LETTER

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Verbal and non-verbal intelligence changes in the teenage brain

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Intelligence quotient (IQ) is a standardized measure of human intellectual capacity that takes into account a wide range of cognitive skills[1]. IQ is generally considered to be stable across the lifespan, with scores at one time point used to predict educational achievement and employment prospects in later years[1]. Neuroimaging allows us to test whether unexpected longitudinal fluctuations in measured IQ are related to brain development. Here we show that verbal and non-verbal IQ can rise or fall in the teenage years, with these changes in performance validated by their close correlation with changes in local brain structure. A combination of structural and functional imaging showed that verbal IQ changed with grey matter in a region that was activated by speech, whereas non-verbal IQ changed with grey matter in a region that was activated by finger movements. By using longitudinal assessments of the same individuals, we obviated the many sources of variation in brain structure that confound cross-sectional studies. This allowed us to dissociate neural markers for the two types of IQ and to show that general verbal and non-verbal abilities are closely linked to the sensorimotor skills involved in learning. More generally, our results emphasize the possibility that an individual's intellectual capacity relative to their peers can decrease or increase in the teenage years. This would be encouraging to those whose intellectual potential may improve, and would be a warning that early achievers may not maintain their potential.

An individual's abilities and capacity to learn can be partly captured by the use of verbal and non-verbal (henceforth performance) intelligence tests. IQ provides a standardized method for measuring intellectual abilities and is widely used within education, employment and clinical practice. In the absence of neurological insult or degenerative conditions, IQ is usually expected to be stable across lifespan, as evidenced by the fact that IQ measurements made at different points in an individual's life tend to correlate well[1,2]. Nevertheless, strong correlations over time disguise considerable individual variation; for example, a correlation coefficient of 0.7 (which is not unusual with verbal IQ) still leaves over 50% of the variation unexplained. The study that we report here tested whether variation in a teenager's IQ over time correlated with changes in brain structure. If it did, this would provide construct validity for the increase or decrease of IQ in the teenage years, because if IQ changes correspond to structural brain changes then they are unlikely to represent measurement error in the IQ tests. In addition, if verbal and performance skills change at different rates in different individuals, the neural markers for verbal and performance IQ changes could in principle be dissociated. This would overcome two of the challenges faced by previous studies of between-subject variability in IQ measures at a given time point: verbal and performance IQ are tightly correlated in individuals, so it has been hard to identify neural structures corresponding to each[3,4]; and there are many sources of between-subject variance in brain structure (for example gender, age, size and handedness) that hide the relevant differences.

Our participants were 33 healthy and neurologically normal adolescents with a deliberately wide and heterogeneous mix of abilities (see Supplementary Information for details and the implications of our sampling for the generalizability of our conclusions). They were first tested in 2004 ('time 1') when they were 12–16 yr old (mean, 14.1 yr). Testing was repeated in 2007/2008 ('time 2') when the same individuals were 15–20 yr old (mean, 17.7 yr). See Table 1 for further details of the participants. During the intervening years, there were no testing sessions, and participants and their parents had no knowledge that they would be invited back for further testing. On both test occasions, each participant had a structural brain scan using magnetic resonance imaging (MRI) and had their IQ measured using the Wechsler Intelligence Scale for Children (WISC-III) at time 1 and the Wechsler Adult Intelligence Scale (WAIS-III) at time 2 (see Supplementary Information for details). These two widely used, age-appropriate assessments[5] produce strongly correlated results at a given time point, consistent with them measuring highly similar constructs[6]. Scores on individual subtests are standardized against age-specific norms and then grouped to produce separate measures of verbal IQ (VIQ) and performance IQ (PIQ), with VIQ encompassing those tests most related to verbal skills and PIQ being more independent of verbal skills. Nevertheless, VIQ and PIQ scores are very significantly correlated with each other across participants: in our sample, the correlations between VIQ and PIQ were $r = 0.51$ at time 1 and $r = 0.55$ at time 2 (in both cases, $n = 33$; $P < 0.01$). Full-scale IQ (FSIQ) is the composite of VIQ and PIQ and is regarded as the best measure of general intellectual capacity (the *g* factor) that has previously been shown to correlate with brain size and cortical thickness in a wide variety of frontal, parietal and temporal brain regions[7,8].

