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The brain dynamics of intellectual development: Waxing and waning white and gray matter

Christian K. Tamnes[a,b,*], Anders M. Fjell[a], Ylva Østby[a], Lars T. Westlye[a], Paulina Due-Tønnessen[c], Atle Bjørnerud[b], Kristine B. Walhovd[a]

[a] Center for the Study of Human Cognition, Department of Psychology, University of Oslo, Norway
[b] The Interventional Centre, Rikshospitalet, Oslo University Hospital, Norway
[c] Department of Radiology, Rikshospitalet, Oslo University Hospital, Norway

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ABSTRACT

Distributed brain areas support intellectual abilities in adults. How structural maturation of these areas in childhood enables development of intelligence is not established. Neuroimaging can be used to monitor brain development, but studies to date have typically considered single imaging modalities. To explore the impact of structural brain maturation on the development of intelligence, we used a combination of cortical thickness, white matter (WM) volume and WM microstructure in 168 healthy participants aged 8–30 years. Principal component analyses (PCAs) were conducted separately for cortical thickness, WM volume, fractional anisotropy (FA) and mean diffusivity (MD) in 64 different brain regions. For all four parameters, the PCAs revealed a general factor explaining between 40% and 53% of the variance across regions. When tested separately, negative age-independent relationships were found between intellectual abilities and cortical thickness and MD, respectively, while WM volume and FA were positively associated with intellectual abilities. The relationships between intellectual abilities and brain structure varied with age, with stronger relationships seen in children and adolescents than in young adults. Multiple regression analysis with the different imaging measures as simultaneous predictors, showed that cortical thickness, WM volume and MD all yielded unique information in explaining intellectual abilities in development. The present study demonstrates that different imaging modalities and measures give complementary information about the neural substrates of intellectual abilities in development, emphasizing the importance of multimodal imaging in investigations of neurocognitive development.

1. Introduction

A fundamental question in cognitive neuroscience regards the relationship between cognitive functions and structural properties of the brain. This is exemplified by the thorough post mortem investigations of the brains of exceptional people such as Albert Einstein. Findings suggest that the gross anatomy of Einstein's brain was within normal limits with the exception of his parietal lobes (Witelson, Kigar, & Harvey, 1999). General intelligence in adults does however rely on spatially distributed brain regions, not isolated structures. A recent lesion mapping study identified a circumscribed but distributed network of regions, and suggested that the connections between these regions are critical to intelligence (Gläscher et al., 2010). The distributed network view is further supported by studies showing links between intelligence and functional connectivity (Song et al., 2008) and structural covariance (Lerch et al., 2006). Using magnetic resonance imaging (MRI), Lerch et al. (2006) found stronger correlations between cortical thickness in a part of the inferior frontal gyrus and multiple frontal and parietal regions for a higher intelligence group of adolescents.

For such distributed networks in adults to be able to support intellectual function, a complex interplay between maturation of cortical structures and the connections between them will have to take place in development. Intellectual abilities improve dramatically in childhood and adolescence (Waber et al., 2007), and neuroimaging studies have confirmed that intellectual development is related to maturation of both gray matter (GM) and white matter (WM) (Shaw et al., 2006; Sowell et al., 2004; Tamnes et al., 2010b). The distributed neural network view of intelligence calls for joint investigations of brain structures and their connections.

Brain maturation in late childhood and adolescence is characterized by cortical thinning and WM volume increases (Brain Development Cooperative Group, in press; Giedd, 2004; Muftuler et al., 2011; Raznahan et al., 2011; Shaw et al., 2008; Sullivan et

* Corresponding author at: Center for the Study of Human Cognition, Department of Psychology, University of Oslo, PO Box 1094 Blindern, 0317 Oslo, Norway. Tel.: +47 22845092; fax: +47 22845001.
E-mail address: c.k.tamnes@psykologi.uio.no (C.K. Tamnes).

