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Original Article

Growth and development of the precuneus in humans from birth to early adulthood

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The precuneus is a main node of the brain organization, and it is crucial to autonoetic consciousness, body awareness, imagination, and the construction of the self. In humans, it displays a remarkable individual variation, which functional consequences are not yet known. Comparative analyses suggest that the expansion of these areas may have had an evolutionary relevance in *Homo sapiens*. In this study, we analyzed the MRI scans of 220 individuals ranging from birth to early adulthood, to investigate the morphological changes of the precuneus along ontogeny. Size changes are only detected between birth and 2–3 years of age. In terms of shape, there is a minor increase in dorsal expansion in the same period, although the mean effect is moderate, and general trends are obscured by the pronounced variability. The remarkable individual differences in precuneus morphology are already established at birth. The dorsal extension is a major determinant of such variability in all age groups, although the analysis reveals multiple factors involved. Importantly, the dorsal and ventral regions of the precuneus are largely independent. Longitudinal studies will be necessary to test the details of its morphological changes through ontogeny, as well as surveys investigating its development in prenatal stages.

Keywords: human brain morphology; ontogeny; restrosplenial cortex; shape analysis; superior parietal lobule.

Introduction

The precuneus is generally defined as the medial region of the parietal lobe, and it has a crucial role in integrating somatic and visual information (Cavanna and Trimble 2006; Margulies et al. 2009; Zhang and Li 2012). In terms of cytoarchitecture, it is an extension of the superior parietal lobule, which is divided into an anterior, middle, and posterior area (Scheperjans et al. 2008). Its inferior region fades instead into the posterior cingulate and retrosplenial cortex, without a defined anatomical boundary. After a general labelling as area 7 in Brodmann's map, it was lately divided into an anterior (somatic) and a posterior (visual) region, subsequently interposed by a middle associative area involved in executive functions, and possibly with up to three additional ventral zones (Yamaguchi and Jitsuishi 2024). Despite the different proposals concerning its parcellation, all schemes agree in interpreting the precuneus morphology as the result of two gradients: a longitudinal one blending somatic and visual information, and a vertical one integrating this visuospatial information with egocentric and episodic memory (Jiang et al. 2023; Bruner 2024; Yamaguchi and Jitsuishi 2024). This double gradient is also expressed by the organization of the laminar features: two (antero-posterior) cortical types above the subparietal sulcus, and 3–4 (dorso-ventral) types below, shifting from eulaminate (above) to agranular (below) cortex (García-Cabezas et al. 2020).

In terms of connectivity, the precuneus represents a central node of brain structure and function, bridging the default mode network with body awareness and attention (Hagmann et al. 2008; Van Den Heuvel et al. 2010; Cunningham et al. 2017; Herbet et al. 2019; Tanglay et al. 2022; Jitsuishi and Yamaguchi 2023). It is a crucial element of dual default mode network systems involved in episodic memory and theory of mind (Dadario and Sughrue 2023), and of a parietal memory network involved in broad memory processing (Gilmore et al. 2015). All these aspects are key integrative functions of the multiple domains that support human cognitive specializations (Laland and Seed 2021).

The morphology of the precuneus displays an outstanding degree of variation in adult humans, mostly in its dorsal longitudinal extension, associated with the amount of cortical surface area and a complex sulcal pattern (Bruner et al. 2014, 2015, 2017a; Pereira-Pedro and Bruner 2016; Bruner and Pereira-Pedro 2020).

Importantly, the precuneus is disproportionately larger in humans than in nonhuman primates. In macaques, it is posterior to area 31, and it is involved in visuospatial cognition, mainly connected with the intraparietal sulcus, inferior parietal lobule, visual cortex, and retrosplenial region (Passarelli et al. 2018). In humans, in contrast, it is expanded dorsally, suggesting that it may be involved in derived cognitive aspects associated with the evolution of our species (Bruner et al. 2017b). The globularity of the modern human head has been in fact hypothesized to be in part due to the development of large parietal lobes (Pereira-Pedro et al. 2020; Bruner et al. 2023). Nonetheless, there is disagreement on whether such derived globular morphology of the braincase

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Table 1. Samples.

Sample	Age range (years)	N	Ref.
Baby Connectome Project	0-2	35	Howell et al. 2019
Calgary Preschool Project	2-6	53	Reynolds et al. 2023
Child Healthy Brain Network	7-17	76	Alexander et al. 2017
Queensland Twin Imaging	18-29	56	Strike et al. 2022

Table 2. Age groups.

	Label	Age range (years)	N
Infancy	INF	0-2	44
Childhood	CHI	3-6	44
Juvenile	JUV	7-12	44
Adolescence	ADO	13-19	44
Early adult	EAD	20-29	44

is attained before or after birth (Gunz et al. 2010; Ponce De León et al. 2016).

In this study, we analyze the morphological variations of the human precuneus in MRI samples ranging from birth to adulthood, to consider whether it displays gradual or discrete changes through growth (size changes) and development (shape changes), and which developmental stages are relevant for generating the phenotypic intra-specific differences.

Materials and methods

In this survey, we employed MRI scans from four different sources (Table 1), with a total sample of 220 individuals (104 males and 116 females). Subjects were divided into five age groups (Table 2), according to the general nomenclature for the human life cycle (Bogin and Smith 1996, 2000). For each subject, after a proper alignment of the brain with the sagittal plane, we selected the parasagittal slice that displays the most comprehensive view of the precuneus (left hemisphere only). On this slice, we measured the following chords (Fig. 1a): brain length (BL: the maximum diameter from the frontal to the occipital pole); brain height (BH: the chord between the bottom of the cerebellum and the central sulcus); precuneus anterior height (PAH: the chord length of the marginal sulcus); precuneus middle height (PMH: the chord from the central point of the subparietal sulcus to the top of the precuneus); precuneus posterior height (PPH: the chord length of the perpendicular fissure); precuneus dorsal length (PDL: the dorsal chord between the postcentral sulcus and the perpendicular fissure); and precuneus ventral length (PVL: the length of the retrosplenial region). Differences between age groups and sexes have been tested through the Mann–Whitney test ($P < 0.05$) after Bonferroni correction.