The wide range of abilities in our sample was confirmed as follows: FSIQ ranged from 77 to 135 at time 1 and from 87 to 143 at time 2, with averages of 112 and 113 at times 1 and 2, respectively, and a tight correlation across testing points ($r = 0.79$; $P < 0.001$). Our interest was in the considerable variation observed between testing points at the individual level, which ranged from −20 to +23 for VIQ, −18 to +17 for PIQ and −18 to +21 for FSIQ. Even if the extreme values of the published 90% confidence intervals are used on both occasions, 39% of the sample showed a clear change in VIQ, 21% in PIQ and 33% in FSIQ. In terms of the overall distribution, 21% of our sample showed

Table 1 | Participants' details

Datum		Age	FSIQ	VIQ	PIQ
Time 1	Mean (s.d.)	14.1 (1.0)	112 (13.9)	113 (15.1)	108 (12.3)
	Min, max	12.6, 16.5	77, 135	84, 139	74, 137
Time 2	Mean (s.d)	17.7 (1.0)	113 (14.0)	116 (18.0)	107 (9.6)
	Min, max	15.9, 20.2	87, 143	90, 150	83, 124
Correlation*	*r*	—	0.792†	0.809†	0.589†
Change (time 2 − time 1)	Mean (s.d.)	3.5 (0.2)	+1.0 (9.0)	+3.0 (10.6)	−1.0 (10.2)
	Min, max	3.3, 3.9	−18, +21	−20, +23	−18, +17

* Correlation coefficient between scores at times 1 and 2. †$P < 0.01$.
$n = 33$ (19 male, 14 female). s.d., standard deviation.

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a shift of at least one population standard deviation (15) in the VIQ measure, and 18% in the PIQ measure. However, only one participant had a shift of this magnitude in both measures, and, for that participant, one measure showed an increase and the other a decrease. This pattern is reflected in the absence of a significant correlation between the change in VIQ and the change in PIQ. The independence of changes in these two measures allows us to investigate the effect of each without confounding influences from the other.

