $p=0.60$, p-0.22). To determine which regions may be affected by these parameters, models were run for gray and white matter volume separately including all 360 participants; effects of age, resolution, gender and site were modeled (one column per site). F-contrasts were used to identify regions showing linear effects of resolution on gray and white matter volume, and non-linear effects of site. We then compared clustering results for models that included these covariates to a set of models that did not include site and resolution covariates, to assess effects of these parameters on clustering results.

Effects of modeling total gray and white matter volume

Many VBM studies model effects of total tissue volume in VBM, enabling the identification of regions that discriminate between groups after differences in total volume are accounted for (Peelle et al., 2012). Significance of regional effects of age are sensitive to the choice of model (Peelle et al., 2012). For the main analysis here, we chose not to account for total gray and white matter volume, as our goal was simply to model age trends and not to identify regions where age effects were greater than the mean. However, to investigate differences in our results when accounting for total volume, two additional models were run, using proportional scaling by total tissue volume and including total tissue volume as a nuisance covariate.

Effects of age on image contrast

T1-image contrast is known to increase over the first few years of childhood (Paus et al., 2001; Shi et al., 2010). Although the population assessed here was older (i.e. the youngest participant was 4.8y), systematic effects of image contrast may nonetheless contribute to variable quality of gray/white segmentation, and these effects may vary between brain regions. To assess effects of image contrast as a function of age, bilateral masks covering frontal, temporal, parietal and occipital gray and white matter regions were generated using the Wake Forest Pick Atlas tool (Maldjian et al., 2003) and the TD-ICBM-152 atlas (Mazziotta et al., 2001). These masks were warped into each participant's native space and used to extract regional gray and white matter values. Contrast was calculated in each subject and each region as: C= (White matter intensity - Gray matter intensity)/ Gray matter intensity. We then assessed effects of age and site on contrast across the sample and within each age bin.

Results

White matter clusters [a] showed a peak silhouette value at the four-cluster solution and gray matter clusters [b] at the two-cluster solution (this solution divided cerebral cortex from cerebellum). As the goal of this study was to identify clusters of white matter regions with coordinated developmental patterns, in relation to gray matter clusters, both gray and white matter were divided into four clusters, which were subsequently paired based on adjacency of regions (Figures 1-

4). Gray and white matter structures were identified through visual inspection and comparison to gray and white matter atlases (Oishi et al., 2011; Tzourio-Mazoyer et al., 2002).

Superior corona radiata white matter / Precuneus and intraparietal sulcus (posterior) gray matter

One white matter cluster included the superior longitudinal fasciculus, superior corona radiata and body of the corpus callosum (Figure 1acd), as well as a region along the posterior thalamic radiation (Figure 1c). White matter voxels were predominantly (68%; Figure 5) superior-inferior in orientation (Figure 5). The most spatially similar gray matter cluster included primarily posterior cortical regions (Figure 1a-d) such as the precuneus (Figure 1b) and bilateral intraparietal sulcus (Figure 1c). This cluster also included anterior temporal cortex (Figure 1a) and smaller bilateral regions of posterior middle frontal gyrus (Figure 1d). The gray matter cluster was characterized by a steep negative slope in the 8-10.5y age bin and more positive slopes in other age groups; white matter age-slopes followed a similar trend, though slopes were generally positive(indicating increasing volume with age; Figure 1e-f).

Medial corpus callosum white matter / Anterior cingulate, prefrontal cortex and insula (anterior) gray matter

A second white matter cluster (Figure 2) included medial corpus callosum (Figure 2a), anterior internal capsule (Figure 2d), superior parietal lobule white matter (Figure 2c), posterior thalamic radiation and retrolenticular portion of the internal capsule (Figure 2d), and inferior frontal gyrus white matter (Figure 2b). White matter voxels were mostly left-right oriented (70%; Figure 5). The corresponding gray matter cluster included anterior cingulate and medial prefrontal cortex (Figure 2abc), as well as insular (Figure 2bd) and temporal regions (Figure 2b). Gray matter age-slopes (Figure 2e-f) indicated the greatest volume decreases in the 8-10.5y age bin, though slopes in all age bins were more moderate than in the posterior cluster (Figure 1e-f). White matter slopes paralleled gray matter, but were generally positive, except for slight volume decreases in the 8-10.5y age bin (Figure 2e-f).

Occipital, parietal and prefrontal white matter / Visual and motor gray matter

A third white matter cluster (Figure 3) included superior cerebellar peduncle (Figure 3a), occipital and superior parietal white matter (Figure 3b), superior frontal gyrus white matter (Figure 3cd), posterior internal capsule (Figure 3c), posterior thalamic radiation (Figure 3bc) and precentral gyrus white matter (Figure 3d). This white matter cluster showed a strong superior-inferior orientation (74%; Figure 5). The corresponding gray matter cluster involved cuneus (Figure 3abc), motor (Figure 3d), superior parietal (Figure 3b) and lateral prefrontal (Figure 3c) regions. Among the identified gray matter clusters, this set of regions showed the most moderate slopes - slightly positive in the youngest age bin and relatively stable across the 8-18.5y age range (Figure 3e-f). White matter slope trajectories, again, followed a similar trend to gray matter, with a moderate but consistently positive slope from ages 8-18.5y (Figure 3e-f).

