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Cortical surface area and cortical thickness in the precuneus of adult humans

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Abstract. The precuneus has received considerable attention in the last decade, because of its cognitive functions, its role as a central node of the brain networks, and its involvement in neurodegenerative processes. Paleoneurological studies suggested that form changes in the deep parietal areas represent a major character associated with the origin of the modern human brain morphology. A recent neuroanatomical survey based on shape analysis suggests that the proportions of the precuneus are also a determinant source of overall brain geometrical differences among adult individuals, influencing the brain spatial organization. Here, we evaluate the variation of cortical thickness and cortical surface area of the precuneus in a sample of adult humans, and their relation with geometry and cognition. Precuneal thickness and surface area are not correlated. There is a marked individual variation. The right precuneus is thinner and larger than the left one, but there are relevant fluctuating asymmetries, with only a modest correlation between the hemispheres. Males have a thicker cortex but differences in cortical area are not significant between sexes. The surface area of the precuneus shows a positive allometry with the brain surface area, although the correlation is modest. The dilation/contraction of the precuneus, described as a major factor of variability within adult humans, is associated with absolute increase/decrease of its surface, but not with variation in thickness. Precuneal thickness, precuneal surface area and precuneal morphology are not correlated with psychological factors such as intelligence, working memory, attention control, and processing speed, stressing further possible roles of this area in supporting default mode functions. Beyond gross morphology, the processes underlying the large phenotypic variation of the precuneus must be further investigated through specific cellular analyses, aimed at considering differences in cellular size, density, composition, and structural covariance compared to other brain areas.

Keywords: brain morphology; parietal lobes; surface-based morphometry; neuroanatomy

Running title: Cortical surface area and thickness of the precuneus

Introduction

The precuneus of the human brain has received much attention in the last decade (Margulies et al., 2009; Zhang and Li, 2012). For long time parietal areas have been somehow neglected in terms of comparative neuroanatomy and functional analyses, at least when compared with other cortical districts that have received more consideration through the history of neuroscience. Generally, studies have been devoted to non-human primates more than to human brain, probably because of the difficulties associated with investigating deeper cortical volumes (see Mountcastle, 1995). The precuneus is involved in integration between visuo-spatial inputs and memory, bridging somatosensory and visual cortex, and directly fading into posterior cingulate and retrosplenial areas (Cavanna and Trimble, 2006). It is a major node of main functional and structural networks of the human brain (Hagmann et al, 2008), with a relevant role within the Default Mode Network (Buckner et al., 2008; Utevsky et al., 2014). Recently, the precuneus has been shown to be also involved in the early stages of Alzheimer's disease, further evidencing the importance of these areas in processes associated with energetic and physiological balance of the human brain (Jacobs et al., 2012; Doré et al., 2013; Huang et al., 2013). The parietal elements are even more interesting considering that spatial changes associated with their size and proportions characterize the geometry of the brain in *Homo sapiens* when compared with the brain form of extinct human species (Bruner et al., 2003; 2011a; Bruner, 2004, 2010).

A recent analysis of the midsagittal morphology showed that the proportions of the precuneus are a major source of brain shape variation among adult humans (Bruner et al., 2014a). The longitudinal extension of this area generates the largest differences among individuals, and it influences the overall form of the brain. The spatial changes associated with intra-specific variation of the precuneus is strongly related to spatial changes associated with cranial differences between modern and non-modern human species, suggesting that the origin of the modern human brain morphology may be associated with form changes in these medial parietal element (Bruner et al., 2014b).

