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Updating the sulcal landscape of the human lateral parieto-occipital junction provides anatomical, functional, and cognitive insights

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Abstract

Recent work has uncovered relationships between evolutionarily new small and shallow cerebral indentations, or sulci, and human behavior. Yet, this relationship remains unexplored in the lateral parietal cortex (LPC) and the lateral parieto-occipital junction (LPOJ). After defining thousands of sulci in a young adult cohort, we revised the previous LPC/LPOJ sulcal landscape to include four previously overlooked, small, shallow, and variable sulci. One of these sulci (ventral supralateral occipital sulcus, slocs-v) is present in nearly every hemisphere and is morphologically, architecturally, and functionally dissociable from neighboring sulci. A data-driven, model-based approach, relating sulcal depth to behavior further revealed that the morphology of only a subset of LPC/LPOJ sulci, including the slocs-v, is related to performance on a spatial orientation task. Our findings build on classic neuroanatomical theories and identify new neuroanatomical targets for future “precision imaging” studies exploring the relationship among brain structure, brain function, and cognitive abilities in individual participants.

eLife assessment

The present work provides new insights into detailed brain morphology. Using state-of-the-art methods, it provides **compelling** evidence for the relevance of sucal morphology for the precise localization of brain function. The **fundamental** findings have great relevance for the fields of imaging neuroscience and individualized medicine as ever-improving techniques improve precision to the point where individual brain anatomy is taking centre stage.

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Introduction

A fundamental goal in psychology and neuroscience is to understand the complex relationship between brain structure and brain function, as well as how that relationship provides a scaffold for efficient cognition and behavior. Of all the neuroanatomical features to target, recent work shows that morphological features of the shallower, later developing, hominoid-specific indentations of the cerebral cortex (also known as putative tertiary sulci, PTS) are not only functionally and cognitively meaningful, but also are particularly impacted by multiple brain-related disorders and aging (Amiez et al., 2018, 2019; Ammons et al., 2021; Cachia et al., 2021; Fornito et al., 2004; Garrison et al., 2015; Harper et al., 2022; Lopez-Persem et al., 2019; Maboudian et al., 2024; Miller et al., 2021; Nakamura et al., 2020; Parker et al., 2023; Ramos Benitez et al., 2024; Voorhies et al., 2021; Weiner, 2019; Willbrand, Ferrer, et al., 2023; Willbrand, Parker, et al., 2022; Willbrand, Voorhies, et al., 2022; Yao et al., 2022). The combination of these findings provides growing support for a classic theory proposing that the late gestational emergence of these PTS in gestation within association cortices, as well as their prolonged development, may co-occur with specific functional and microstructural features that could support specific cognitive abilities that also have a protracted development (Sanides, 1964). Nevertheless, despite the developmental, evolutionary, functional, cognitive, and theoretical relevance of these findings, PTS have mainly been restricted to only a subset of association cortices such as the prefrontal, cingulate, and ventral occipitotemporal cortices (Amiez et al., 2018, 2019; Ammons et al., 2021; Cachia et al., 2021; Fornito et al., 2004; Garrison et al., 2015; Harper et al., 2022; Hathaway et al., 2023; Lopez-Persem et al., 2019; Miller et al., 2020, 2021; Nakamura et al., 2020; Parker et al., 2023; Voorhies et al., 2021; Weiner, 2019; Willbrand, Ferrer, et al., 2023; Willbrand, Maboudian, et al., 2023; Willbrand, Parker, et al., 2022; Willbrand, Voorhies, et al., 2022; Yao et al., 2022). Thus, examining the relationship among these PTS relative to architectonic and functional features of the cerebral cortex, as well as relative to cognition, remains uncharted in other association cortices such as the lateral parietal cortex (LPC).