Cerebellar peduncles / Cerebellum

A fourth pair of gray and white matter clusters captured the cerebellum and cerebellar peduncles (Figure 4). The white matter cluster included bilateral cerebellar peduncles (Figure 4a), and portions of the superior longitudinal fasciculus (Figure 4c); voxels were mainly anterior-posterior oriented (58%; Figure 5). The gray matter cluster included bilateral cerebellum (Figure 4a), but also caudate (Figure 4b) and dorsomedial prefrontal cortex (Figure 4d). For both gray and white matter, the slopes for this cluster were generally positive; white matter slope was slightly negative in the 8-10.5y age bin and gray matter slopes became slightly negative in the 14-18.5y age bin (Figure 4e-f).

Effects of data collection site and resolution

Previous studies have noted that VBM estimates of gray and white matter volume are sensitive to differences in MR scanner and image resolution (Focke et al., 2011; Pardoe et al., 2008; Pereira et al., 2008; Takao et al., 2013). As the present study made use of a multi-site dataset, additional analyses were run to estimate potential impact of these factors on our results. A general linear model was estimated using the entire sample of 360 participants, including a linear effect of resolution and separate regressors modeling effects of each site. F-contrasts were used to identify regions sensitive to these effects. Results of F-contrasts for site are shown in Figure 6ab, thresholded at $p<0.001$ uncorrected, for gray and white matter, respectively. We observe significant effects of site around the posterior putamen, orbitofrontal, inferior temporal and peripheral gray matter in Figure 6a. Significant effects on white matter volume were most prominent around the internal capsule (Figure 6b). Results of F-contrasts for resolution are shown in Figure 6cd, thresholded at $p<0.001$ uncorrected, for gray and white matter, respectively. Affected gray matter regions were similarly concentrated around the posterior putamen and insula, occipital and dorsal prefrontal regions (Figure 6c). For white matter, similar to effects of site, effects of resolution were largely concentrated around the internal capsule (Figure 6d). We next compared clustering results for age β-values from models that did and did not include effects of site and resolution. These results are shown in Figure 6ef. We note that clustering results were largely similar between these two models. Figure 6gh show gray and white matter clusters obtained from these two models overlaid, regions of overlap are shown in purple. The only regions where cluster assignment substantially differed was around the putamen and internal capsule. Overall these results suggest that effects of site and resolution may have a fairly localized effect in sub-cortical regions, and we note that reliability of cluster assignment in these regions is a limitation of the present work.

Effects of modeling total gray and white matter volume

Two additional analyses were run using proportional scaling by total tissue volume and including total tissue volume as a covariate (ANCOVA). The resulting parameter estimates for age were entered into a similar cluster analysis as that described above. These analyses identified very similar clusters (Figure 7), however with some differences specifically in white matter clustering in the midbrain for the ANCOVA model.

Effects of image contrast

White/gray matter contrast values for each lobe (frontal, temporal, parietal, occipital) were entered into ANOVAs modeling effect of site with age as a covariate. Models were run across the entire sample, as well as within each age bin. This analysis showed a significant effect of site in the temporal ($F(1,357)=16.6$, $p<0.001$) lobe, and a trend level effect in the frontal lobe ($F(1,357)=4.3$, $p=0.04$ uncorrected for multiple comparisons). Over the entire sample there was a trend-level, negative, association with age in the parietal cortex ($F(1,357)=3.9$, $p=0.048$ uncorrected). However, age was not a significant predictor of contrast within any of the age bins, for any of the lobes. From these results we conclude that image contrast is unlikely to have biased age-slopes in this analysis.

Statistical table

	Data structure	Type of test	Power
a	White matter volume (normally distributed)	K-means clustering, Silhouette Values	n/a
b	Gray matter volume (normally distributed)	K-means clustering, Silhouette Values	n/a

Discussion

In this study, white and gray matter volumes were divided into clusters based on the similarity of age-related volume changes from 4-18 years. The four identified white matter clusters each showed a dominant orientation of fibers (anterior-to-posterior, left-to-right, and two clusters with superior-to-inferior), and could be uniquely matched to a spatially proximal gray matter volume cluster. Gray matter clusters corresponded to cerebellar, medial/anterior, and sensorimotor clusters, respectively. Within gray and white matter network pairs, slopes followed similar trajectories across ages.

To our knowledge, this study is the first to investigate the organization of age-related structural variability in white matter volumes. Our results suggest that data-driven clustering of age-related variability in white matter volume can, to some extent, recover anterior-to-posterior, left-to-right and superior-to-inferior directional components. While previous work has shown region- and tract-specific white matter volume changes with age (Lebel and Beaulieu, 2011; Tamnes et al., 2010), our results suggest a relationship between age-related variability in white matter volume and fiber direction. We also note that the identified clusters generally did not segregate deep from superficial white matter. Together these findings add to our understanding of properties of white matter volume development.