We further investigated the precuneus shape by using a 2D model based on 30 landmarks (Fig. 1b). Anatomical landmarks include the anterior and posterior points of the dorsal boundaries (dorsal endpoint of the marginal sulcus and dorsal endpoint of the perpendicular fissure, respectively), the anterior margin of the *tentorium cerebelli*, the posterior margin of the splenium, and the inferior end of the marginal sulcus (see Bruner et al. 2014). All the other landmarks along the boundaries of the precuneus are semilandmarks positioned at equally-spaced intervals between these anatomical references. We also added a central landmark at the most central region of the subparietal sulcus, to separate the dorsal region of the precuneus (precuneus *sensu stricto*) from the ventral region (fading into the retrosplenial and posterior cingulate areas). Shape analysis was computed according to the principles of geometric morphometrics (Slice 2007; Mitteroecker and Gunz 2009; Cooke and Terhune 2015; Mitteroecker and Schaefer 2022). Coordinate systems of all the subjects have been registered through Procrustes Superimposition, which includes translation to a common centroid, scaling to unitary centroid size, and rotation to minimize the least-square differences between corresponding landmarks (Zelditch et al. 2012). Shape variation and shape differences have been investigated through Principal Component Analysis and Discrimination Analysis, computed on the covariance matrix of the shape coordinates. Tentatively, we also computed a modularity analysis taking into account the contiguity of landmarks. Following the Delaunay triangulation as adjacency model, the two-module partition with minimum covariation was calculated by using the RV coefficient as proxy of independence between blocks (Klingenberg 2009). Taking into account that the current configuration is largely based on outline semilandmarks and not on homologous references, this analysis must be intended as exploratory. Landmarks were sampled with tpsDig 2.32 (Rohlf 2017) and statistics was performed with MorphoJ 1.08.01 (Klingenberg 2011) and PAST 4.05 (Hammer et al. 2001).

Results

Traditional metrics

Table 3 shows the correlations between the brain chords, and the corresponding p-values. Along the whole ontogenetic series, there is a good correlation among the three precuneus heights ($R_{mean} = 0.60$), which have instead a modest correlation with the

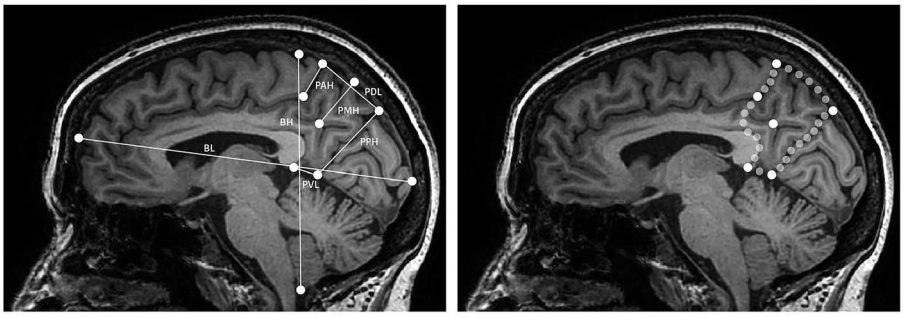

Fig. 1. a) Chords used for traditional metrics and b) landmark model employed for the shape analysis. See text for labels and definitions.

Table 3. Correlations (R/p).

		BL	BH	PAH	PMH	PPH	PDL	PVL
Brain size	BL		1.65E-72	9.55E-20	6.13E-20	2.66E-24	2.46E-16	7.20E-07
	BH	0.88		3.40E-24	5.30E-25	3.81E-25	2.71E-20	3.55E-05
Precuneus heights	PAH	0.56	0.61		3.66E-26	5.83E-18	1.77E-07	1.02E-03
	PMH	0.56	0.62	0.63		1.87E-25	5.15E-08	6.03E-04
	PPH	0.62	0.62	0.54	0.63		6.45E-06	5.60E-01
Precuneus lengths	PDL	0.52	0.57	0.34	0.36	0.30		3.60E-01
	PVL	0.33	0.27	0.22	0.23	−0.04	0.06	

dorsal length ($R_{mean} = 0.33$). Heights display a poor (PAH, PMH; $R_{mean} = 0.22$) or no (PPH) correlation with the ventral length. Ventral length is not even correlated with the dorsal length. All chords display a good correlation with the BL and height ($R_{mean} = 0.59$), except for the ventral length, for which the correlation is moderate ($R_{mean} = 0.30$). The correlation between BL and PDL shows an increase of variation for the latter chord at larger brain size (Fig. 2a). A log–log regression, nonetheless, displays a slope of 0.99 (CI: 0.79–1.20), suggesting isometry. Comparing the precuneus metrics between the age groups, the only significant difference in all cases can be detected between the infants and all the other groups (see Fig. 2b; all the other variables display a similar pattern). The exception is the PVL, for which the only significant difference is between infancy and adolescence. In this case, the lack of statistical differences between infants and adults is probably due to the large overlap between groups, and a subtle mean decrease in PVL for the adult group when compared with the preceding ones. Nonetheless, the overlap of all the groups is consistent for all the variables, and the effect is poor.

Plotting the chords against age, we can observe in all cases an abrupt increase until 3–5 years of age, followed by a plateau (Fig. 2c and d). The boost is strictly associated with the first age group (0–2 years). There is, nonetheless, a pronounced individual variability. There is no correlation between the relative precuneus dorsal length (PDL/BL) and age ($P = 0.18$), suggesting that the longitudinal proportion of the precuneus, namely its length relative to the BL, does not change with age. Sexual differences for all these chords are not significant.

Shape analysis

A Principal Component Analysis of the shape coordinates found five components with eigenvalues above the threshold of random variation, which also explain more than 5% of the total variance each (Fig. 3). Nonetheless, the first component is dominant, explaining 37% of the whole variance. This shape vector is associated with the dorsal longitudinal expansion/reduction of the precuneus. The following four vectors are associated with the expansion/reduction of the anterior ventral region, of the retrosplenial region, of the subparietal region, and with the curvature of the perpendicular fissure, respectively. The correlation between shape and age is significant ($P = 0.01$) but negligible, explaining only 1.5% of the variance. This age-related shape vector is similar to PC4. In fact, when considering the first five PCs separately, age displays a minor correlation with PC4 ($P = 0.003$; $R = 0.20$) and PC5 ($P = 0.04$; $R = -0.14$). A Discriminant Analysis between the sequential age groups is significant only when comparing adolescents with adults (T-square permutation tests < 0.0001), with the latter group displaying a subtle reduction of the ventral proportions, as observed in PC2. The correlation between shape variation and brain size (brain length and width) is significant ($P < 0.0001$), but each of these variables explains a very minor part of the geometric differences (3.4%), through a minor dorsal expansion, as observed in PC1. In fact, BL and PC1 display a low but significant correlation ($R = 0.24$; $P = 0.0003$). The dorsal chord of the precuneus, associated with PC1, explains 26% of the total shape variance, while the PMH explains only 2.4% of the shape differences. There are no sexual differences in the overall shape or the first five shape components.