As LPC is a cortical extent that has expanded extensively throughout evolution (Van Essen et al., 2018; Zilles et al., 2013), there is great interest in the structure and function of LPC in development, aging, across species, and in different patient populations. Yet, key gaps in knowledge relating individual differences in the structure of LPC to individual differences in the functional organization of LPC and cognitive performance remain for at least four main reasons. First, one line of recent work shows that LPC displays a much more complex sulcal patterning than previously thought (Drudik et al., 2023; Petrides, 2019; Segal & Petrides, 2012; Zlatkina & Petrides, 2014), while a second line of work shows that LPC is tiled with many maps and discrete functional regions spanning modalities and functions such as vision, memory, attention, action, haptics, and multisensory integration in addition to theory of mind, cognitive control, and subdivisions of the default mode network (Goodale & Milner, 1992; Harvey et al., 2013, 2015; Humphreys & Tibon, 2023; Konen & Kastner, 2008; Mackey et al., 2017; Schurz et al., 2017). Second, a majority of the time, the two lines of work are conducted independently from one another and the majority of human neuroimaging studies of LPC implement group analyses on average brain templates—which causes LPC sulci to disappear (**Fig. 1**). Third, despite the recently identified complexity of LPC sulcal patterning, recent studies have also uncovered previously overlooked PTS in association cortices (for example, in the posterior cingulate cortex; (Willbrand, Maboudian, et al., 2023; Willbrand, Parker, et al., 2022). Thus, fourth, it is unknown if additional LPC PTS are waiting to be detailed and if so, could improve our understanding of the structural-functional organization of LPC with potential cognitive insights as in other association cortices. Critically, while such findings would have developmental, evolutionary, functional, cognitive, and theoretical implications for addressing novel questions in future studies, they would also have translational applications as sulci serve as biomarkers in neurodevelopmental disorders (Ammons et al., 2021; Cachia et al., 2021; Garrison et al., 2015; Nakamura et al., 2020) and “corridors” for neurosurgery (Tomaiuolo et al., 2022; Tomaiuolo & Giordano, 2016).

In the present study, we first manually defined LPC sulci in 144 young adult hemispheres using the most recent definitions of LPC sulci (Petrides, 2019). By manually labeling over 2,000 sulci, we detail four previously undescribed (Supplementary Methods and Supplementary Figs. 1-4 for historical details) sulci in the cortical expanse between the caudal branches of the superior temporal sulcus (cSTS) and two parts of the intraparietal sulcus (IPS)—a cortical expanse recently referenced as containing sensory “bridge” regions of the temporal-parietal-occipital junction (Glasser et al., 2016)—which we term the supralateral occipital sulci (ventral: slocs-v; dorsal: slocs-d) and posterior angular sulci (ventral: pAngs-d; dorsal: pAngs-d). We then utilized morphological (depth and surface area), architectural (gray matter thickness and myelination), and functional (resting-state functional connectivity) data available in each participant to assess whether the most common of these structures (slocs-v) was dissociable from surrounding sulci. Finally, we assessed whether the updated view of the LPC/LPOJ sulcal landscape provided cognitive insights using a model-based, data-driven approach (Voorhies et al., 2021) relating sulcal morphology to behavior on tasks known to activate regions within this cortical expanse [for example, reasoning and spatial orientation (Gur et al., 2000; Karnath, 1997; Vendetti & Bunge, 2014; Wendelken, 2014)].

Results

Four previously undefined small and shallow sulci in the lateral parieto-occipital junction (LPOJ)

In previous research in small sample sizes, neuroanatomists noticed shallow sulci in this cortical expanse (Supplementary Methods and Supplementary Figs. 1-4 for historical details). In the present study, we fully update this sulcal landscape considering these overlooked indentations. In addition to defining the 13 sulci previously described within the LPC/LPOJ, as well as the posterior superior temporal cortex (**Methods**) (Petrides, 2019) in individual participants, we could also identify as many as four small and shallow PTS situated within the LPC/LPOJ that were highly variable across individuals and uncharted until now (Supplementary Methods and Supplementary Figs. 1-4). Macroanatomically, we could identify two sulci between the cSTS3 and the IPS-PO/lTOS ventrally and two sulci between the cSTS2 and the pips/IPS dorsally. We focus our analyses on the slocs-v since it was identifiable in nearly every hemisphere.