Further, our results demonstrate a spatial and temporal relationship between patterns of age variability in white and gray matter volume. Previous work had shown that in individuals aged 8-30 years, (Tamnes et al., 2010) there are negative correlations between cortical thickness and volumes of corresponding gyral white matter. Wu et al. (2014) found that the association between superficial white matter FA and cortical thickness was positive in unimodal sensory areas, but negative in polymodal regions. In adolescents, a negative correlation between gray matter density and FA in the right superior corona radiata has been described (Giorgio et al., 2008). Together, these studies show that the general pattern of maturational contraction of gray matter is coupled with changes in white matter properties, including increased FA and volume. The present study builds on these findings by showing that there is a network organization in patterns of age-related variability in both gray and white matter volumes, and that these clusters are coupled based on both spatial proximity and similarity in age-slopes.

White matter development across childhood and adolescence is characterized by increased FA and volume, and reduced MD (Barnea-Goraly et al., 2005; Ben Bashat et al., 2005; Giorgio et al., 2008; Lebel and Beaulieu, 2011). These processes occur asynchronously across white matter regions (Lebel et al., 2008), and are believed to reflect changes in myelination and axonal packing (Beaulieu, 2002; Yakovlev and Lecours, 1967). White matter properties such as FA appear to be influenced by both genetic (Kochunov et al., 2015) and environmental (Hofstetter et al., 2013) factors. We speculate that genes expressed within regions or networks may contribute to coordinated patterns of volume development observed here. Though often considered separately, gray and white matter development may reflect processes occurring in the same cells (though changes in gray matter may also reflect changes in glial cells or vasculature (Zatorre et al., 2012)). We further speculate that coordinated white matter expansion and gray matter contraction may reflect a synergistic process of increased myelination and decreased synaptic or dendritic density that occurs as networks mature. We note however that MRI studies are quite limited in resolution and thus have limited ability to test these hypotheses directly.

Different distributed networks have been identified in functional MRI connectivity studies, including default-mode or task-negative, fronto-parietal / dorsal attention / task positive, ventral attention, salience, visual, motor and sub-cortical networks (Fox et al., 2005; Power et al., 2011). A previous, seed-based, study showed that longitudinal change in cortical thickness in core regions of the task-positive and task-negative networks are correlated (Raznahan et al., 2011). We note that using a data-driven approach, the gray matter clusters identified here did not specifically resemble either of these two networks. Instead, we found a posterior cluster that included both precuneus and bilateral intraparietal sulcus,

regions associated with both the task positive and negative networks. An anterior cluster included both medial prefrontal task negative regions, as well as cingulate and dorsal prefrontal regions associated with task positive and salience networks. A recent study using a qualitatively similar approach to that described here also identified one primarily parietal network and several networks that bisected the prefrontal cortex into superior and inferior regions (Alexander-Bloch et al., 2014). Although similarities in network properties of maturational and functional networks have been shown (Alexander-Bloch et al., 2013), recent results (Alexander-Bloch et al., 2014), together with those reported here, suggest that the spatial distribution of maturational structural covariance networks may not map directly onto canonical functional networks. Further work is required to carefully characterize the relationship between developmental gray matter networks and brain systems defined based on functional connectivity.

Our results suggest a period of particular cortical thinning in late childhood in the anterior and posterior gray matter clusters that consist of more cognitive frontal, parietal, insular and temporal regions. This has also been noted as a period of non-linear change in cortical thickness networks, when local efficiency is reduced but global efficiency increases (Khundrakpam et al., 2013). In terms of cognitive development, late childhood corresponds to a period of rapid maturation of attention and executive functions (Hommel et al., 2004; Pennington and Groisser, 1991; Zhan et al., 2011). Our data suggest that cortical thinning most prominently in parietal regions, but also in the more anterior cortical network, may play a role in this process. A goal for future longitudinal studies will be to consider the maturational trajectories of gray and white matter networks in relation to cognitive maturation.

There are several limitations associated with this study. We used single time-point rather than longitudinal measurements to identify age-slopes. Male and female participants were included in our analysis in similar numbers, though previous studies have shown evidence for sexually dimorphic trajectories in gray and white matter development (Giedd et al., 1997; Lenroot et al., 2007; Raznahan et al., 2011). Voxel-based morphometry analyses do not allow for separation of volume into thickness and surface area components, which make distinct contributions to volume development (Raznahan et al., 2011). The age windows used here were defined to correspond with recent reports (Khundrakpam et al., 2013; Zielinski et al., 2010), however these are somewhat arbitrary divisions and may not reflect optimal boundaries for transitions in age-slope. The 'optimal' number of clusters as defined using silhouette values did not match for gray and white matter clusters; the gray matter solution peaked at two clusters, separating cortical from cerebellar regions, while the white matter solution peaked at four clusters. We chose to model gray matter using a four-cluster solution, to match the white optimal white matter solution, and therefore note that gray matter clusters in the cortex may reflect gradations of a largely similar age-related volume pattern rather than substantially distinct clusters. Significant effects of data acquisition site and resolution were most prominent around the internal capsule, putamen and posterior insula; clustering results in these areas may therefore be less reliable. Finally, we note that our analysis identified a set of gray and white matter clusters that covered regions which are very different in terms of cellular composition. As such, this analysis did not perform well at identifying regions with particular properties.