In this study, we analyze the variation of the precuneal cortical thickness (CT) and cortical surface area (CSA) in a sample of modern adult humans by using surface-based morphometry (SBM), taking into account the overall brain measurements, sexual differences, and hemispheric asymmetries. CSA and CT are associated with cellular mechanisms which genetically and phenotypically show negligible correlations (Chen et al, 2013; Panizzon et al., 2009; Winkler et al., 2010). According to the radial-unit hypothesis, CSA is primarily determined by the number of radial columns perpendicular to the pial surface, and CT is determined by the horizontal layers in the cortical columns (Rakic, 2009). Therefore, individual differences in CSA depend upon the number of these columns, and individual differences in CT depend on the number of cells within a given column. Therefore, these two variables can give a reliable quantification of factors involved in cortical volume differences. We also evaluate, by using the shape groups evidenced in our previous study (Bruner et al., 2014a), whether precuneal thickness and surface area are involved in those main shape changes. Finally, we tested whether precuneal morphological variation is correlated with a set of psychometric scores tapping cognitive functions of increased complexity, namely processing speed, attention control, working memory, and intelligence. We have previously published analyses of correlation between brain geometry and standard cognitive variables (Bruner et al., 2011b; Martin-Loeches et al., 2013). Generally, most cognitive factors do not display patent associations with brain form, although some of them (attention control and processing speed, in particular) may show weak but consistent relationships with shape changes. Taking into consideration the neuroanatomical relevance of the precuneus in terms of both functional and spatial organization, the degree of correlation between its morphology and standard cognitive scores deserves close inspection.

Materials and methods

Sample and MRI data collection

The sample includes MRI data from 104 adult individuals (45 males and 59 females; mean age and standard deviation 19.9 ± 1.7 years). Exclusion criteria included neurological or psychiatric illness, considering a history of serious head injury and substance abuse. Informed consent was obtained following the Helsinki guidelines, and the study was approved by the Ethics Committee of Universidad Autónoma de Madrid. MRIs were obtained with a 3T scanner (GEHC Waukesha, WI, 3 T Excite HDX) 8 channels coil. 3D: FSPGR with IR preparation pulse (repetition time (TR) 5.7 ms, echo time (TE) 2.4 ms, inversion time (TI) 750 ms, flip angle 12), with sagittal sections of 0.8 mm thickness, full brain coverage (220 slices), matrix 266 x 266, Field of View (FOV) 24 (isotropic voxels 0.7 cm^3).

Surface-based morphometry

MR images were submitted to the CIVET 1.1.9 pipeline developed at the Montreal Neurological Institute (Ad-Dab'bagh et al., 2006). Surface-based Morphometry (SBM) was applied for computing cortical surface area (CSA) and cortical thickness (CT), according to the following steps: 1) registration of the MR images to standardized MNI-Talairach space based on the ICBM152 template (Collins et al., 1994; Mazziotta et al., 1995; Talairach and Tournoux, 1988); 2) correction for non-uniformity artifacts using the N3 approach; 3) classification of the images in gray matter, white matter and cerebrospinal fluid; 4) generation of high-resolution hemispheric surfaces with 40.962 vertices each; 5) registration of surfaces to a high resolution average surface template; 6) application of a reverse of step 'a' allowing surface or thickness estimations in native space for each subject; (7) smoothing data using 20 mm kernel for CT and 40 mm kernel for CSA; (8) computation of surface and thickness values at each vertex (see Karama et al. 2009, 2011 for further details). Finally, we delimited the region corresponding to the precuneus in the standard template using as approximate boundaries the subparietal sulcus, the marginal branch of the cingulate sulcus, and the parieto-occipital sulcus (Figure 1), and applied a mask to compute the brain indices for the region of interest (ROI) only. This analysis was performed with the SurfStat toolbox designed for MATLAB (The Math-Works, Inc.). Mean CT and total CSA were calculated for the left and right precuneus for each subject. These absolute non-normalized volumetric values were analyzed in the sample, and regressed onto the shape vector obtained in the previous study after geometric registration and size normalization.

Psychometric tests

We also evaluated the association of precuneal shape, cortical thickness, and cortical surface area with a set of cognitive factors: 1) abstract-fluid intelligence (Gf) measures the complexity level that subjects can resolve in situations at which previous knowledge is irrelevant. Gf was measured with Raven Advanced Progressive Matrices Test (RAPM), the inductive reasoning subtest from the PMA (PMA-R), and the abstract reasoning subtest from the DAT (DAT-AR); 2) verbal-crystallized intelligence (Gc) is considered as the ability to face academic types of skills and knowledge, such reading or math. Gc was defined by the vocabulary subtests from the PMA (PMA-V), the verbal reasoning subtest from the DAT (DAT-VR), and the numerical reasoning subtest from the DAT (DAT-NR); 3) visuospatial intelligence (Gv) is involved in the construction, temporary retention, and manipulation of mental images. Gv was measured by the rotation of solid figures test, the mental rotation subtest from the PMA (PMA-S), and the spatial relations subtest from the DAT (DAT-SR); 4) working memory capacity (WMC) captures the ability for temporarily store-varied amounts of information while facing a concurrent processing requirement. WMC was defined by the reading span, computation span, and dot matrix tasks; 5) attention control was measured as the control of automatic responses (inhibition) defined by the verbal and numerical flanker tasks, along with the Simon task; 6) processing speed is usually measured by reaction time tasks (numerical, verbal and spatial) were administered in the present study. (see Colom et al., 2013 for more information on the standard psychometric tests used, as well as for a complete analysis of these variables).