Ventrally, we refer to these sulci as ventral (slocs-v; sulcus 6 in **Fig. 1**) and dorsal (slocs-d; sulcus 7 in **Fig. 1**) components of the supralateral occipital sulcus. The slocs-v, located between the posterior cSTS3 and lTOS, was present in 98.6% of hemispheres (left hemisphere: N = 71/72; right hemisphere: N = 71/72; **Fig. 1**). Conversely, the more variable slocs-d, located between the cSTS3 and IPS-PO, was present 68.0% of the time (left hemisphere: N = 50/72; right hemisphere: N = 48/72; **Fig. 1**). Dorsally, we refer to the other newly described sulci as the ventral (pAngs-v; sulcus 8 in **Fig. 1**) and dorsal (pAngs-d; sulcus 9 in **Fig. 1**) components of the posterior angular sulcus. The pAng components were more rare than the slocs components. Specifically, pAngs-v, located between cSTS2 and pips, was identifiable 31.3% of the time (19 left and 26 right hemispheres; **Fig. 1**). Located between cSTS2 and the IPS, pAngs-d was identifiable only 13.2% of the time (8 left and 11 right hemispheres; **Fig. 1**). These incidence rates were significantly different (GLM, main effect of sulcus: $\chi2(3)$L=L166.53, p < .0001; no hemispheric effects: ps > .68). The slocs-v was more common than the other three sulci (ps < .0001), slocs-d was more common than the pAngs components (ps < .0001), and pAngs-v was more common than pAngs-d (p = .002).