In summary, this work describes a correspondence between clusters of white and gray matter regions, defined in terms of age-related variability in volume across childhood and adolescence. We found that white matter voxels clustered together based largely on fiber direction, and gray matter regions divided into anterior, posterior, sensorimotor and cerebellar clusters. These gray and white matter clusters could nonetheless be uniquely matched on the basis of spatial proximity, and showed parallel trajectories in age-related variability. This study identifies a previously unreported property of directional selectivity in white matter volume development, and demonstrates that white and gray matter volume clusters are linked across childhood and adolescence. There is a growing interest in understanding the role of anatomical networks in neurodevelopmental (Zielinski et al., 2012), neuropsychiatric (Alexander-Bloch et al., 2014) and

neurodegenerative (Douaud et al., 2014) disorders; these results lay a foundation for studying network-level abnormalities in white matter volume, and their relationship to gray matter covariance networks.

Figure captions

Figure 1. Superior corona radiata / posterior gray matter clusters. This white matter cluster included deep white matter of the superior longitudinal fasciculus, superior corona radiata and body of the corpus callosum (acd) and included mostly (68% of voxels) superior-inferior oriented voxels. The corresponding gray matter cluster included primarily posterior cortical regions (a-d), including precuneus (b) and bilateral intraparietal sulcus (c). Mean gray and white matter slopes for the cluster with standard deviations (e) and a graphical illustration of volume trajectories (f) are shown for all four age bins.

Figure 2. Medial callosal white matter / anterior gray matter clusters. This white matter cluster included medial corpus callosum (a), anterior internal capsule (d) and superior parietal lobule white matter (c) and was primarily ordered left-right (70%). The corresponding gray matter cluster included anterior cingulate and medial prefrontal cortex (abc), as well as insular (bd) and temporal regions (b). Mean gray and white matter slopes for the cluster with standard deviations (e) and a graphical illustration of volume trajectories (f) are shown for all four age bins.

Figure 3. Frontal and occipital white matter / visuo-motor gray matter. This white matter cluster included mostly superior-inferior oriented voxels (74%) in superior cerebellar peduncle (a), occipital and superior parietal (b) and superior frontal gyrus white matter (cd), posterior thalamic radiation (bc) and precentral gyrus white matter (d). The corresponding gray matter cluster recruited cuneus (abc), motor (d), superior parietal (b) and lateral prefrontal (c) regions. Mean gray and white matter slopes for the cluster with standard deviations (e) and a graphical illustration of volume trajectories (f) are shown for all four age bins.

Figure 4. Cerebellar white and gray matter clusters. This white matter cluster included the cerebellum and cerebellar peduncles (a), including white matter in portions of the superior longitudinal fasciculus (c); voxels in this cluster were predominantly oriented anterior-posterior (58%). The corresponding gray matter cluster included the bilateral cerebellum (a), caudate (b) and dorsomedial prefrontal cortex (d). Mean gray and white matter slopes for the cluster with standard deviations (e) and a graphical illustration of volume trajectories (f) are shown for all four age bins.

Figure 5. Preferred white matter direction in each cluster. For this analysis, the voxels within each cluster were thresholded to only those voxels with an eigenvalue >=0.4 in one of the three canonical directions. Panel (a) shows the proportion of voxels for with the maximum value in each direction. Panel (b) illustrates eigenvalues for all three directions across all voxels with at least one eigenvalue >=0.4, sorted by maximum value in each row (i.e. each row is one voxel; heat map indicates the eigenvalue at that voxel for each canonical direction). SCR=superior corona radiata, CC=corpus callosum, FO=Fronto-occipital. AP=anterior-posterior, LR=left-right, SI=superior-inferior.

Figure 6. Effects of site and resolution on regional volume and clustering results. Panels (a) and (b) show the results of an F-contrast for effects of site, thresholded at $p<0.001$ uncorrected, on gray and white matter volume respectively. Site effects were identified around the putamen and internal capsule, as well as medial orbital and peripheral gray matter. Panels (c) and (d) show the results of an F-contrast for effects of resolution, thresholded at $p<0.001$ uncorrected, on gray and white matter volume respectively. Effects were again concentrated around the internal capsule, with gray matter effects in dorsal prefrontal, occipital cortices and cerebellum. Panels (e) and (f) illustrate clustering results for age-β estimates from gray (e) and white (f) matter models that included effects of site and resolution (left and superior panels) and from models that did not include these effects (right and inferior panels). We note that these are largely similar. Panels (g) and (h) illustrate regions of overlap (purple) and difference (red and blue) in cluster assignment for gray (g) and white (h) matter clusters when site and resolution are taken into account. The only substantial differences in clustering results were in posterior putamen and near the internal capsule.