Statistical analysis

For each individual, we computed the average cortical thickness and cortical surface area for the precuneus, on the left and right hemispheres (see below). Total brain values were also calculated, to quantify the allometric relationship between the brain and precuneal surfaces. Age variation is not investigated here because of the narrow age-range associated with this sample.

In a previous analysis using the same sample, we showed that the main pattern of morphological variation for the midsagittal brain section was associated with relative dilation/contraction of the precuneus (Bruner et al., 2014a). Following these results, we selected the specimens which showed the ten most extreme values along that shape vector in each direction, namely the ten individuals with the most dilated precuneus and the ten individuals with the most reduced precuneus, to test differences associated with this morphological change (herein referred to as *precuneal shape groups*).

It must be noted that our previous shape analysis was based on spatial superimposition and size normalization, through Procrustes registration. This transformation computes a translation of all the sets of coordinates onto the same centroid (mean coordinates), then performing a size normalization and a rotation as to minimize the least square difference between corresponding landmarks (Bookstein, 1991). Normalization is performed by scaling the centroid size of each set (namely the sum of the squared distances of every landmark from the centroid) to one. Shape changes are then analyzed according to the residual variation. Hence, increase or decrease of a part of the configuration must be intended in relative terms, and not necessarily as an actual size variation of that area. This is why in morphometrics the term “shape” is used only when dealing with the relative spatial organization, while the term “form” is used when dealing with shape and size components at the same time. A second limit of the method concerns the distribution of the variance, which is homogeneously weighted on the whole configuration. If some areas are more variable than others, that variation will be loaded on the entire set of coordinates. Although this does not change the underlying covariation patterns (which is the ultimate target of the study) it may however give a false perspective when interpreting strictly the observed spatial changes. For these reasons, geometrical modeling is a powerful heuristic tool, but it requires a successive evaluation of the actual anatomical changes involved. Accordingly, the axis of dilation/contraction of the precuneus described in our previous work and considered in this current study is associated with its relative proportions and not with its absolute size. This further analysis is therefore necessary to confirm whether a relative spatial dilation of this area is also associated with absolute increase of its cortical volume, and whether cortical thickness or surface area are responsible for the observed variations.

To average the effect of asymmetries on size differences, we also computed a major axis between the values of the two hemispheres, using the resulting scores along this vector as an index of average precuneal size. The resulting vector (herein referred to as *precuneal size vector*) represents an axis of precuneal size increase which optimizes the values of both hemispheres, giving an overall estimate of size.

Correlations were tested through the Pearson correlation coefficient. Group-differences were tested using ANOVA and t-Test (paired and unpaired) when using the whole sample, and Mann-Whitney test and permutations when using the extreme groups, with smaller sample size. Statistics were computed with PAST 2.17c (Hammer et al., 2001).

Results

According to the Shapiro-Wilk test, normality cannot be rejected for thickness or surface distribution values. There is no correlation between cortical thickness and surface area in the precuneus (p = 0.75). Considering the whole sample, the average cortical thickness of the precuneus is strongly correlated with the average cortical thickness of the whole brain (r = 0.81; p = 0.001). However, the mean thickness of the precuneus is slightly smaller than for the whole brain (mean 3.38 and 3.41 mm respectively; ANOVA p = 0.01; paired t-Test p < 0.001) and the value is more variable (Levene Test p = 0.01). The correlation between thickness of the two sides is moderate (r = 0.62; p = 0.0001) and the left side is thicker than the right side (p = 0.0007). Males showed larger thickness values than females (ANOVA p < 0.001).