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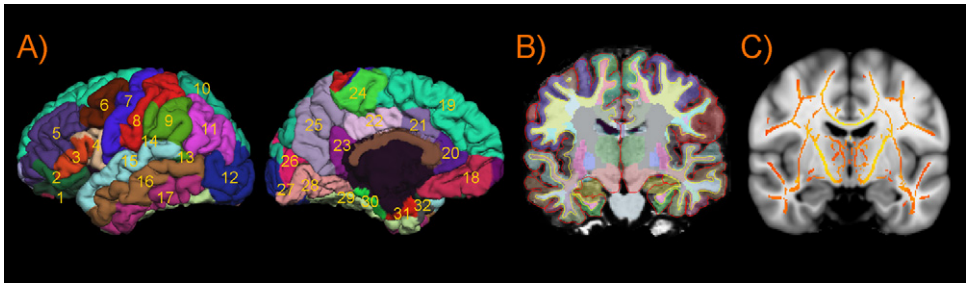

Fig. 1. Example imaging data from a 10 year old female participant. (A) Lateral and medial views of the left hemisphere cortical surface from FreeSurfer. The surface was parcellated and mean thickness values were calculated in the ROIs. Thirty-two different gyral-based areas in each hemisphere were used and different areas are shown in different colors. The cortical labels are: (1) lateral orbitofrontal, (2) pars orbitalis, (3) pars triangularis, (4) pars opercularis, (5) rostral middle frontal, (6) caudal middle frontal, (7) precentral, (8) postcentral, (9) supramarginal, (10) superior parietal, (11) inferior parietal, (12) lateral occipital, (13) banks superior temporal sulcus, (14) transversetemporal, (15) superior temporal, (16) middle temporal, (17) inferior temporal, (18) medial orbitofrontal, (19) superior frontal, (20) rostral anterior cingulate, (21) caudal anterior cingulate, (22) posterior cingulate, (23) isthmus cingulate, (24) paracentral, (25) precuneus, (26) cuneus, (27) pericalcarine, (28) lingual, (29) fusiform, (30) parahippocampal, (31) entorhinal, (32) temporal pole. (B) Coronal slice of T1 image. Both the cortical parcellations and the gyral WM segmentation from FreeSurfer are shown, with different areas in different color. The WM regions correspond to the cortical labels. (C) Coronal slice of the TBSS FA skeleton overlaid on the standard MNI152 T1 template. The skeleton was thresholded at FA > 0.25. Voxels intersecting both the skeleton and the WM areas were used in the analyses. The coronal slices are shown in radiological convention.

al., 2011; Tamnes et al., 2010a), both likely partly responsible for the rapid development of intelligence. Microstructural WM maturation can be studied by diffusion tensor imaging (DTI). The most commonly reported diffusion parameters are fractional anisotropy (FA), which indexes degree of directionality in water diffusion in the tissue, and mean diffusivity (MD), reflecting average magnitude of water diffusion. These indices show substantially developmental differences (Bava et al., 2010; Giorgio et al., 2010; Lebel & Beaulieu, 2011; Westlye et al., 2010), and are promising WM phenotypes related to cognitive development (Johansen-Berg, 2010; Madsen et al., 2010). By studying cortical thickness, WM volume and WM microstructure simultaneously, a fuller picture can be attained of the transition of the immature child brain to an adult brain with its distributed and finely tuned neural networks supporting intellectual function.

Here, we used MRI to assess cortical thickness, WM volume and DTI parameters in 168 healthy participants aged 8–30 years. Principal component analyses (PCAs) were conducted on regional brain measures to extract general factors of cortical thickness, subcortical WM volume and WM mictrostructure. These factors were then used in brain-behavior analyses, where our main aim was to determine whether cortical thickness and structural properties of the subcortical WM provide unique information in explaining intellectual abilities in development.