Figure 7. Gray and white matter clusters derived from models accounting for total tissue volume. Panels a) and b) show gray matter clusters for models using proportional scaling (a) and ANCOVA (b). Panels c) and d) show white matter clusters for models using proportional scaling (c) and ANCOVA (d) models. Clusters are similar to Figure 6e and 6f, with a notable difference in the white matter cluster in the midbrain for the ANCOVA model (panel d).

Tables

Table 1. Participant demographics. Mean, standard deviation (SD), and range were calculated for age and IQ in each group. Handedness reflects right (R) versus left (L) hand preference. Mean adjusted income is measured in thousands of dollars.

	Group 1	Group 2	Group 3	Group 4
Mean Age (SD) (y)	6.47 (0.81)	9.16 (0.76)	12.04 (0.84)	16.03 (1.27)
Age Range (y)	4.80-7.85	8.02-10.47	10.68-13.50	13.99-18.35
Mean IQ (SD)	110.9(16.0)	112.5 (12.9)	112.1 (10.7)	109.0 (11.4)
IQ Range	79-156	77-160	84-131	78-132
Handedness R:L	83:7	80:10	80:10	81:9
Gender M:F	45:45	45:45	45:45	45:45
Mean Adjusted Income (Thousands)(SD)	71.1 (32.5)	70.0 (30.6)	70.1 (32.0)	70.0 (31.4)

References

Alexander-Bloch, A., Giedd, J. N., and Bullmore, E. (2013). Imaging structural co-variance between human brain regions. Nat. Rev. Neurosci, 14, 322-36.

Alexander-Bloch, A., Raznahan, A., Bullmore, E., and Giedd, J. (2013). The convergence of maturational change and structural covariance in human cortical networks. J Neurosci, 33, 2889-99.

Alexander-Bloch, A. F., Reiss, P. T., Rapoport, J., McAdams, H., Giedd, J. N., Bullmore, E. T., and Gogtay, N. (2014). Abnormal Cortical Growth in Schizophrenia Targets Normative Modules of Synchronized Development. Biol. Psychiatry.

Ashburner, J. (2007). A fast diffeomorphic image registration algorithm. Neuroimage, 38, 95-113.

Barnea-Goraly, N., Menon, V., Eckert, M., Tamm, L., Bammer, R., Karchemskiy, A., Dant, C. C., et al. (2005). White matter development during childhood and adolescence: a cross-sectional diffusion tensor imaging study. Cereb. Cortex, 15, 1848-54.

Beaulieu, C. (2002). The basis of anisotropic water diffusion in the nervous system - a technical review. NMR Biomed, 15, 435-55.

Ben Bashat, D., Ben Sira, L., Graif, M., Pianka, P., Hendler, T., Cohen, Y., and Assaf, Y. (2005). Normal white matter development from infancy to adulthood: comparing diffusion tensor and high b value diffusion weighted MR images. J Magn Reson Imaging, 21, 503-11.

Benes, F. M., Turtle, M., Khan, Y., and Farol, P. (1994). Myelination of a key relay zone in the hippocampal formation occurs in the human brain during childhood, adolescence, and adulthood. Arch. Gen. Psychiatry, 51, 477-84.

Benes, F. M. (1989). Myelination of cortical-hippocampal relays during late adolescence. Schizophr Bull, 15, 585-93.

Chen, Z. J., He, Y., Rosa-Neto, P., Germann, J., and Evans, A. C. (2008). Revealing modular architecture of human brain structural networks by using cortical thickness from MRI. Cereb. Cortex, 18, 2374-81.

Cotter, D., Mackay, D., Chana, G., Beasley, C., Landau, S., and Everall, I. P. (2002). Reduced neuronal size and glial cell density in area 9 of the dorsolateral prefrontal cortex in subjects with major depressive disorder. Cereb. Cortex, 12, 386-94.