Precuneal surface area scales with positive allometry when compared with the whole brain surface area, with a slope between 1.45 and 2.10 (95% confidence after permutation) in a log-log regression between whole brain surface area and total precuneal area (both hemispheres). Results are the same when considering the hemispheres separately. However, the correlation between total area and precuneal area is modest ($r = 0.41$; $p < 0.0001$). The correlation between the two hemispheres for precuneal cortical area is moderate ($r = 0.55$, $p = 0.0001$), and the right side is slightly larger than the left one (paired t-Test $p = 0.007$). Males have slightly larger precuneal surface area, but this difference is not statistically significant ($p = 0.10$).

Considering the two extreme shape groups (relatively enlarged/reduced precuneus) according to the shape vector reported previously (Bruner et al., 2014a), cortical thickness shows no significant differences, while precuneal cortical surface area is larger in the group with a dilated precuneus (Mann-Whitney $p = 0.008$; Figure 2).

Neither precuneal cortical thickness nor precuneal surface areas were correlated with any cognitive factor. Figure 3 shows a principal component analysis of these cognitive factors, showing the position of the individuals with the largest and smallest precuneal surface according to the precuneal size vector. Along the first axis (64% of the variance) there is an increase in the intelligence factors plus working memory, and decrease in attention control and processing speed. Note that intelligence and working memory are based on accuracy scores (higher values mean better performance) whereas attention control and processing speed are based on reaction time scores (lower values mean better performance). Therefore, greater accuracy scores are expected to covary with smaller reaction times. In the second axis (20%), all the variables increase, most notably processing speed and attention control. However this second component is already below a broken stick threshold, and therefore sensitive to random noise. The third one is even below the Jolliffe cut-off threshold, and will not be considered here. Individuals with the smallest and largest precuneus according to the precuneal size vector are scattered in this multivariate space, without any detectable differences. Although the group with a larger precuneus shows higher values along the second component (involving a generalized improvement in all the psychometric performances), such differences are not statistically significant. The result does not change when using the most extreme individuals (10 individuals per group; $p = 0.10$), a larger selection (20 individuals per group; $p = 0.72$), or the precuneal shape groups (dilated/reduced precuneus; $p = 0.68$).

Discussion

Recent studies on the functional, structural, metabolic, and evolutionary role of the precuneus have evidenced the importance of this area in several biological processes, while at the same time indicating a limited knowledge on this medial parietal element (e.g., Zhang and Li, 2012; Utevsky et al., 2014). It is important to fill this gap, supplying new data from different fields and crossing results to supply and support basic information. The current study provides information on three aspects of the precuneal morphology. First, it quantifies and compares cortical variations of the adult precuneus in terms of relative proportions, asymmetries, allometry, and sexual dimorphism. Second, it represents an essential test to investigate the differences which have been previously described as a main source of geometrical variation among individuals. Third, it considers possible correlations between precuneal morphology and a set of cognitive factors.

Precuneal cortical variation

As described in other studies on the brain cortex (e.g., Panizzon et al., 2009), precuneal surface area and thickness are not correlated. Precuneal cortical thickness is proportional to general thickness values in the brain, although it is possibly thinner and more variable than the average brain figure. Precuneal surface area scales with positive allometry when compared with the whole brain surface, and therefore larger brains generally have a relatively larger precuneal cortex. However, the substantial individual variation makes such patterns scarcely predictive. In fact, precuneal surface shows only a modest correlation with overall brain surface, suggesting relevant individual variation and idiosyncratic components associated with the morphogenesis of the precuneal area.

Comparing the hemispheres, the left side is thicker and smaller than the right side. Because of this inverse relationship between thickness and surface area of the two hemispheres, and because of the constrained spatial position of the precuneus, we can wonder whether such inverse relationships can be a consequence of spatial packing of the cortex in the deep medial areas of the brain volume, rather than an intrinsic pattern of the cortical organization. However, the scarce correlations between the values of the two hemispheres for both thickness and surface area suggest important fluctuating asymmetries, associated with local and individual factors.

Sexual differences can only be confirmed for precuneal thickness, but not for precuneal surface area. Considering that males have a larger brain size, and the positive allometry of the precuneus, a larger precuneus in this group is to be expected. We can therefore infer that any sexual difference, probably based on secondary allometric variation, is obscured by the marked individual variation.

It is worth noting that different normalization processes necessary to compare thickness and surface area may provide different results (Martinez et al., 2014). Hence, currently these analyses are useful to provide comparative information only within the same analytical context, but not to provide absolute metric values to be directly compared across studies.