There is a slightly significant difference for PC1 between infants and juveniles ($P = 0.02$), adolescents ($P = 0.06$), and early adults ($P = 0.03$), but these differences are no longer significant after Bonferroni correction. Although this difference generates a slight increase in PC1 (dorsal extension) from the first to the third age group (see Fig. 3), the effect is minor, and the individual variation is extremely large. A correlation between age and PC1 within the first age group only (infants) is not even significant ($P = 0.44$).

Analyzing the whole covariation pattern, the best two-module partition according to a contiguity criterion separates the dorsal and the ventral regions (Fig. 4). In particular, the ventral block includes the subparietal region and a large part of the anterior border, while the dorsal block includes most of the posterior (occipital) border.

Discussion

Morphological changes and ontogeny

The precuneus displays, in adult humans, a noticeable individual variability, mostly considering its dorsal extension and the folding pattern (Bruner et al. 2014, 2017a; Pereira-Pedro and Bruner 2016). In terms of functions, the dorsal region integrates the somatic and visual information, supplying a key reference to the default mode network that is essential to the construction of self and consciousness (Northoff and Bermpohl 2004; Cavanna 2014; Freton et al. 2014; Darby et al. 2018; Bruner 2023; Lyu et al. 2023). The remarkable individual variation is associated with an increase/decrease in the cortical surface area and, therefore, should be associated with a corresponding cognitive diversity that, at present, has not been sufficiently investigated (Bruner et al. 2015). The present survey is aimed at analyzing the morphological changes of the precuneus through ontogeny, namely from birth to early adulthood, to give a quantitative view of its growth and development.

Concerning growth (changes in size), the current data show that the precuneus displays a standard pattern shared with most brain metric variables (including BL), in which the main increase is associated with the first 2 years after birth (Neubauer et al. 2009; Neubauer and Hublin 2012). Apparently, the diameters of the precuneus do not experience major changes after that. A general growth model applied to the whole database suggests a plateau after 5 years, but the exponential growth is, in this case, largely associated with the infant group (0–2 years). Actually, a

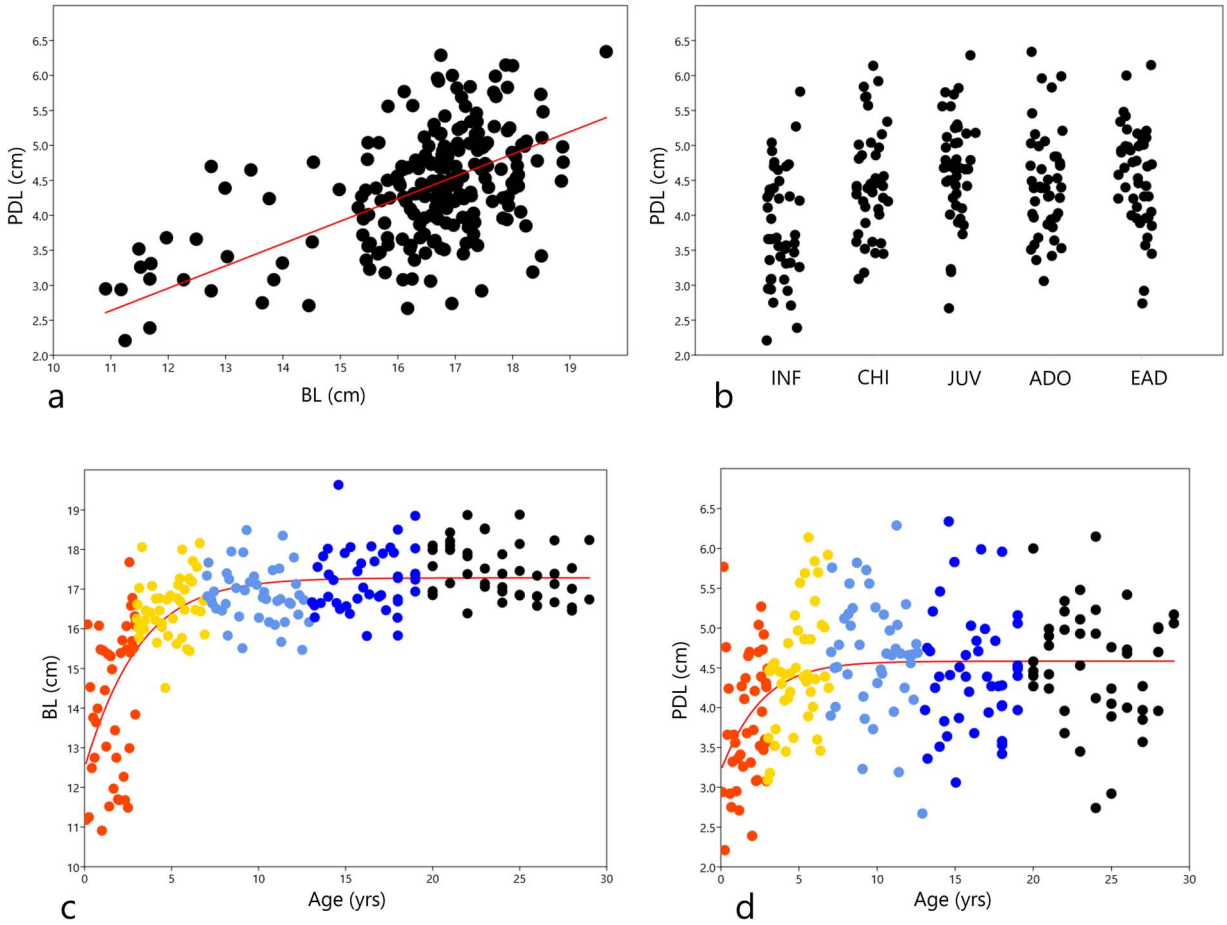

Fig. 2. a) Correlation between brain length (BL) and precuneus dorsal length (PDL), with major axis regression fit (red); b) jitterplot for the values of the precuneus dorsal length for each age class; c and d) age changes for brain length and precuneus dorsal length for infants (orange), children (yellow), juveniles (light blue), adolescents (dark blue), and adults (black), with Gompertz growth model fit (red curve; Sadeghi et al. 2013).

recent comprehensive analysis suggests that gray matter volume does increase until 6 years, although the parietal cortex peaks two years before this maximum (Bethlehem et al. 2022). Our results are in agreement with this general scenario.