416 Douaud, G., Groves, A. R., Tamnes, C. K., Westlye, L. T., Duff, E. P., Engvig, A., Walhovd, K. B., et al. (2014). A common
417 brain network links development, aging, and vulnerability to disease. Proc. Natl. Acad. Sci. U.S.A, 111, 17648-53.
418 Drevets, W. C., Ongür, D., and Price, J. L. (1998). Neuroimaging abnormalities in the subgenual prefrontal cortex:
419 implications for the pathophysiology of familial mood disorders. Mol. Psychiatry, 3, 220-6, 190-1.
420 Elgeti, H., Elgeti, R., and Fleischhauer, K. (1976). Postnatal growth of the dorsal lateral geniculate nucleus of the cat.
421 Anat. Embryol, 149, 1-13.
422 Evans, A. C., and Brain Development Cooperative Group,. (2006). The NIH MRI study of normal brain development.
423 Neuroimage, 30, 184-202.
424 Evans, A. C. . (2013). Networks of anatomical covariance. Neuroimage, 80, 489-504.
425 Focke, N. K., Helms, G., Kaspar, S., Diederich, C., Tóth, V., Dechent, P., Mohr, A., et al. (2011). Multi-site voxel-based
426 morphometry--not quite there yet. Neuroimage, 56, 1164-70.
427 Fox, M. D., Snyder, A. Z., Vincent, J. L., Corbetta, M., Van Essen, D. C., and Raichle, M. E. (2005). The human brain is
428 intrinsically organized into dynamic, anticorrelated functional networks. Proc. Natl. Acad. Sci. U.S.A, 102, 9673-8.
429 Giedd, J. N., Blumenthal, J., Jeffries, N. O., Castellanos, F. X., Liu, H., Zijdenbos, A., Paus, T., et al. (1999). Brain
430 development during childhood and adolescence: a longitudinal MRI study. Nat. Neurosci, 2, 861-3.
431 Giedd, J. N., Castellanos, F. X., Rajapakse, J. C., Vaituzis, A. C., and Rapoport, J. L. (1997). Sexual dimorphism of the
432 developing human brain. Prog. Neuropsychopharmacol. Biol. Psychiatry, 21, 1185-201.
433 Giorgio, A., Watkins, K. E., Douaud, G., James, A. C., James, S., De Stefano, N., Matthews, P. M., et al. (2008). Changes in
434 white matter microstructure during adolescence. Neuroimage, 39, 52-61.
435 Gogtay, N., Giedd, J. N., Lusk, L., Hayashi, K. M., Greenstein, D., Vaituzis, A. C., Nugent, 3. T. F. ,., et al. (2004a). Dynamic
436 mapping of human cortical development during childhood through early adulthood. Proc. Natl. Acad. Sci. U.S.A,
437 101, 8174-9.
438 Gogtay, N., Giedd, J. N., Lusk, L., Hayashi, K. M., Greenstein, D., Vaituzis, A. C., Nugent, T. F., et al. (2004b). Dynamic
439 mapping of human cortical development during childhood through early adulthood. Proc. Natl. Acad. Sci. U.S.A,
440 101, 8174-9.

441 Gong, G., He, Y., Chen, Z. J., and Evans, A. C. (2012). Convergence and divergence of thickness correlations with diffusion
442 connections across the human cerebral cortex. Neuroimage, 59, 1239-48.
443 Hofstetter, S., Tavor, I., Tzur Moryosef, S., and Assaf, Y. (2013). Short-term learning induces white matter plasticity in the
444 fornix. J. Neurosci, 33, 12844-50.
445 Hommel, B., Li, K. Z., and Li, S. C. (2004). Visual search across the life span. Dev Psychol, 40, 545-58.
446 Huttenlocher, P. R. (1979). Synaptic density in human frontal cortex - developmental changes and effects of aging. Brain
447 Res, 163, 195-205.
448 Innocenti, G. M., and Price, D. J. (2005). Exuberance in the development of cortical networks. Nat. Rev. Neurosci, 6, 955-
449 65.
450 Kaufman L. and Rousseeuw P. J. (1990). Finding Groups in Data: An Introduction to Cluster Analysis. Hoboken, NJ: John
451 Wiley & Sons, Inc. Finding Groups in Data: An Introduction to Cluster Analysis.
452 Khundrakpam, B. S., Reid, A., Brauer, J., Carbonell, F., Lewis, J., Ameis, S., Karama, S., et al. (2013). Developmental
453 changes in organization of structural brain networks. Cereb. Cortex, 23, 2072-85.
454 Kochunov, P., Jahanshad, N., Marcus, D., Winkler, A., Sprooten, E., Nichols, T. E., Wright, S. N., et al. (2015). Heritability
455 of fractional anisotropy in human white matter: A comparison of Human Connectome Project and ENIGMA-DTI
456 data. Neuroimage, 111, 300-311.
457 Lebel, C., Gee, M., Camicioli, R., Wieler, M., Martin, W., and Beaulieu, C. (2012). Diffusion tensor imaging of white matter
458 tract evolution over the lifespan. Neuroimage, 60, 340-52.
459 Lebel, C., Walker, L., Leemans, A., Phillips, L., and Beaulieu, C. (2008). Microstructural maturation of the human brain
460 from childhood to adulthood. Neuroimage, 40, 1044-55.
461 Lebel, C., and Beaulieu, C. (2011). Longitudinal development of human brain wiring continues from childhood into
462 adulthood. J Neurosci, 31, 10937-47.
463 Lenroot, R. K., Gogtay, N., Greenstein, D. K., Wells, E. M., Wallace, G. L., Clasen, L. S., Blumenthal, J. D., et al. (2007).
464 Sexual dimorphism of brain developmental trajectories during childhood and adolescence. Neuroimage, 36,
465 1065-73.