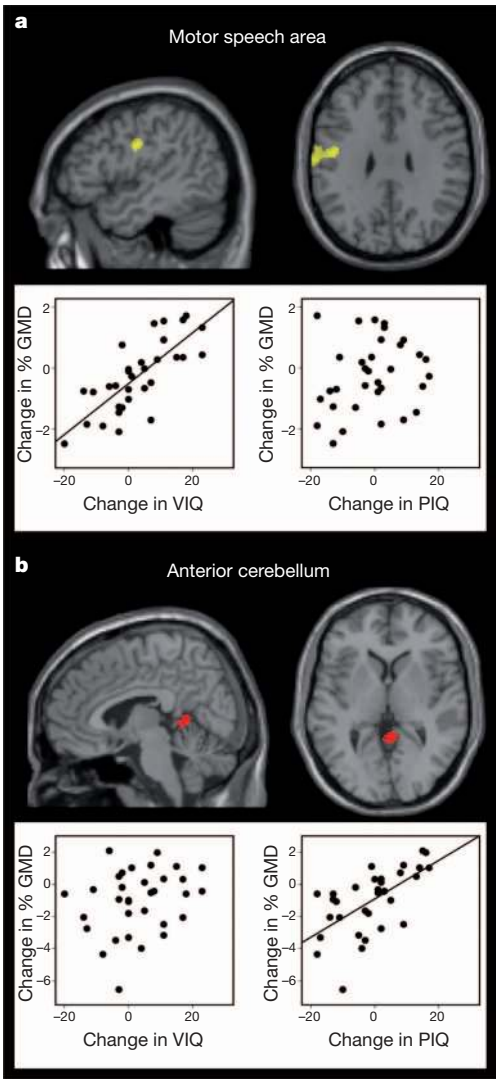

Figure 1 | Location of brain regions where grey matter changed with VIQ and PIQ. **a**, Correlation between change in grey matter density and change in VIQ (yellow) in the left motor speech region (peak in the left precentral gyrus at $x = -47$ mm, $y = -9$ mm, $z = +30$ mm, measured in Montreal Neurological Institute (MNI) space, with a Z-score of 5.2 and 681 voxels at $P < 0.001$). The corresponding effect on volume was slightly less significant (Z-score, 3.5; 118 voxels at $P < 0.001$). **b**, Correlation between change in PIQ (red) and change in grey matter density in the anterior cerebellum (peak at $x = +6$ mm, $y = -46$ mm, $z = +3$ mm, in MNI space, with a Z-score of 3.9 and 210 voxels at $P < 0.001$). Both effects were significant at $P < 0.05$ after familywise error correction for multiple comparisons in extent based on the number of voxels in a cluster that survived $P < 0.001$ uncorrected. In addition, the VIQ effect was significant at $P < 0.05$ after familywise error correction for multiple comparisons in height. The statistical threshold used in the figure ($P < 0.001$) illustrates the extent of the effects. Plots show the change in grey matter density versus the change in both VIQ and PIQ at the voxel with the highest Z-score in the appropriate region. Linear regression lines are shown for significant correlations. Changes in the motor speech region correlated with changes in VIQ but not changes in PIQ, whereas changes in the anterior cerebellum correlated with changes in PIQ but not changes in VIQ ($P < 0.001$). $n = 33$; GMD, grey matter density.

To test whether the observed IQ changes were meaningfully reflected in brain structure, we correlated them with changes in local brain structure. This within-subject correlation obviates the many possible sources of between-subject variance and may have sensitized our analysis to neural markers of VIQ and PIQ that have not previously been revealed. Given the distributed nature of brain regions associated with between-subject differences in FSIQ[7–9], regions of interest were not used in this analysis, and the results of the whole-brain analysis were only considered to be significant at $P < 0.05$ after familywise error correction in either height (peak signal at a single voxel) or extent (number of voxels that were significant at $P < 0.001$).

Using regression analysis, we studied the brain changes associated with a change in VIQ, PIQ or FSIQ (see Methods Summary for details). The results (Fig. 1) showed that changes in VIQ were positively correlated with changes in grey matter density (and volume) in a region of the left motor cortex that is activated by the articulation of speech[10]. Conversely, changes in PIQ were positively correlated with grey matter density in the anterior cerebellum (lobule IV), which is associated with motor movements of the hand[11,12]. *Post hoc* tests that correlated structural change with change in each of the nine VIQ and PIQ subtest scores that were common in the WISC and WAIS assessments found that the neural marker for VIQ indexed constructs that were shared by all VIQ measures and that the neural marker for PIQ indexed constructs that were common to three of the four PIQ measures (Table 2). This indicates that our VIQ and PIQ markers indexed skills that were not specific to individual subtests. There were no other grey or white matter effects that reached significance in a whole-brain structural analysis of VIQ, PIQ or FSIQ. See Supplementary Information for details of further *post hoc* tests.

Our findings that VIQ changes were related to a motor speech region and PIQ changes were related to a motor hand region are consistent with previous claims that cognitive intelligence is partly dependent on sensorimotor skills[13–18]. Using functional imaging in the same 33 participants performing a range of sensory, motor and language tasks, we confirmed that the left motor speech region identified in the VIQ structural analysis was more activated by articulation tasks (naming, reading and saying "one, two, three") than by semantic or perceptual tasks that required a finger press response (see Supplementary Information for details). In contrast, a region very close to the anterior cerebellum region identified in the PIQ structural analysis was more activated during tasks involving finger presses than during tasks involving articulation. Figure 2 shows these results at both the group level and the individual level. The locations of the grey

Table 2 | Correlations between grey matter density and score

	Test type	Motor speech region (r)	Anterior cerebellum (r)
Verbal tests	Vocabulary	0.284*	0.142
	Similarities	0.438†	−0.021
	Arithmetic	0.477†	0.304‡
	Information	0.314‡	0.185
	Comprehension	0.541†	0.183
Non-verbal tests	Picture completion	0.038	0.363‡
	Digit symbol coding	0.003	−0.028
	Block design	0.000	0.306‡
	Picture arrangement	0.126	0.437†

*Trend (one-tailed) at $P = 0.0545$. †Significant (one-tailed) at $P < 0.01$. ‡Significant (one-tailed) at $P < 0.05$.