Concerning the precuneus shape, instead, three major conclusions could be evidenced, namely on its ontogenetic changes, on the establishment of its morphological diversity, and on its patterns of integration.

About shape variation from birth to adulthood, these results suggest that precuneus changes are, on average, not noticeable. The increase of the dorsal length looks isometric with the general increase of the brain length. The main feature associated with its morphological variation, namely the dorsal longitudinal expansion, displays nonetheless a minor increase in the first age class (0–2 years), reaching a plateau in the following group (3–6 years). This change is, however, not consistent, and a clear statistical trend is largely obscured by the pronounced individual variability.

It is worth noting that the geometry of a given cortical element is not only due to its growth and development, but also to its topological environment, namely the spatial influences of the neighboring elements (Rasskin-Gutman and Esteve-Altava 2014). In the case of the precuneus, its medial position makes it sensitive to multiple structural influences, especially in its ventral region (Schuurman and Bruner 2023). The fact that its gross shape does not follow a consistent pattern of change after birth may suggest that the spatial arrangement of the whole posterior parietal region might be settled as well.

Some subtle age changes should, however, be discussed further. The fourth and fifth shape components display a slight correlation with age, concerning the curvature of the anterior and posterior boundaries, respectively. As mentioned above, these changes can be associated with intrinsic variations (changes of the precuneus histological elements) or else with extrinsic factors (expansion or readjustments of the frontal and occipital regions, respectively). Taking into consideration the position of the precuneus, constrained between the anterior and posterior cerebral districts, this latter case looks reasonable, although pending confirmation through more targeted analyses. Nonetheless, all these changes have, on average, a minor effect, and the pattern is negligible when the remarkable individual variability is taken into account. Therefore, these minor trends can suggest some underlying biological factors, but are not sufficient to reveal consistent ontogenetic schemes.

The second general conclusion concerns the pronounced individual variability of the precuneus, due to its dorsal longitudinal extension. The current study clearly suggests that this large variability is common to all the age groups and, importantly, already established at birth. Most individual differences in gross proportions, therefore, should be determined before birth,

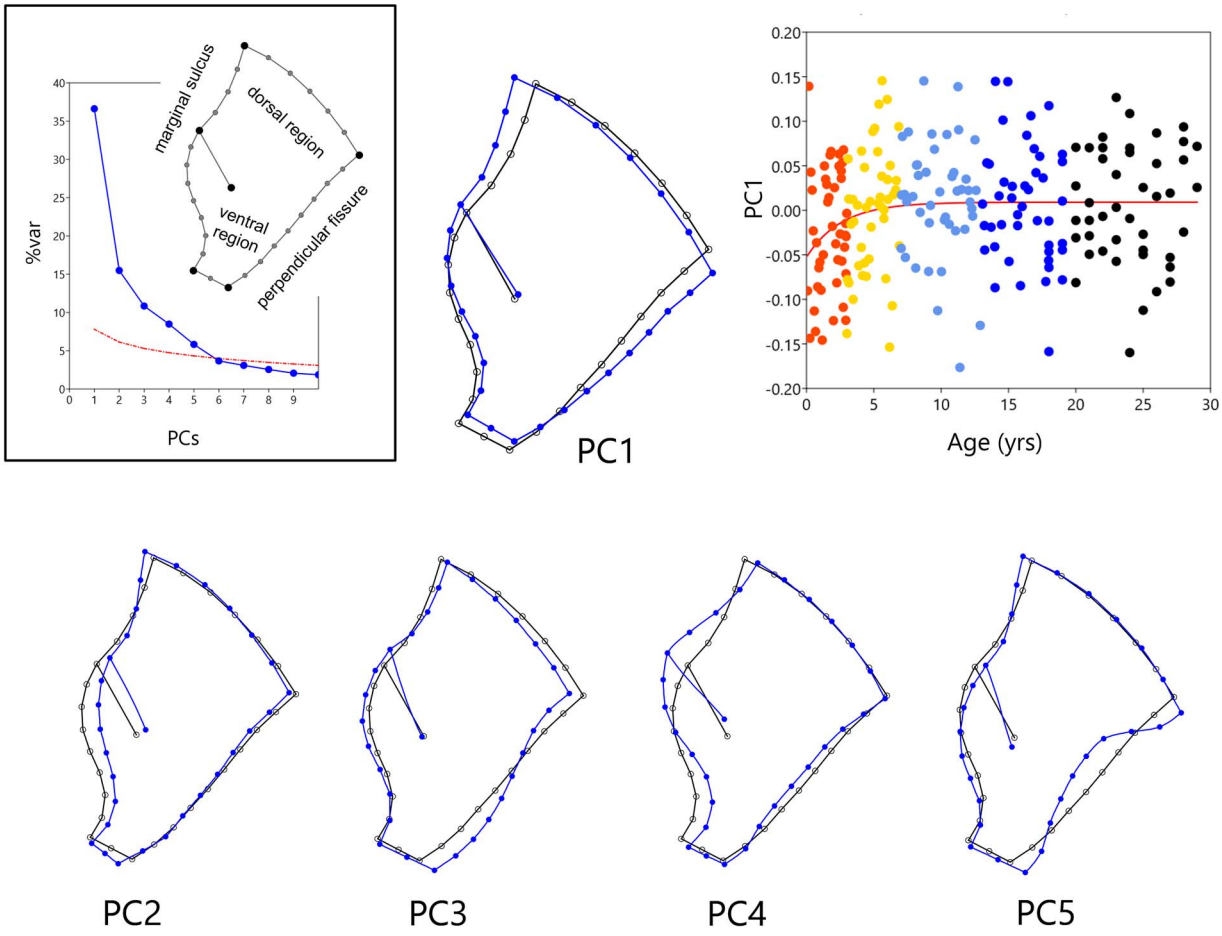

Fig. 3. In the box (top left), the scree plot from the Principal Component Analysis of the shape coordinates (showing the eigenvalues of the first components and the threshold of random variation—red curve), and the wireframe used to display the shape components (black dots: anatomical landmarks). The wireframes show the shape changes associated with the first five vectors (PC1–PC5). The plot shows the correlation between age and PC1 (colors as in Fig. 2; red line: growth model).