2. Materials and methods

2.1. Participants

The study was approved by the Regional Ethical Committee of South Norway. Written informed consent was obtained from all participants older than 12 years of age and from a parent of participants under 18 years of age. Oral informed consent was given by participants under 12 years of age. Volunteers were recruited through newspaper advertisements and schools. Standardized health screening interviews were conducted with participants and/or a parent. Participants were required to be right handed, fluent Norwegian speakers, have normal or corrected to normal vision and hearing, not have history of injury or disease known to affect central nervous system (CNS) function, including neurological or psychiatric illness or serious head trauma, not be under psychiatric treatment, not use medicines or psychoactive drugs known to affect CNS functioning, not have had complicated or premature birth, and not have MRI contraindications. One hundred and seventy-six participants satisfied these criteria. Seven participants were excluded due to incomplete or inadequate quality MRI data. All MR scans were examined by a neuroradiologist and the participants were required to be deemed free of significant injuries or conditions. One participant was excluded on this basis. Further details regarding recruitment and enrolment are given elsewhere (Østby et al., 2009; Tamnes et al., 2010a). For the included 168 participants (87 females), mean age was 17.7 years (SD = 6.1, range = 8.2–30.8). Mean age for females and males were 18.0 (SD = 6.1) and 17.4 (SD = 6.1) years respectively ($t(166) = 0.66$, $p = .513$).

2.2. Assessment of intellectual abilities

IQ was assessed by Wechsler Abbreviated Scale of Intelligence (WASI) (Wechsler, 1999). Mean IQ for the total sample was 110.4 (SD = 9.9, range = 82–141). Raw performance scores that are not standardized to the norms of the same age group has been suggested to be particularly suited for periods of relatively rapid intellectual change, such as childhood (Shaw, 2007), and was therefore used in the present study. Raw scores on all four WASI tasks were subjected to PCA, which yielded a component explaining 80.2% of the variance (eigenvalue = 3.21). The factor loadings for Vocabulary, Similarities, Matrix reasoning and Block design were 0.91, 0.92, 0.85 and 0.91, respectively. Mean intellectual abilities scores for females and males were not different ($t(166) = 0.02$, $p = .986$). This procedure was employed as it has been argued that a PCA derived g-factor is a more optimal measure of general intelligence (Deary, Penke, & Johnson, 2010). The PCA derived component was interpreted as a general intellectual abilities factor and used in all further analyses.

2.3. Neuroimaging acquisition

A 12 channel head coil on a 1.5 T Siemens Avanto scanner (Siemens Medical Solutions, Erlangen, Germany) was used. The pulse sequences used for morphometry analysis were two repeated T1-weighted magnetization prepared rapid gradient echo (MPRAGE) sequences (repetition time (TR)/echo time (TE)/time to inversion/flip angle = 2400 ms/3.61 ms/1000 ms/8°, matrix 192 × 192, field of view = 192 mm, 160 sagittal slices, voxel size 1.25 mm × 1.25 mm × 1.20 mm, acquisition time 7:42). To increase the signal-to-noise ratio (SNR) the two runs were averaged during post-processing. Primarily due to motion distortion, only one usable MPRAGE was available for 25 participants (14.9%). Most of these were younger participants and males (10 girls of mean age 10.1 years and 25 boys of mean age 11.1, in total mean age was 10.7 years, SD = 2.0, range = 8.4–16.4). This might represent a possible confound, although the number of acquisitions (single vs. multiple averaged) has previously been found to have negligible effects on reliability of cortical thickness measurements (Han et al., 2006). In a previous study, we directly tested the effects of including one or two acquisitions and found that there were overall few and relatively restricted regions showing absolute differences exceeding 0.10 mm (Tamnes et al., 2010c). For DTI, we used a single-shot twice-refocused spin–echo echo planar imaging pulse sequence with 30 diffusion sensitized gradient directions (TR/TE = 8200 ms/82 ms, b-value = 700 s/mm^2, voxel size = 2.0 mm × 2.0 mm × 2.0 mm, 64 axial slices, two successive runs with 10 non-diffusion-weighted and 30 diffusion-weighted images, acquisition time 11:21). The acquisitions were combined during post-processing to increase SNR.