Correlations were calculated using changes in scaled (that is, age-adjusted) scores in the various subtests that were common to both the WISC and the WAIS. The change in grey matter density in the motor speech region correlated significantly with changes in scores in four of the five verbal subtests, and there was a near-significant trend in the fifth but it did not correlate significantly with changes in scores in any of the four tests that comprise PIQ. Conversely, the change in grey matter density in the anterior cerebellum correlated significantly with changes in scores in three of the four tests that comprise PIQ (the exception being the digit symbol coding test, which has a particular loading on processing speed) but correlated with changes in scores in only one of the verbal tests (the arithmetic test, which probably has the smallest verbal component of the verbal tasks).

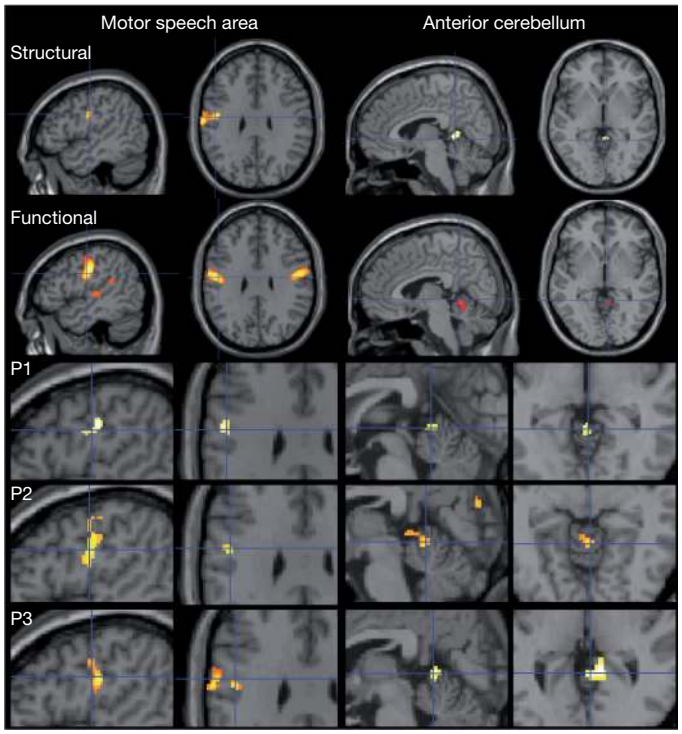

Figure 2 | Functional activations in the regions identified by the structural analysis. The motor speech region was more activated by articulation tasks than by finger press tasks ($x = -48$ mm, $y = -10$ mm, $z = +30$ mm (MNI); $t = 14.7$; $P < 0.05$ familywise-error-corrected for multiple comparisons across the whole brain), and corresponds to the region identified in the structural analysis for VIQ. These effects were consistently observed at the same coordinates for all individual subjects. In the three exemplar participants shown here (P1, P2, P3), the *Z*-scores were 3.9, 3.5 and 3.0, respectively. The anterior cerebellum region was more activated during finger presses than during articulation at both the group level (peak at $x = +6$ mm, $y = -48$ mm, $z = -4$ mm (MNI); *Z*-score, 3.7; 216 voxels at $P < 0.001$ corrected for multiple comparisons in extent) and the individual level (P1: $x = +12$ mm, $y = -48$ mm, $z = +2$ mm (MNI); *Z*-score, 3.7; P2: $x = +6$ mm, $y = -50$ mm, $z = -6$ mm (MNI); *Z*-score, 3.3; P3: $x = +12$ mm, $y = -46$ mm, $z = +2$ mm (MNI); *Z*-score, 4.9). In all cases, the activation peaks were identified from whole-brain analyses and the peak effects for the correlation with structure are illustrated with blue cross hairs in both the structural results and the functional results. This illustrates that the location of the structural effects is within the regions identified by the functional effects.

matter changes associated with VIQ and PIQ changes do not correspond to the anterior frontal and parietal regions associated with general intelligence[7] (*g* factor). It may therefore be the case that *g* remains relatively constant across ages, but changes in the ability to perform individual subtests depend on changes in sensorimotor skills. It is also notable that although completion of the subtests comprising verbal and performance measures must implicate a network of brain regions, only structural changes in regions associated with sensorimotor skills showed correlations with changes in VIQ and PIQ.