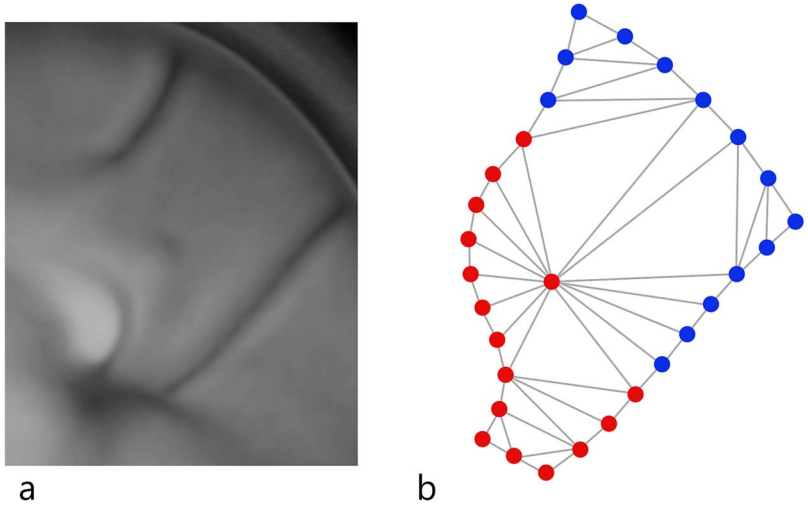

Fig. 4. a) The whole MRI sample superimposed after Procrustes registration, showing the mean morphology and variability of the precuneus. b) The two modules (blue and red) identified according to the contiguity principle.

and influenced by the genetic background and/or environmental intrauterine factors.

An additional note should be provided on a minor result of this study: the slight reduction of the ventral and retrosplenial region in the adult group. This region displays a noticeable topological complexity, in terms of spatial relationships, heat management, and vascular supply (Bruner 2022; Schuurman and Bruner 2023; Bruner and Jacobs 2024). Importantly, it experiences a progressive reduction in normal aging and neurodegenerative diseases (Karas et al. 2007; Bruner et al. 2025). This survey suggests that this

reduction can begin in early adulthood, although more data are necessary to test this specific hypothesis.

Morphological integration

The third conclusion provided by the current results deals with the morphological integration of the precuneus. The shape analysis reveals at least five different shape components. That is, there are up to five important determinants of the precuneus geometry, and this suggests a low level of integration. In fact, when an anatomical element is strongly integrated, its variation is explained by a smaller number of factors (Wagner 1984). The scarce integration, and the influence of several distinct factors, can explain the outstanding variability of this cortical region, which can indeed be parceled into several distinct areas associated with different structures and functions (Scheperjans et al. 2008; Glasser et al. 2016; Luo et al. 2020; Yamaguchi and Jitsuishi 2024). Nonetheless, this survey shows that the dorsal extension of the precuneus remains the key factor determining most of the individual differences, in all ages. The first principal component, associated with dorsal extension/reduction, is definitely dominant, explaining 37% of the morphological differences. In adults, this component explains 25%–30% of the variance (Bruner et al. 2014, 2017a). In this ontogenetic sample, the dorsal chord alone explains in fact 26% of the morphological differences, while the dorsal height only accounts for 2% of the variation. This result points once more to the importance of the dorsal extension of the superior parietal lobule when dealing with individual brain differences. Noticeably, the dorsal parietal region has been identified as the pole of the third spatial gradient associated with the topological organization of the human brain, preceded only by the vertical (dorsoventral) and longitudinal (anteroposterior) developmental axes (Vogel et al. 2024). Also, the precuneus heights are much more correlated and integrated than the precuneus lengths which, furthermore, are not even correlated with each other. This scenario is well summarized by the modularity analysis that, although exploratory, supports a morphological independence between the dorsal part (including most of the occipital boundary) and the ventral part (including the boundaries with the cingulate and marginal regions).

We can therefore explain the remarkable individual variation of the precuneus mainly as the result of these two factors: the noticeable variation of the dorsal region, and the independence (lack of integration) between dorsal and ventral regions. This last aspect is also important because the term "precuneus" is often used to describe the whole medial extension of the parietal lobe. Instead, despite the smooth and blurred boundaries, the dorsal and the ventral regions are associated with different functions and topological organization. Averaging these two parts in structural and functional analyses could be, therefore, misleading. The term *precuneus* should be limited to the region above the subparietal sulcus (eg Yamaguchi and Jitsuishi 2024), eventually considering its continuity with the rest of the superior parietal lobule (Scheperjans et al. 2008). It is worth noting that a proper knowledge of the morphological variation of the precuneus is also relevant in neurosurgery, taking into account the central position of this cortical element in many parietal surgical treatments (Dziedzic et al. 2021).

Cognition and evolution

At present, it is not clear whether the morphological variation of the precuneus can be associated with functional or cognitive differences, although it is related to the amount of cortical surface area (Bruner et al. 2015). Concerning nonhuman primates, most of the available information concerns macaques, in which the precuneus is defined as an area (PGm or 7m) involved in visuospatial cognition, particularly connected with the intraparietal sulcus, inferior parietal lobule, visual cortex, and restrosplenial region (Passarelli et al. 2018). The latter is a key node for the limbic system and episodic memory, bridging working memory with long-term memory (Kobayashi and Amaral 2000, 2003). A smaller anterior region (area 31) is more specialized for somatomotor planning, and connected with the anterior cingulate cortex (Passarelli et al. 2018). In humans, area PGm is likely to have expanded as the dorsal part of the precuneus, while area 31 becomes the dorsal region of the posterior cingulate cortex. The expanded human precuneus is further subdivided according to an antero-posterior (somato-visual) axis and a dorso-ventral (visuospatial-episodic) axis, generating an elaborate cortical map (Yamaguchi and Jitsuishi 2024) which is reflected by different laminar features (García-Cabezas et al. 2020).