2.4. Morphometric analysis

Cortical thickness was estimated using FreeSurfer by means of an automated surface reconstruction scheme described elsewhere (Dale & Sereno, 1993; Dale, Fischl, & Sereno, 1999; Fischl & Dale, 2000; Fischl, Sereno, & Dale, 1999a; Fischl, Sereno, Tootell, & Dale, 1999b; Fischl, Liu, & Dale, 2001; Segonne et al., 2004; Segonne, Grimson, & Fischl, 2005). The cortical surface was then parcellated (Desikan et al., 2006; Fischl et al., 2004), and mean thickness values were calculated in the ROIs. Thirty-two cortical parcellations in each hemisphere were used as ROIs. The frontal pole ROIs were excluded because a few subject did not have voxels intersecting both the FA skeleton and the frontal pole WM regions. Subcortical WM was automatically segmented according to the cortical surface parcellation (Fjell et al., 2008; Salat et al., 2009). With a 5 mm distance limit, WM voxels were labeled

according to the label of the nearest cortical voxel, and the volume of each region was calculated.

The surface reconstruction, cortical parcellation and WM segmentation procedures (further described in Tamnes et al. (2010a)) are run automatically, but require supervision of the accuracy of spatial registration and tissue segmentations. All volumes were inspected for accuracy and minor manual edits were performed by trained operators on most subjects (>80%), usually restricted to removal of non-brain tissue included within the cortical boundary. The cortical and the subcortical WM regions are shown for a 10 year old female participant in Fig. 1.

2.5. DTI analysis

Analyses were performed using tract-based spatial statistics (TBSS) in FSL (Jenkinson & Smith, 2001; Smith, 2002; Smith et al., 2004, 2006, 2007) and are further described elsewhere (Tamnes et al., 2010b; Westlye et al., 2010). Briefly, individual masks based on the gyral WM segmentations in FreeSurfer were created and mean FA/MD from the overlap between the TBSS skeleton and the WM labels were calculated. Voxels intersecting both the skeleton and the WM areas were used in the analyses, yielding 32 bilateral ROIs. All DTI volumes were visually inspected for accuracy. The FA skeleton is shown for one representative participant in Fig. 1C.

2.6. Statistical analyses

Statistical procedures were performed using PASW Statistics (SPSS) for Windows, release version 18.0.0 (IBM Corporation, Armonk, NY). First, to extract general factors of cortical thickness, WM volume, FA and MD, we ran four separate PCAs. In addition to identifying shared variance across regions, these analyses also alleviated the multiple comparisons problem by reducing the number of variables. Next, to investigate age-independent brain-behavior relationships, we performed multiple regressions on intellectual abilities with sex, age and the general factors of cortical thickness, WM volume, FA and MD, respectively, as predictor variables. Third, we investigated if the relationships between intellectual abilities and brain structures varied with age, by testing for interactions between brain measures and age on intellectual abilities. To interpret these effects, intellectual abilities were correlated with cortical thickness, WM volume, FA and MD, controlling for the effects of sex, after splitting the sample in two at the median age (17.2 years). For the group of 84 children and adolescents (41 females), mean age was 12.6 years (SD = 2.7, range = 8.2–17.1). For the 84 young adults (46 females), mean age was 22.8 years (SD = 3.8, range = 17.3–30.8). Mean IQ for the children and adolescents was 107.7 (SD = 10.7, range = 82–141), while for the young adult group it was 113.0 (SD = 8.3, range = 91–132). As a further investigation, these analyses were also performed after splitting the sample in three age-groups as described in Table 1. Finally, to test whether the different MRI measures provided unique information in explaining the variance in intellectual abilities in development, we performed multiple regressions with sex, age, cortical thickness, WM volume and FA/MD simultaneously as predictor variables.