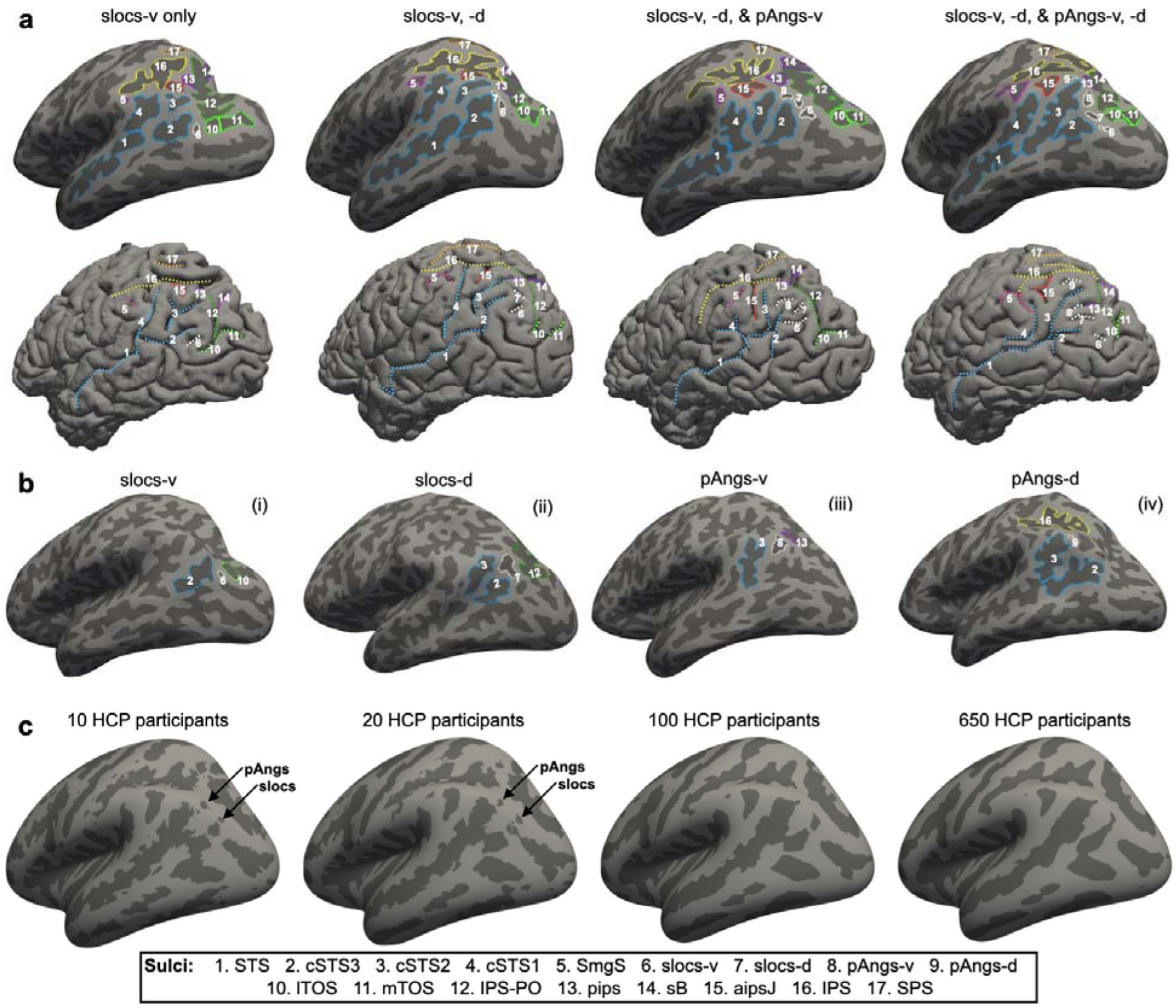


Fig. 1.

Four previously undefined small and shallow sulci in the lateral parieto-occipital junction (LPOJ).

a. Four example inflated (top) and pial (bottom) left hemisphere cortical surfaces displaying the 13-17 sulci manually identified in the present study. Each hemisphere contains 1-4 of the previousl undefined and variable LOC/LPOJ sulci (slocs and pAngs). Each sulcus is numbered according to the legend. **b.** Criteria for defining slocs and pAngs components. (i) Slocs-v is the cortical indentation between the cSTS3 and lTOS. (ii) Slocs-d is the indentation between cSTS3/cSTS2 and IPS-PO. (iii) pAngs-v is the indentation between the cSTS2 and pips. (iv) pAngs-d is the indentation between cSTS2/cSTS1 and IPS. **c.** The variability of the slocs and pAng components can cause them to disappear when individual surfaces are averaged together. Left to right: (i) 10 HCP participants, (ii) 20 HCP participants, (iii) 100 HCP participants, and iv) 650 HCP participants. The disappearance of these sulci on average surfaces, which are often used for group analyses in neuroimaging research, emphasizes the importance of defining these structures in individual hemispheres.

Beyond characterizing the incidence of sulci, it is also common in the neuroanatomical literature to qualitatively characterize sulci on the basis of fractionation and intersection with surrounding sulci (termed "sulcal types"; for examples in other cortical expanses, see (Chiavaras & Petrides, 2000; Drudik et al., 2023; Miller et al., 2021; Paus et al., 1996; Weiner et al., 2014; Willbrand, Parker, et al., 2022). All four sulci most commonly did not intersect with other sulci (see **Supplementary Tables 1-4** for a summary of the sulcal types of the slocs and pAngs dorsal and ventral components). The sulcal types were also highly comparable between hemispheres (rs > .99, *p*s < .001). Though we characterize these sulci in this paper for the first time, the location of these four sulci is consistent with the presence of variable "accessory sulci" in this cortical expanse mentioned in prior modern and classic studies (Supplementary Methods). We could also identify these sulci in post-mortem hemispheres (Supplementary Figs. 2, 3), ensuring that these sulci were not an artifact of the cortical reconstruction process.

Given that sulcal incidence and patterning is also sometimes related to demographic features (Cachia et al., 2021; Leonard et al., 2009; Wei et al., 2017), subsequent GLMs relating the incidence and patterning of the three more variable sulci (slocs-d, pAngs-v, and pAngs-d) to demographic features (age and gender) revealed no associations for any sulcus (*p*s > .05). Finally, to help guide future research on these newly- and previously-classified LPC/LPOJ sulci, we generated probabilistic maps of each of these 17 sulci and share them with the field with the publication of this paper (Supplementary Fig. 6; **Data availability**).