The remarkable individual variability of the precuneus, described in this study since the earliest postnatal stages, is largely due to the dorsal region, which is expected to be an integrative node for somatic and visual information (Cavanna and Trimble 2006; Margulies et al. 2009; Zhang and Li 2012; Luo et al. 2020). This integration is crucial to many complex cognitive levels, including autobiographical memory, working memory, and self-construction (eg Wallentin et al. 2008; Freton et al. 2014; Yeager et al. 2022). In particular, both the intra-specific and inter-specific variations are spatially localized in the anterior areas of the dorsal region, in terms of both dimensions and sulcal complexity (Bruner et al. 2017a, 2017b). These areas are those especially involved in body awareness and the construction of the self (Herbet et al. 2019; Lyu et al. 2023). It is expected that a larger cortical proportion (ie relative volume) dedicated to somatic and visual association could trigger more elaborated levels of visuospatial integration. It can also be hypothesized that an increased complexity in the regions involved in body awareness and self-perception can influence key functions associated with consciousness and attention. However, the evidence in this sense is still insufficient to consider this aspect in detail when dealing with individual differences. Taking into account the outstanding morphological variability observed at the dorsal precuneus, this topic surely merits further attention, especially when considering that, beyond a minor postnatal expansion, most of its diversity might already be established at birth.

Beyond the considerations on brain development, these results may also add to some evolutionary hypotheses associated with the evolution of *H. sapiens*. The precuneus is larger in humans than in apes, and it displays a more complex sulcal pattern in our species (Bruner et al. 2017b; Willbrand et al. 2023). The dorsal parietal regions also look more expanded in modern humans when compared with extinct hominids (Pereira-Pedro et al. 2020), and this might contribute to the globularisation observed in the modern human brain in the last 50–100,000 years (Neubauer et al. 2018). However, there is a disagreement on whether such a derived modern human feature is associated with a postnatal stage (Gunz et al. 2010; Ponce De León et al. 2016). The current analysis suggests that, although a minor precuneus expansion can be detected in the earliest years of life, the remarkable individual variability is already established at birth, and the contribution of this region to the overall brain globularity may be hence distributed through the perinatal period (that is, including both pre and postnatal changes).

Limitations of the study and future research

This study has three major limitations that should be considered. First, because of the extensive age range considered here, we relied on different samples, produced with different protocols and scanning parameters. This limitation is common for ontogenetic studies that require a large chronological span to be evaluated. Therefore, the results presented here could be further validated by using scans obtained from the same imaging protocol, as to limit possible inter-sample bias, and reduce eventual noise. Nonetheless, in this study, we have evaluated macroscopic features (ie the boundaries of the precuneus) that are easily recognizable through any magnetic resonance protocol. Furthermore, the sampling procedure (ie landmarking) employed in this study is not automated, but manual, and based on visual inspection, and else not sensitive to different scanning parameters. Finally, there is a good correspondence between the shape analysis performed here and those from previous surveys relying on adult samples (eg Bruner et al. 2014, 2017a). All these considerations suggest that, although using different samples is not an optimal choice, the noise introduced by this limitation would not substantially influence the general results. Of course, the similarities and differences described here between birth and adulthood only deal with the general shape of the precuneus, and we must assume that, during ontogeny, there are variations that go beyond the gross geometrical aspects, even in some anatomical aspects. For example, as frequently occurs with newborns and infants, the sulcal morphology of the precuneus appears more compact and convoluted in these early ontogenetic stages. At the same time, MRI scans from infants generally display a reduced quality when compared with other stages, because of methodological restrictions associated with these subjects. Probably, high-quality images from newborns can be used to further validate and extend the current results, adding specific information on the ontogeny of the sulcal variations.

The second limitation deals with the fact that this analysis only considers the sagittal morphology, in two dimensions. However, previous works suggested that the lateral extension of the precuneus is low when compared with the noticeable sagittal variability (Pereira-Pedro and Bruner 2016). Nonetheless, it is true that the precuneus also shows a coronal variation which is independent of the sagittal extension (Bruner and Pereira-Pedro 2020) and, although it is less pronounced, following analyses should consider this aspect further. In this case, however, the whole superior parietal lobule should probably be taken into account, because of the histological continuity between these regions (Scheperjans et al. 2008).

The third limitation concerns the fact that this study is based on transversal samples (different groups with different ages), and not longitudinal ones (the same group analyzed at different times). The fact that the ontogenetic patterns are elusive, and that most of the individual differences are already established at birth, makes longitudinal samples necessary to describe with more precision the subtle postnatal changes. Of course, this study also evidences the need for surveys on prebirth stages, which are mandatory to investigate further the developmental patterns of the parietal lobes.

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Author contributions

Emiliano Bruner (Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Writing—original draft), and Rafael Gallareto-Sande (Data curation, Formal analysis, Resources, Software, Writing—review & editing)

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References

Alexander LM et al. 2017. An open resource for transdiagnostic research in pediatric mental health and learning disorders. *Sci Data*. 4:170181. https://doi.org/10.1038/sdata.2017.181.

Bethlehem RAI et al. 2022. Brain charts for the human lifespan. *Nature*. 604:525–533. https://doi.org/10.1038/s41586-022-04554-y.

Bogin B, Smith BH. 1996. Evolution of the human life cycle. *Am J Hum Biol*. 8:703–716. https://doi.org/10.1002/(SICI)1520-6300(1996)8:6<703::AID-AJHB2>3.0.CO;2-U.

Bogin B, Smith BH. 2000. Evolution of the human life cycle. In: *Human biology: an evolutionary and biocultural perspective* Huss-Ashmore R, D O'R (eds). Wiley-Liss, NY, pp 377–424.

Bruner E. 2022. A network approach to the topological organization of the Brodmann map. *Anat Rec*. 305:3504–3515. https://doi.org/10.1002/ar.24941.

Bruner E. 2023. The evolution of the parietal lobes in the genus homo: the fossil evidence. In: *Cognitive archaeology, body cognition, and the evolution of visuospatial perception* Bruner E (ed). Elsevier, pp 153–179.

Bruner E, Jacobs HIL. 2024. Alzheimer's disease, the parietal lobes, and the evolution of the human genus. In: Diederich N, Brüne M, Amunts K, Goetz C (eds). *The Evolutionary Roots of Human Brain Diseases*, Oxford Academic, pp 181–204.

Bruner E, Pereira-Pedro S. 2020. A metric survey on the sagittal and coronal morphology of the precuneus in adult humans. *Brain Struct Funct*. 225:2747–2755. https://doi.org/10.1007/s00429-020-02152-0.

Bruner E et al. 2014. Midsagittal brain variation and MRI shape analysis of the precuneus in adult individuals. *J Anat*. 224:367–376. https://doi.org/10.1111/joa.12155.