3. Results

Descriptive data on global MRI variables for the sample in total and in each of three age groups is displayed in Table 1. To extract general factors of cortical thickness, WM volume, FA and MD, we ran four separate PCAs on the regional measures. Prior to performing PCAs the suitability of data for factor analysis was assessed. The Kaiser–Meyer–Olkin values in the four analyses ranged between .93 and .96, exceeding the recommended value of .60 and Bartlett's test of sphericity was significant in all cases, supporting the factorability of the correlation matrices. For all imaging measures, the PCA indicated a clear principal component. For cortical thickness, the first unrotated factor explained 52.9% of the variance (eigenvalue = 33.85), for WM volume 44.3% (eigenvalue = 28.37), for FA 40.2% (eigenvalue = 25.61) and for MD 51.2% (eigenvalue = 32.78). In all four analyses, nearly all regions showed large factor loadings on the first unrotated factor (number of regions with positive factor loadings >.40: cortical thickness: 58, WM volume: 63, FA: 55, MD: 62). Thus, about half of the variance in cortical thickness, WM volume, FA and MD, respectively, was shared between regions, indicating general factors of cortical structure, WM structure and WM microstructure in development. Partial correlations between these general factors and age, controlling for the effects of sex, showed a strong relationship for the cortical thickness factor ($r = -0.82$) and moderate associations for WM volume (0.47), FA (0.40) and MD (−0.46). The general factors, one for each type of MRI measure, was used in the further brain-behavior analyses.

Table 2 shows the results from four multiple regression analyses on intellectual abilities with sex, age and the general factors of cortical thickness, WM volume, FA and MD, respectively, as predictor variables. The MRI variables contributed independently of age and sex in all cases. Negative relationships were found between intellectual abilities and cortical thickness and MD, and positive for WM volume and FA. The relationships between intellectual abilities and the separate MRI variables are shown in Fig. 2 as standardized partial regression plots based on above multiple regression analyses. To complement the above cortical thickness result, we performed a multiple regression analysis on the age-normed IQ scores with sex, age and cortical thickness as predictor variables. Cortical thickness was not significantly related to IQ, but the direction of the association was still negative ($\beta = -0.12$, $p = .343$).

Next, we investigated if the relationships between intellectual abilities and brain structure vary with age. To test this we performed four multiple regressions on intellectual abilities, with sex, age, MRI measure and the interaction term MRI measure × age as predictor variables. This was performed separately with cortical thickness, WM volume, FA and MD and the results are shown in Table 3. Significant positive relationships between intellectual abilities and the interaction terms cortical thickness × age and MD × age were found, while there were negative relationships between intellectual abilities and WM volume × age and FA × age. Thus, the relationships between intellectual function and cortical structure, WM structure and WM microstructure, varied with age. To interpret these interaction effects, intellectual abilities were correlated with the MRI measures after splitting the sample in two at the median age (17.2 years), controlling for the effects of sex. Significant correlations were observed for all four measures in the group of children and adolescents (cortical thickness: −0.61, WM volume: 0.52, FA: 0.29, MD: −0.41), but not in the young adult group (cortical thickness: −0.10, WM volume: 0.18, FA: −0.03, MD: 0.06). The differences of the Fisher z-transformed correlation coefficients were tested for significance, and all correlations were significantly ($p < .05$) stronger in the group of children and adolescents. To further investigate how the relationships between intellectual abilities and brain structure vary with age, these partial correlation analyses were repeated after splitting the sample in the three age-groups (as described in Table 1). Significant correlations with intellectual abilities were observed for cortical thickness and WM volume in the youngest group (cortical thickness: −0.46, WM volume: 0.51, FA: 0.17, MD: −0.23), while no significant correlations were found in the middle group (cortical thickness: −0.17, WM volume: 0.10, FA: 0.25, MD: −0.23) or the oldest group (cortical thickness: −0.07, WM volume: 0.03, FA: −0.09, MD: 0.03).

To test whether cortical thickness and subcortical WM structure provided statistically unique information in explaining the variance in intellectual abilities in development, we performed a multiple regression analysis with sex, age, cortical thickness, WM volume and FA as simultaneous predictors. As shown in Table 4, we found significant unique contributions of cortical thickness and WM volume on intellectual abilities after controlling for the effects of sex and age, while FA only showed a tendency. An analysis with MD instead of FA as the diffusion parameter revealed significant unique contributions from cortical thickness, WM volume and MD on intellectual abilities.