Precuneal morphology

The second result of the present investigation concerns the possibility to test and evaluate the structural factors behind the large variation observed in precuneal shape among adult individuals. Our previous shape analysis revealed that geometric variation of the precuneus represents an important source of midsagittal brain differences in adult humans (Bruner et al., 2014a). According to the current results, we can state that the extreme cases of that pattern of precuneal dilation/contraction displays differences in the precuneal surface area, but not in the precuneal thickness. Hence, we can confirm that the increase in precuneal proportions associated with the principal morphological variability of the midsagittal brain section is actually associated with a change in the surface area of the precuneal cortex, and not on its thickness.

An association between shape variation and surface area is relevant for three main reasons. First, our previous shape analysis of the precuneus was computed only in the midsagittal section. In general, a midsagittal slice can only show the boundaries of one hemisphere. In contrast, here we included data for both hemispheres and asymmetries. Second, the shape analysis was computed in two dimensions, while in this study the whole precuneal morphology has been considered, in three dimensions. Third, shape analysis is based on superimposition procedures, minimizing differences and normalizing size (Bookstein, 1991). Hence, the major axis of covariance characterizing shape variation was associated with a relative increase/decrease of the precuneus, and not necessarily with differences in the absolute values. The present study shows that such relative increase/decrease is actually associated with an absolute volumetric change. Such volumetric change is not associated with increase/decrease of cortical thickness, but with variations of cortical surface area.

Cognition and function

The last result concerns the correlation between precuneal morphology and cognitive performance. The current data failed to reveal correlations between precuneal morphology and the set of considered cognitive scores. The six scores show a first component associated with increased accuracy (intelligence and working memory) and reduced reaction times (attention control and processing speed). A second component, less decisive, associates increasing intelligence and working memory with decreasing performance in attention and speed. The precuneal dimensions (thickness, surface area) and shape seem to have no correlations with any of these scores. In general, the correlation between overall brain shape and cognitive scores is scanty but, nonetheless, we found in our previous works that brain geometry shows a weak association (3% of the variation) specifically with attention control and processing speed (Bruner et al., 2011b; Martin-Loeches et al., 2013). In contrast, at least according to our current data, despite the remarkable functions of the precuneus and although its variation represents a principal source of morphological difference among individuals, its shape and size do not show any significant associations with cognitive performance. This absence of correlation is informative, taking into account that the precuneus is involved in relevant processes, including some cognitive functions tapped by the set of psychological tests and tasks completed by the participants of this study (such as visuospatial integration). Tentatively, this absence of correlation may be interpreted at least in three different ways.

First, following a functional perspective, it can be hypothesized that the relevant cognitive processes associated with the precuneus are not captured by these standard psychological factors. In this case, the functional effect of volumetric differences in the precuneus is simply not detected by this set of cognitive factors. It is worth noting that the precuneus is central to the Default Mode Network (DMN)(Utevsky et al., 2014). All our standard cognitive measures are based on specific active external-focused tasks, while the activity of the DMN is particularly expressed in absence of any task. In fact, the DMN is involved in brain intrinsic activity, defined as the “ongoing neural and metabolic activity which is not directly associated with subjects’ performance of a task” (Raichle, 2010; p.180). In this case, the interpretation of specific functional differences associated with shape and size changes in the precuneus are strictly intertwined with the functions of the DMN, and further research in this sense will be crucial.

A second hypothesis may associate the dimensions of the precuneus to non-neural factors, such as those involved in management of metabolism or other physiological balances. Increase in non-neural cells and tissues (like glia or vessels) may be in part responsible for changes in volumetric changes. Although the blood flow of the precuneus is mainly supplied by the posterior cerebral artery, this area represents the meeting point of all the other arterial territories, with the anterior cerebral artery approaching its anterior portion and the middle cerebral artery approaching its lateral parts. The complex vascular system of the precuneal area is also associated with its outstanding metabolic levels (Sotero and Iturria-Medina, 2011). Interestingly, the evolution of the modern human brain is characterized by a dilation of the parietal lobes associated with a patent increase of the parietal meningeal (Bruner et al., 2011c) and diploic (Hershkovitz et al., 1999) vascular systems. This evidence may suggest a general increase in the vascular growth factors associated with the parietal vascular network in our species, when compared with other hominids.