Lerch, J. P., Worsley, K., Shaw, W. P., Greenstein, D. K., Lenroot, R. K., Giedd, J., and Evans, A. C. (2006). Mapping anatomical correlations across cerebral cortex (MACACC) using cortical thickness from MRI. Neuroimage, 31, 993-1003.

Maldjian, J. A., Laurienti, P. J., Kraft, R. A., and Burdette, J. H. (2003). An automated method for neuroanatomic and cytoarchitectonic atlas-based interrogation of fMRI data sets. Neuroimage, 19, 1233-1239.

Mazziotta, J., Toga, A., Evans, A., Fox, P., Lancaster, J., Zilles, K., Woods, R., et al. (2001). A four-dimensional probabilistic atlas of the human brain. J Am Med Inform Assoc, 8, 401-30.

Mechelli, A., Friston, K. J., Frackowiak, R. S., and Price, C. J. (2005). Structural covariance in the human cortex. J. Neurosci, 25, 8303-10.

Mori, S., Oishi, K., Jiang, H., Jiang, L., Li, X., Akhter, K., Hua, K., et al. (2008). Stereotaxic white matter atlas based on diffusion tensor imaging in an ICBM template. Neuroimage, 40, 570-82.

Oishi, K., Faria, A., van Zijl, P., and Mori, S. (2011). MRI Atlas of Human White Matter. Elsevier.

Pardoe, H., Pell, G. S., Abbott, D. F., Berg, A. T., and Jackson, G. D. (2008). Multi-site voxel-based morphometry: methods and a feasibility demonstration with childhood absence epilepsy. Neuroimage, 42, 611-6.

Paus, T., Collins, D. L., Evans, A. C., Leonard, G., Pike, B., and Zijdenbos, A. (2001). Maturation of white matter in the human brain: a review of magnetic resonance studies. Brain Res. Bull, 54, 255-66.

Paus, T., Zijdenbos, A., Worsley, K., Collins, D. L., Blumenthal, J., Giedd, J. N., Rapoport, J. L., et al. (1999). Structural maturation of neural pathways in children and adolescents: in vivo study. Science, 283, 1908-11.

Paus, T. (2010). Growth of white matter in the adolescent brain: myelin or axon?. Brain Cogn, 72, 26-35.

Peelle, J. E., Cusack, R., and Henson, R. N. (2012). Adjusting for global effects in voxel-based morphometry: gray matter decline in normal aging. Neuroimage, 60, 1503-16.

Pennington, B. F., and Groisser, D. B. (1991). A normative-developmental study of executive function: A window on prefrontal function in children. Dev. Neuropsych., 7, 131-49.

Pereira, J. M., Nestor, P. J., and Williams, G. B. (2008). Impact of inconsistent resolution on VBM studies. Neuroimage, 40, 1711-7.

491 Power, J. D., Cohen, A. L., Nelson, S. M., Wig, G. S., Barnes, K. A., Church, J. A., Vogel, A. C., et al. (2011). Functional
492 network organization of the human brain. Neuron, 72, 665-78.
493 Rademacher, J., Engelbrecht, V., Bürgel, U., Freund, H., and Zilles, K. (1999). Measuring in vivo myelination of human
494 white matter fiber tracts with magnetization transfer MR. Neuroimage, 9, 393-406.
495 Raznahan, A., Cutter, W., Lalonde, F., Robertson, D., Daly, E., Conway, G. S., Skuse, D. H., et al. (2010). Cortical anatomy
496 in human X monosomy. Neuroimage, 49, 2915-23.
497 Raznahan, A., Lerch, J. P., Lee, N., Greenstein, D., Wallace, G. L., Stockman, M., Clasen, L., Shaw, P. W., et al. (2011).
498 Patterns of coordinated anatomical change in human cortical development: a longitudinal neuroimaging study
499 of maturational coupling. Neuron, 72, 873-84.
500 Raznahan, A., Shaw, P., Lalonde, F., Stockman, M., Wallace, G. L., Greenstein, D., Clasen, L., Gogtay, N., et al. (2011). How
501 does your cortex grow?. The Journal of Neuroscience, 31, 7174-7.
502 Reid, A. T., van Norden, A. G., de Laat, K. F., van Oudheusden, L. J., Zwiers, M. P., Evans, A. C., de Leeuw, F. E., et al.
503 (2010). Patterns of cortical degeneration in an elderly cohort with cerebral small vessel disease. Hum Brain
504 Mapp, 31, 1983-92.
505 Ridgway, G. R., Omar, R., Ourselin, S., Hill, D. L., Warren, J. D., and Fox, N. C. (2009). Issues with threshold masking in
506 voxel-based morphometry of atrophied brains. Neuroimage, 44, 99-111.
507 Seeley, W. W., Crawford, R. K., Zhou, J., Miller, B. L., and Greicius, M. D. (2009). Neurodegenerative diseases target large-
508 scale human brain networks. Neuron, 62, 42-52.
509 Segall, J. M., Allen, E. A., Jung, R. E., Erhardt, E. B., Arja, S. K., Kiehl, K., and Calhoun, V. D. (2012). Correspondence
510 between structure and function in the human brain at rest. Front Neuroinform, 6, 10.
511 Shaw, P., Kabani, N. J., Lerch, J. P., Eckstrand, K., Lenroot, R., Gogtay, N., Greenstein, D., et al. (2008).
512 Neurodevelopmental trajectories of the human cerebral cortex. J. Neurosci, 28, 3586-94.
513 Shi, F., Fan, Y., Tang, S., Gilmore, J. H., Lin, W., and Shen, D. (2010). Neonatal brain image segmentation in longitudinal
514 MRI studies. Neuroimage, 49, 391-400.