4. Discussion

The present study investigated the neuroanatomical basis of intellectual abilities in development using multiple structural imaging measures. PCAs were conducted to extract general factors of cortical thickness, WM volume and WM microstructure. Intellectual abilities were negatively related to cortical thickness and MD

Table 1
Descriptive data on global MRI variables for the sample in total and in each of three age groups. Mean and standard deviation are shown for cortical thickness (weighted by area) and total white matter (WM) volume for all used regions, and fractional anisotropy (FA) and mean diffusivity (MD) for the whole white matter skeleton.

Age group	Total sample	Children	Adolescents	Adults
Age range	8.2–30.8 years	8.2–14.1 years	14.1–20.3 years	20.6–30.8 years
N (females)	168 (87)	56 (27)	56 (30)	56 (30)
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
GM thickness (mm)	2.65 (0.15)	2.80 (0.10)	2.64 (0.09)	2.51 (0.08)
WM volume (mm^3)	393500 (44881)	371625 (39362)	394925 (41374)	413948 (44044)
FA	0.491 (0.018)	0.480 (0.015)	0.495 (0.016)	0.499 (0.016)
MD (10^{-6} mm^2/s)	768.35 (23.19)	785.16 (20.87)	760.89 (20.46)	759.01 (18.60)

Table 2
Multiple regression analyses on intellectual abilities with sex, age and separate MRI measures as predictor variables. Bold characters indicate $P < 0.05$. df = 3,164.

MRI measure	Sex β (P)	Age β (P)	MRI measure β (P)	Model R^2	Model F (P)
GM thickness	−0.01 (.858)	**0.47** (<.001)	**−0.33** (<.001)	0.58	**75.81** (<.001)
WM volume	0.10 (.128)	**0.64** (<.001)	**0.25** (<.001)	0.58	**75.40** (<.001)
FA	−0.03 (.594)	**0.69** (<.001)	**0.13** (.022)	0.56	**69.35** (<.001)
MD	−0.04 (.478)	**0.66** (<.001)	**−0.18** (.002)	0.57	**72.56** (<.001)

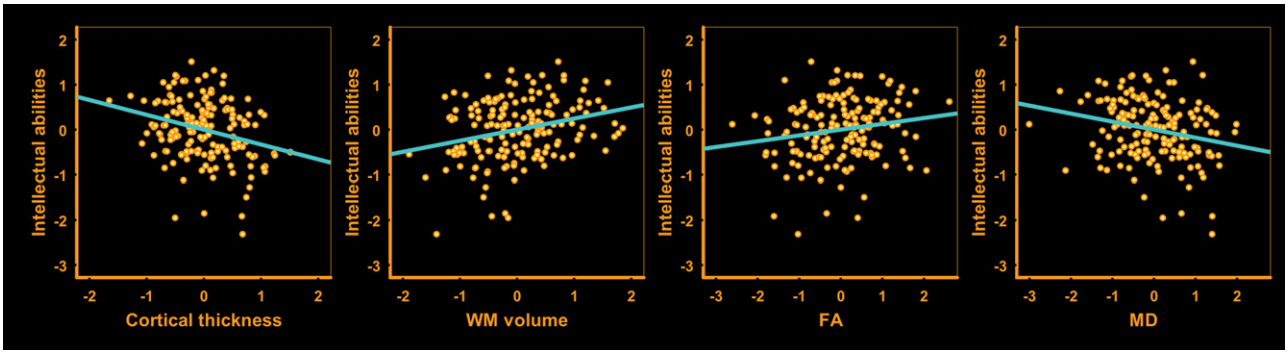

Fig. 2. Relationships between intellectual abilities and brain structure. Standardized partial regression plots based on the multiple regression analyses on intellectual abilities with sex, age and the separate MRI measures as covariates (see Table 2). All variables are shown as *z*-scores.