Third, following a structural perspective, it can be hypothesized that geometric and volumetric differences of the precuneus are passive results of "space filling adjustments" along the morphogenetic trajectory of the brain. Actually, the parietal areas are constrained between the frontal and occipital areas, and their morphology can in part be the secondary consequence of spatial and structural arrangements due to topological organization of these areas (Bruner, 2004). At least in terms of cranial evidence, there are patterns of morphological integration between parietal and occipital areas during human evolution (Gunz and Harvati, 2007). Although brain and bone patterns are not necessarily associated (Bruner et al., 2014b), also the tight structural contact between parietal and occipital lobes would suggest a degree of integration (Ebeling, and Steinmetz, 1995). The relationships with the frontal areas may be even more stringent, considering the functional relevance of the fronto-parietal system (Jung and Haier, 2007; Hetch et al., 2013). Structural covariance among brain areas can reveal functional relationships underlying the brain levels of organization (Alexander-Bloch et al., 2013), and the precuneus is a major "connector node" between brain modules (Meunier et al., 2010). Taking into consideration its marked variability and its role as a key brain hub (Hagmann et al., 2009), further quantitative and comparative studies aimed at disclosing its connections and associations in terms of form and functions are mandatory.

According to this structural hypothesis, a different organization of the cellular space can simulate patterns of dilation/contraction, and decisive information on this issue will be provided by further studies at the cellular level. In terms of cytoarchitecture, differences in cellular size, density, and composition may supply a more detailed picture of the processes behind the morphological variations of the precuneal area. Actually, cell number, density and distribution are receiving attention as major factors influencing brain organization (Azevedo et al., 2009; Herculano-Houzel, 2012; Ribeiro et al., 2013). The cytoarchitecture of the precuneus should be also considered in a comparative perspective, considering that the intraparietal sulcus, approaching the lateral extension of the medial parietal elements, has been shown to include important differences between humans and non-human primates (e.g., Vanduffel et al., 2002; Orban et al., 2006).

It is worth noting that here we have considered a large area which can actually comprise different functional parts, difficult to recognize only in terms of macroanatomy. As a matter of fact, the precuneus is part of the posteromedial cortex, a system which is highly connected with the rest of the brain, but formed by distinct modules (Parvizi et al., 2006). Hence, specific effects of more inclusive cortical elements may be masked when considering the precuneal area as a whole.

Conclusions

Because of the neuroanatomical relevance of the precuneus, basic structural information on its morphology is relevant to provide the background of future analytic studies regarding this parietal element. The present study provides two main findings. First, the principal source of midsagittal brain form variation in adult humans, namely a relative dilation of the precuneal morphology, is associated with an absolute increase of its cortical surface area. Second, such morphological differences are not correlated with general cognitive functions, as measured by standard psychometric tests. Larger brains show relatively larger precuneus, at least in terms of cortical surface area. Nonetheless, the marked individual variation and important fluctuating asymmetries make trends rather weak. The relative and absolute proportions of the precuneus due to differences on its surface area represent a principal source of individual morphological variation among adult human brains. However, such differences in the precuneus do not involve observable differences in cognitive performance. These differences might be interpreted in terms of non-neural components (vascular and metabolic managements), secondary spatial adjustments, or most probably with intrinsic brain activities associated with the Default Mode Network.

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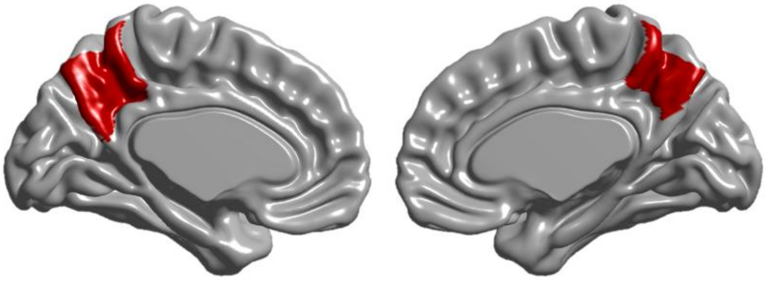

Figure 1. Template model for the precuneus. The boundary has been set approximately following the course of the subparietal sulcus, the marginal branch of the cingulate sulcus, and the parieto-occipital sulcus.