The changes in brain structure that correlated with changes in IQ allow us to explain some of the variance in terms of brain development. Specifically, 66% of the variance in VIQ at time 2 was accounted for by VIQ at time 1, a further 20% was accounted for by the change in grey matter density in the left motor speech region, with the remaining 14% unaccounted for. Similarly, 35% of the variance in PIQ at time 2 was accounted for by PIQ at time 1, with 13% accounted for by the change in grey matter density in the anterior cerebellum, leaving 52% unaccounted for. Future studies may be able to account for more of the between-subject variability by using a similar methodology with larger samples or other methodologies that measure structural or functional connectivity[8,19].

Our findings demonstrate considerable effects of brain plasticity in our sample during the teenage years, over and above normal development. By obviating the many sources of between-subject variance and controlling for global changes in brain structure, our within-subject analysis has allowed us to dissociate brain regions where structure reflects individual differences in verbal or non-verbal performance, in a way that has proved difficult in previous studies using behavioural data from a single point in time. We have also shown that the changes observed over time in the IQ scores of teenagers cannot simply be measurement error, because they correlate with independently measured changes in brain structure in regions that are plausibly related to the verbal and non-verbal functions tested. Further studies are required to determine the generalizability of this finding; for example, the same degree of plasticity may be present throughout life or the adolescent years covered by this study may be special in this regard. In addition, future work could consider the causes of the identified changes both in intelligence and in brain structure and how they impact on educational performance and employment prospects. The implication of our present findings is that an individual's strengths and weaknesses in skills relevant to education and employment are still emerging or changing in the teenage years.

METHODS SUMMARY

This study was approved by the Joint Ethics Committee of the Institute of Neurology and the National Hospital for Neurology and Neurosurgery, London, UK. All structural and functional scans at times 1 and 2 were acquired from the same Siemens 1.5T Sonata MRI scanner (Siemens Medical Systems). The structural images were acquired using a T1-weighted modified driven equilibrium Fourier transform sequence with 176 sagittal partitions and an image matrix of 256×224, yielding a final resolution of 1 mm^3 (repetition time, 12.24 ms; echo time, 3.56 ms; inversion time, 530 ms). To pre-process the 66 structural images (33 participants $\times$ 2 time points), we used SPM8 (http://www.fil.ion.ucl.ac.uk/spm) with the DARTEL toolbox to segment and spatially normalize the brains into the same template, with and without modulation. Modulated images incorporate a measure of local brain volume, whereas unmodulated images, used with proportional scaling to correct for global grey matter, provide a measure of regional grey matter density. Previous studies[20–22] have shown that the correlations between brain structure and cognitive ability are better detected by grey matter density. Coordinates for each voxel were converted to standard MNI space. Images were smoothed using a Gaussian kernel with an isotropic full-width of 8 mm at half-maximum. The relationship between change in IQ and change in brain structure was investigated by entering the appropriate pre-processed images (modulated or unmodulated grey or white matter) into within-subject paired *t*-tests, with change in IQ (VIQ, PIQ or FSIQ) and year of scan as covariates. The degree to which IQ at time 2 was predicted by changes in brain structure was investigated in a hierarchical regression analysis with IQ at time 1 entered before change in brain structure. Details of the functional imaging method have been reported elsewhere[23–25] and are summarized in Supplementary Information.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Contributions C.J.P. designed and supervised the study. C.J.P. and C.S. recruited the participants. C.S., S.R. and G.J. collected the data. F.M.R., S.R., C.E., M.L.S. and C.J.P. analysed the data. S.R., M.S.C.T. and C.J.P. wrote the manuscript and all authors edited the manuscript.

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