Table 3
Multiple regression analyses on intellectual abilities with sex, age, MRI measures and interactions terms MRI measures × age as predictor variables. Bold characters indicate $P < 0.05$. df = 4,163.

MRI measure	Sex β (P)	Age β (P)	MRI measure β (P)	MRI measure × age β (P)	Model R^2	Model F (P)
GM thickness	−0.04 (.332)	**0.65** (<.001)	**−1.18** (<.001)	**1.06** (<.001)	0.70	**93.10** (<.001)
WM volume	0.07 (.236)	**0.64** (<.001)	**0.93** (<.001)	**−0.74** (<.001)	0.64	**70.76** (<.001)
FA	−0.04 (.432)	**0.67** (<.001)	**0.63** (<.001)	**−0.52** (.001)	0.59	**57.76** (<.001)
MD	−0.06 (.211)	**0.63** (<.001)	**−0.89** (<.001)	**0.74** (<.001)	0.63	**68.80** (<.001)

and positively associated with WM volume and FA independently of age. Furthermore, the strength of these relationships varied with age. The main novel finding was that cortical thickness, WM volume and WM microstructure all accounted for unique portions of the variance in intellectual abilities in development. This is in accordance with established theories of distributed brain networks underlying intellectual function.

Cortical thickness, WM volume and DTI indices are weakly to moderately correlated in adults (Abe et al., 2008; Fjell et al., 2008) and in children/adolescents (Tamnes et al., 2010a). This suggests that the MRI measures used in the present study are sensitive to different structural properties of the brain and that they might provide complementary information about the mechanisms controlling intellectual development. Although the included imaging markers in the present study cannot be used alone to isolate the specific biological processes involved, it is likely that multiple neurobiological mechanisms support intellectual development, and several of these give rise to structural changes that can be observed with MRI. Such neurodevelopmental processes include synaptic pruning and associated reduction in neuropil and increases in axonal size and myelination, and likely lead to increased processing efficiency and specialization at the cost of reduced plasticity (Huttenlocher & Dabholkar, 1997; Yakovlev & Lecours, 1967).

A number of imaging studies have investigated structural and microstructural correlates of intellectual abilities in adults (Chiang et al., 2009; Choi et al., 2008; Luders, Narr, Thompson, & Toga,

Table 4
Multiple regression analyses on intellectual abilities with sex, age and multiple MRI measures as predictor variables. Bold characters indicate $P < 0.05$. df = 5,162.

MRI measures	Sex β (P)	Age β (P)	GM β (P)	WM β (P)	DTI β (P)	Model R^2	Model F (P)
GM, WM and FA	0.10 (.103)	**0.41** (<.001)	**−0.26** (.003)	**0.20** (.004)	0.10 (.075)	0.61	**50.96** (<.001)
GM, WM and MD	0.10 (.103)	**0.40** (<.001)	**−0.23** (.010)	**0.21** (.002)	**−0.15** (.009)	0.62	**52.90** (<.001)

2009) and in children/adolescents (Frangou, Chitins, & Williams, 2004; Ganjavi et al., 2011; Karama et al., 2009; Schmithorst, Wilke, Dardzinski, & Holland, 2005; Wilke, Sohn, Byars, & Holland, 2003), but studies combining different measures have been lacking (but see Pangelinan et al. (2011)). In the present developmental study, we found that, independently of age, intellectual abilities were negatively related to cortical thickness and MD and positively related to WM volume and FA. It is reasonable to hypothesize that such age-independent associations are mediated, at least to some extent, by developmental variability, i.e. variability among children of similar age in the phase of brain maturation (Jernigan, Baare, Stiles, & Madsen, 2011). For instance, given the pronounced cortical thinning in late childhood and adolescence, it may be that thinner cortex at a given age reflects earlier brain maturation and that cortical thickness is therefore negatively associated with intellectual abilities independently of chronological age in development. However, this needs not be the case, as subjects with thicker cortex to start with could also be those with higher ability, a conclusion supported by studies finding positive associations between cortical GM and IQ in development (Karama et al., 2009; Pangelinan et al., 2011). The complex and dynamic relationship between intellectual development and brain maturation is illustrated by Shaw et al. (2006) who observed a shift from a predominantly negative correlation between intelligence and cortical thickness in early childhood to a positive correlation in late childhood and beyond. Importantly, the present results extend previous findings by showing that the strength of the relationships between intellectual abilities and cortical thickness, WM volume and WM microstructure varies with age, with stronger associations seen in children and adolescents than in young adults. This is in line with the notion that brain structure may be more strongly related to cognitive abilities during periods of marked change than in the stable dimensions of adulthood (Van Petten, 2004).