Bruner E, Amano H, De La Cuétara JM, Ogihara N. 2015. The brain and the braincase: a spatial analysis on the midsagittal profile in adult humans. *J Anat*. 227:268–276. https://doi.org/10.1111/joa.12355.

Bruner E, Pereira-Pedro AS, Chen X, Rilling JK. 2017a. Precuneus proportions and cortical folding: a morphometric evaluation on a racially diverse human sample. *Ann Anat*. 211:120–128. https://doi.org/10.1016/j.aanat.2017.02.003.

Bruner E, Preuss TM, Chen X, Rilling JK. 2017b. Evidence for expansion of the precuneus in human evolution. *Brain Struct Funct*. 222:1053–1060. https://doi.org/10.1007/s00429-015-1172-y.

Bruner E, Battaglia-Mayer A, Caminiti R. 2023. The parietal lobe evolution and the emergence of material culture in the human genus. *Brain Struct Funct*. 228:145–167. https://doi.org/10.1007/s00429-022-02487-w.

Bruner E et al. 2025. Morphological variations and cortical atrophy of the precuneus in normal aging and Alzheimer's disease. *J Anat*. https://doi.org/10.1111/joa.70027.

Cavanna AE. 2014. The origin of consciousness and beyond. *Front Psychol*. 5:1–2. https://doi.org/10.3389/fpsyg.2014.01385.

Cavanna AE, Trimble MR. 2006. The precuneus: a review of its functional anatomy and behavioural correlates. *Brain*. 129:564–583. https://doi.org/10.1093/brain/awl004.

Cooke SB, Terhune CE. 2015. Form, function, and geometric morphometrics. *Anat Rec*. 298:5–28. https://doi.org/10.1002/ar.23065.

Cunningham SI, Tomasi D, Volkow ND. 2017. Structural and functional connectivity of the precuneus and thalamus to the default mode network. *Hum Brain Mapp*. 38:938–956. https://doi.org/10.1002/hbm.23429.

Dadario NB, Sughrue ME. 2023. The functional role of the precuneus. *Brain*. 146:3598–3607. https://doi.org/10.1093/brain/awad181.

Darby RR, Joutsa J, Burke MJ, Fox MD. 2018. Lesion network localization of free will. *Proc Natl Acad Sci USA*. 115:10792–10797. https://doi.org/10.1073/pnas.1814117115.

Dziedzic TA, Bala A, Marchel A. 2021. Cortical and subcortical anatomy of the parietal lobe from the neurosurgical perspective. *Front Neurol*. 12:727055. https://doi.org/10.3389/fneur.2021.727055.

Freton M et al. 2014. The eye of the self: precuneus volume and visual perspective during autobiographical memory retrieval. *Brain Struct Funct*. 219:959–968. https://doi.org/10.1007/s00429-013-0546-2.

García-Cabezas MA, Hacker JL, Zikopoulos B. 2020. A protocol for cortical type analysis of the human neocortex applied on histological samples, the atlas of Von Economo and Koskinas, and magnetic resonance imaging. *Front Neuroanat*. 14:576015. https://doi.org/10.3389/fnana.2020.576015.

Gilmore AW, Nelson SM, McDermott KB. 2015. A parietal memory network revealed by multiple MRI methods. *Trends Cogn Sci*. 19:534–543. https://doi.org/10.1016/j.tics.2015.07.004.

Glasser MF et al. 2016. A multi-modal parcellation of human cerebral cortex. *Nature*. 536:171–178. https://doi.org/10.1038/nature18933.

Gunz P, Neubauer S, Maureille B, Hublin J-J. 2010. Brain development after birth differs between Neanderthals and modern humans. *Curr Biol*. 20:R921–R922. https://doi.org/10.1016/j.cub.2010.10.018.

Hagmann P et al. 2008. Mapping the structural Core of human cerebral cortex. *PLoS Biol*. 6:e159. https://doi.org/10.1371/journal.pbio.0060159.

Hammer O, Harper DAT, Ryan PD. 2001. PAST: paleontological statistics software package for education and data analysis, PAST. *Palaeontologia Electronica* 4:1.

Herbet G, Lemaitre A-L, Moritz-Gasser S, Cochereau J, Duffau H. 2019. The antero-dorsal precuneal cortex supports specific aspects of bodily awareness. *Brain*. 142:2207–2214. https://doi.org/10.1093/brain/awz179.

Howell BR et al. 2019. The UNC/UMN Baby Connectome Project (BCP): An overview of the study design and protocol development. *Neuroimage*. 185:891–905. https://doi.org/10.1016/j.neuroimage.2018.03.049.

Jiang P et al. 2023. The hierarchical organization of the precuneus captured by functional gradients. *Brain Struct Funct*. 228:1561–1572. https://doi.org/10.1007/s00429-023-02672-5.

Jitsuishi T, Yamaguchi A. 2023. Characteristic cortico-cortical connection profile of human precuneus revealed by probabilistic tractography. *Sci Rep*. 13:1936. https://doi.org/10.1038/s41598-023-29251-2.

Karas G et al. 2007. Precuneus atrophy in early-onset Alzheimer's disease: a morphometric structural MRI study. *Neuroradiology*. 49:967–976. https://doi.org/10.1007/s00234-007-0269-2.

Klingenberg CP. 2009. Morphometric integration and modularity in configurations of landmarks: tools for evaluating a priori hypotheses. *Evol Dev*. 11:405–421. https://doi.org/10.1111/j.1525-142X.2009.00347.x.

Klingenberg CP. 2011. MorphoJ an integrated software package for geometric morphometrics. *Mol Ecol Resour*. 11:353–357. https://doi.org/10.1111/j.1755-0998.2010.02924.x.

Kobayashi Y, Amaral DG. 2000. Macaque monkey retrosplenial cortex: I. three-dimensional and cytoarchitectonic organization. *J Comp Neurol*. 365:339–365. https://doi.org/10.1002/1096-9861(20001023)426:3<339::AID-CNE1>3.0.CO;2-8.

Kobayashi Y, Amaral DG. 2003. Macaque monkey retrosplenial cortex: II. cortical afferents. *J Comp Neurol*. 466:48–79. https://doi.org/10.1002/cne.10883.

Laland K, Seed A. 2021. Understanding human cognitive uniqueness. *Annu Rev Psychol*. 72:689–716. https://doi.org/10.1146/annurev-psych-062220-051256.

Luo Z et al. 2020. Functional parcellation of human brain precuneus using density-based clustering. *Cereb Cortex*. 30:269–282. https://doi.org/10.1093/cercor/bhz086.