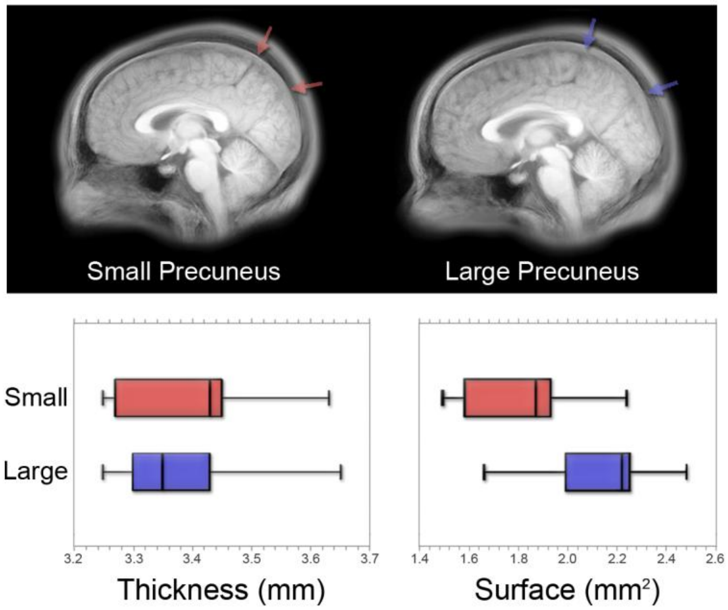

Figure 2. In a previous analysis we showed that the principal source of midsagittal morphological variation in the adult brain is the relative proportions of the precuneus (Bruner et al., 2014a). According to this shape vector, from that previous study we selected ten specimens with higher and ten specimens with lower values along this component. The image shows the average superimposed specimens with reduced (left) and dilated (right) precuneus (the arrows show the anterior and posterior limits of the precuneus, namely the marginal branch of the cingulate sulcus and the parieto-occipital sulcus). The boxplots show median, interquartile, and range, for precuneal cortical thickness and surface area in both groups: the phenotype with larger precuneal proportions is associated with larger precuneal surface but not thicker precuneal cortex.

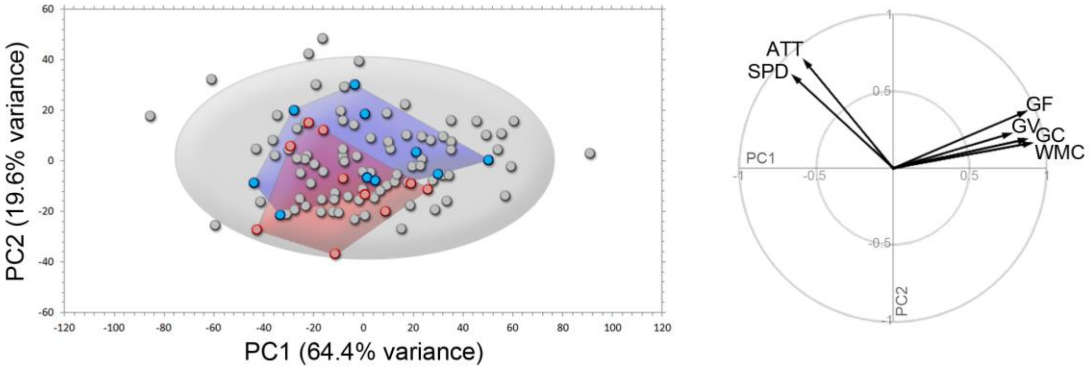

Figure 3. Principal component analysis of the six composite cognitive factors. First principal component explains 64% of the variance, being associated with an increase in intelligence scores (GF: fluid intelligence; GV: spatial intelligence; GC: crystallized intelligence) and working memory (WMC), and decrease in attention (ATT) and mental/processing speed (SPD). Note that intelligence and working memory scores are based on accuracy whereas attention and speed are based on reaction times. The second component explains 20% of the variance, being associated with an increase in all the variables, particularly attention and mental speed. Individuals with a small precuneus (red) and large precuneus (blue) according to a precuneal size vector overlap with the rest of the sample, although the latter group displays a minor and not significant shift toward higher values of the second component.