In a longitudinal study, Shaw et al. (2006) demonstrated that children at different intellectual levels show different cortical maturational trajectories. Similarly, interactions between age and verbal intelligence on DTI measures have been reported (Tamnes et al., 2010b), indicating that the relationships between age and WM microstructure in development are modulated by intellectual abilities. The current results extend these previous findings by showing that cortical thickness, WM volume and WM microstructure (MD) each accounted for unique portions of the variance in intellectual abilities. Thus, a combination of cortical thickness and WM properties (volume and microstructure) explain intellectual abilities in development better than either measure alone, and a fuller picture of the relationship between intellectual development and brain maturation can be attained by inclusion of multiple brain characteristics.

The present results stress the importance of both cortical GM and structural properties of the connecting WM pathways for development of higher order cognitive functions. This finding adheres to the general notion that intellectual abilities rely on distributed neural networks (Deary et al., 2010; Gläscher et al., 2010; Jung & Haier, 2007). The present study was not designed to delineate the networks involved in cognitive development; rather, the main aim was to test whether principal factors for cortical structure and the underlying WM account for unique portions of the variance in intellectual abilities in a developing sample. An alternative approach would be to build a model based on theoretical knowledge. Brain regions central to intelligence likely include lateral prefrontal, cingulate, posterior parietal, and subareas of the temporal and occipital cortices, as well as WM tracts connecting these regions (Shaw, 2007). However, since the relationships between intellectual function and the different imaging measures and the allocation of shared and unique variance among them are not well established, we preferred a more global, explorative approach. A similar approach was recently employed on DTI, reaction time and IQ data from a sample of elderly (Penke et al., 2010). Note that our sample had a broad age-range and that the general intellectual abilities component therefore explained a large amount of the variance in the test scores. Furthermore, the extracted factors for cortical thickness, WM volume, FA and MD were correlated with age, especially the cortical thickness factor. It is possible that the covariance between different regions varies with age during development, and thus that the principal factor will vary somewhat across different age groups. Future studies could employ more sophisticated approaches for fusing data across multiple modalities (Groves, Beckmann, Smith, & Woolrich, 2011), for instance by extracting PCA components across different brain measures. Future studies could also investigate the regional specificity in the simultaneous relationships between intellectual abilities and GM and WM.

Some limitations must be considered in the interpretation of the present results. First, the sample scored above population mean with respect to IQ and is not representative of the full range of individual differences in intellectual abilities. As Shaw et al. (2006) have shown that developmental paths differ as a function of ability level, it is conceivable that the results would not have been identical if more children scoring in the lower parts of the normal range had been included. Second, the results were obtained by cross-sectional analyses. The links between intellectual development and brain maturation should be further investigated with longitudinal data.

In conclusion, we found that cortical thickness, WM volume and MD yield complementary information about the structural brain properties underlying intellectual abilities in development. Increased knowledge about the structural and microstructural correlates of intellectual abilities in development is important for understanding the neural basis of cognitive function and the mechanisms leading to improvement in development, and also to be able to understand the mechanisms at play in deviant development associated with neurological or psychiatric disease. Our results emphasize the importance of combining multiple neuroimaging measures.

Conflict of interest

None.

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