Lyu D et al. 2023. Causal evidence for the processing of bodily self in the anterior precuneus. *Neuron*. 111:2502–2512. https://doi.org/10.1016/j.neuron.2023.05.013.

Margulies DS et al. 2009. Precuneus shares intrinsic functional architecture in humans and monkeys. *Proc Natl Acad Sci USA*. 106:20069–20074. https://doi.org/10.1073/pnas.0905314106.

Mitteroecker P, Gunz P. 2009. Advances in geometric morphometrics. *Evol Biol*. 36:235–247. https://doi.org/10.1007/s11692-009-9055-x.

Mitteroecker P, Schaefer K. 2022. Thirty years of geometric morphometrics: achievements, challenges, and the ongoing quest for biological meaningfulness. *Am J Biol Anthropol*. 178:181–210. https://doi.org/10.1002/ajpa.24531.

Neubauer S, Hublin J-J. 2012. The evolution of human brain development. *Evol Biol*. 39:568–586. https://doi.org/10.1007/s11692-011-9156-1.

Neubauer S, Gunz P, Hublin J-J. 2009. The pattern of endocranial ontogenetic shape changes in humans. *J Anat*. 215:240–255. https://doi.org/10.1111/j.1469-7580.2009.01106.x.

Neubauer S, Hublin J-J, Gunz P. 2018. The evolution of modern human brain shape. *Sci Adv*. 4:eaao5961. https://doi.org/10.1126/sciadv.aao5961.

Northoff G, Bermpohl F. 2004. Cortical midline structures and the self. *Trends Cogn Sci*. 8:102–107. https://doi.org/10.1016/j.tics.2004.01.004.

Passarelli L et al. 2018. Uniformity and diversity of cortical projections to precuneate areas in the macaque monkey: what defines area PGm? *Cereb Cortex*. 28:1700–1717. https://doi.org/10.1093/cercor/bhx067.

Pereira-Pedro AS, Bruner E. 2016. Sulcal pattern, extension, and morphology of the precuneus in adult humans. *Ann Anat*. 208:85–93. https://doi.org/10.1016/j.aanat.2016.05.001.

Pereira-Pedro AS, Bruner E, Gunz P, Neubauer S. 2020. A morphometric comparison of the parietal lobe in modern humans and Neanderthals. *J Hum Evol*. 142:102770. https://doi.org/10.1016/j.jhevol.2020.102770.

Ponce De León MS, Bienvenu T, Akazawa T, Zollikofer CPE. 2016. Brain development is similar in Neanderthals and modern humans. *Curr Biol*. 26:R665–R666. https://doi.org/10.1016/j.cub.2016.06.022.

Rasskin-Gutman D, Esteve-Altava B. 2014. Connecting the dots: anatomical network analysis in morphological EvoDevo. *Biol Theory*. 9:178–193. https://doi.org/10.1007/s13752-014-0175-x.

Reynolds J et al. 2023. Calgary Preschool MRI Dataset. https://doi.org/10.17605/OSF.IO/AXZ5R.

Rohlf FJ. 2017. *tpsDig, digitize landmarks and outlines, version 2.05. Stony brook*. Department of Ecology and Evolution, State University of New York, NY.

Sadeghi N et al. 2013. Regional characterization of longitudinal DT-MRI to study white matter maturation of the early developing brain. *NeuroImage*. 68:236–247. https://doi.org/10.1016/j.neuroimage.2012.11.040.

Scheperjans F et al. 2008. Observer-independent cytoarchitectonic mapping of the human superior parietal cortex. *Cereb Cortex*. 18:846–867. https://doi.org/10.1093/cercor/bhm116.

Schuurman T, Bruner E. 2023. A comprehensive anatomical network analysis of human brain topology. *J Anat*. 242:973–985. https://doi.org/10.1111/joa.13828.

Slice DE. 2007. Geometric morphometrics. *Annu Rev Anthropol*. 36:261–281. https://doi.org/10.1146/annurev.anthro.34.081804.120613.

Strike LT et al. 2022. Queensland Twin IMaging (QTIM). https://doi.org/10.18112/openneuro.ds004169.v1.0.6.

Tanglay O et al. 2022. Anatomy and white-matter connections of the precuneus. *Brain Imaging Behav*. 16:574–586. https://doi.org/10.1007/s11682-021-00529-1.

Van Den Heuvel MP, Mandl RCW, Stam CJ, Kahn R, Hulshoff PH. 2010. Aberrant frontal and temporal complex network structure in schizophrenia: a graph theoretical analysis. *J Neurosci*. 30:15915–15926. https://doi.org/10.1523/JNEUROSCI.2874-10.2010.

Vogel JW et al. 2024. Deciphering the functional specialization of whole-brain spatiomolecular gradients in the adult brain. *Proc Natl Acad Sci USA*. 121:e2219137121. https://doi.org/10.1073/pnas.2219137121.

Wagner GP. 1984. On the eigenvalue distribution of genetic and phenotypic dispersion matrices: evidence for a nonrandom organization of quantitative character variation. *J Math Biol*. 21:77–95. https://doi.org/10.1007/BF00275224.

Wallentin M, Weed E, Østergaard L, Mouridsen K, Roepstorff A. 2008. Accessing the mental space—spatial working memory processes for language and vision overlap in precuneus. *Hum Brain Mapp*. 29:524–532. https://doi.org/10.1002/hbm.20413.

Willbrand EH et al. 2023. Sulcal morphology of posteromedial cortex substantially differs between humans and chimpanzees. *Commun Biol*. 6:586. https://doi.org/10.1038/s42003-023-04953-5.

Yamaguchi A, Jitsuishi T. 2024. Structural connectivity of the precuneus and its relation to resting-state networks. *Neurosci Res*. 209:9–17. https://doi.org/10.1016/j.neures.2023.12.004.

Yeager BE et al. 2022. Central precuneus lesions are associated with impaired executive function. *Brain Struct Funct*. 227:3099–3108. https://doi.org/10.1007/s00429-022-02556-0.

Zelditch ML, Swiderski DL, Sheets HD. 2012. *Geometric morphometrics for biologists*, Second edn. Academic Press.

Zhang S, Li CR. 2012. Functional connectivity mapping of the human precuneus by resting state fMRI. *NeuroImage*. 59:3548–3562. https://doi.org/10.1016/j.neuroimage.2011.11.023.

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