515 Sowell, E. R., Peterson, B. S., Thompson, P. M., Welcome, S. E., Henkenius, A. L., and Toga, A. W. (2003). Mapping cortical
516 change across the human life span. Nature Neuroscience, 6, 309-15.
517 Sowell, E. R., Thompson, P. M., Leonard, C. M., Welcome, S. E., Kan, E., and Toga, A. W. (2004). Longitudinal mapping of
518 cortical thickness and brain growth in normal children. J Neurosci, 24, 8223-31.
519 Sowell, E. R., Trauner, D. A., Gamst, A., and Jernigan, T. L. (2002). Development of cortical and subcortical brain
520 structures in childhood and adolescence: a structural MRI study. Dev Med Child Neurol, 44, 4-16.
521 Takao, H., Hayashi, N., and Ohtomo, K. (2013). Effects of the use of multiple scanners and of scanner upgrade in
522 longitudinal voxel-based morphometry studies. J Magn Reson Imaging, 38, 1283-91.
523 Taki, Y., Thyreau, B., Hashizume, H., Sassa, Y., Takeuchi, H., Wu, K., Kotozaki, Y., et al. (2013). Linear and curvilinear
524 correlations of brain white matter volume, fractional anisotropy, and mean diffusivity with age using voxel-
525 based and region-of-interest analyses in 246 healthy children. Hum Brain Mapp, 34, 1842-56.
526 Tamnes, C. K., Ostby, Y., Fjell, A. M., Westlye, L. T., Due-Tønnessen, P., and Walhovd, K. B. (2010). Brain maturation in
527 adolescence and young adulthood: regional age-related changes in cortical thickness and white matter volume
528 and microstructure. Cereb. Cortex, 20, 534-48.
529 Tijms, B. M., Seriès, P., Willshaw, D. J., and Lawrie, S. M. (2012). Similarity-based extraction of individual networks from
530 gray matter MRI scans. Cereb. Cortex, 22, 1530-41.
531 Tzourio-Mazoyer, N., Landeau, B., Papathanassiou, D., Crivello, F., Etard, O., Delcroix, N., Mazoyer, B., et al. (2002).
532 Automated anatomical labeling of activations in SPM using a macroscopic anatomical parcellation of the MNI
533 MRI single-subject brain. Neuroimage, 15, 273-289.
534 Vaidya, J. G., Paradiso, S., Boles Ponto, L. L., McCormick, L. M., and Robinson, R. G. (2007). Aging, grey matter, and blood
535 flow in the anterior cingulate cortex. Neuroimage, 37, 1346-53.
536 Wu, M., Lu, L. H., Lowes, A., Yang, S., Passarotti, A. M., Zhou, X. J., and Pavuluri, M. N. (2014). Development of superficial
537 white matter and its structural interplay with cortical gray matter in children and adolescents. Hum Brain Mapp,
538 35, 2806-16.

539 Yakovlev, P., and Lecours, A. (1967). The myelogenetic cycles of regional maturation of the brain. Boston, Mass:
540 Blackwell Scientific Publications Inc. In A. Minkowski,, 3-70.
541 Zatorre, R. J., Fields, R. D., and Johansen-Berg, H. (2012). Plasticity in gray and white: neuroimaging changes in brain
542 structure during learning. Nature neuroscience, 15, 528-36.
543 Zhan, J. Y., Wilding, J., Cornish, K., Shao, J., Xie, C. H., Wang, Y. X., Lee, K., et al. (2011). Charting the developmental
544 trajectories of attention and executive function in Chinese school-aged children. Child Neuropsychol, 17, 82-95.
545 Zielinski, B. A., Anderson, J. S., Froehlich, A. L., Prigge, M. B., Nielsen, J. A., Cooperrider, J. R., Cariello, A. N., et al. (2012).
546 scMRI reveals large-scale brain network abnormalities in autism. PLoS ONE, 7, e49172.
547 Zielinski, B. A., Gennatas, E. D., Zhou, J., and Seeley, W. W. (2010). Network-level structural covariance in the developing
548 brain. Proc. Natl. Acad. Sci. U.S.A, 107, 18191-6.