The slocs-v is morphologically, architecturally, and functionally dissociable from nearby sulci

Given that the slocs-v was present in the majority of participants (98.6% across hemispheres) and the other three sulci were far more variable (<70% of hemispheres), we focused our analyses on this stable sulcal feature of the LPOJ. To do so, we first tested whether the slocs-v was morphologically (depth and surface area) and architecturally (gray matter thickness and myelination) distinct from the two sulci surrounding it: the cSTS3 and lTOS (**Fig. 1**). These metrics are provided for all 17 sulci in Supplementary Figure 7. An rm-ANOVA (within-participant factors: sulcus, metric, and hemisphere for standardized metric units) revealed a sulcus x metric interaction ($F(4, 276.19) = 179.15$, $\eta 2 = 0.38$, $p < .001$). Post hoc tests showed four main differences: (i) the slocs-v was shallower than cSTS3 ($p < .001$) but not lTOS ($p = .60$), (ii) the slocs-v was smaller than both the cSTS3 and lTOS (*p*s < .001), (iii) the slocs-v showed thicker gray matter than both the cSTS3 and lTOS (*p*s < .001), and iv) the slocs-v was less myelinated than both the cSTS and lTOS (*p*s < .001; **Fig. 2a**). There was also a sulcus x metric x hemisphere interaction ($F(4.20, 289.81) = 4.16$, $\eta 2 = 0.01$, $p = .002$; hemispheric effects discussed in Supplementary Results).

We then tested whether the slocs-v was also functionally distinct from the cSTS3 and lTOS by leveraging resting-state network parcellations for each individual participant to quantify "connectivity fingerprints" for each sulcus in each hemisphere of each participant (**Methods**) (Kong et al., 2019). An rm-ANOVA (within-participant factors: sulcus, network, and hemisphere for Dice coefficient overlap) revealed a sulcus x network interaction ($F(32, 2144) = 80.18$, $\eta 2 = 0.55$, $p < .001$). Post hoc tests showed that this interaction was driven by four effects: (i) the cSTS3 overlapped more with the Default A subnetwork than both the slocs-v and lTOS (*p*s < .001), (ii) the slocs-v overlapped more with the Default C subnetwork than the lTOS ($p < .001$) and marginally than the cSTS3 ($p = .077$), (iii) the slocs-v overlapped more with the Dorsal Attention A subnetwork than both the cSTS3 and lTOS (*p*s < .001), and iv) the lTOS overlapped more with the Visual A and Visual B subnetworks than both the cSTS3 and slocs-v (*ps* < .004; **Fig. 2b**). There was also a sulcus x network x hemisphere interaction ($F(32, 2144) = 3.99$, $\eta 2 = 0.06$, $p < .001$; hemispheric effects discussed in Supplementary Results). Together, these results indicate that the slocs-v is a morphologically, architecturally, and functionally distinct structure from its sulcal neighbors, and thus, deserves a distinct neuroanatomical definition.

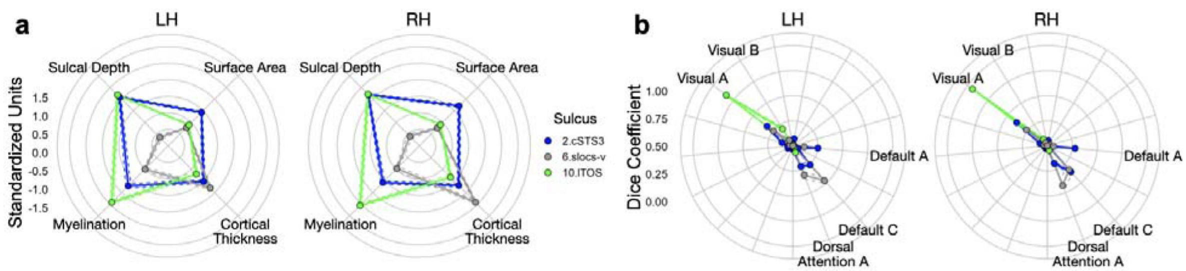


Fig. 2.

The slocs-v is morphologically, architecturally, and functionally dissociable from nearby sulci.

a. Radial plot displaying the morphological (upper metrics: depth, surface area) and architectural (lower metrics: cortical thickness, myelination) features of the slocs-v (gray), cSTS3 (blue), and lTOS (green). Each dot and solid line represents the mean. The dashed lines indicate ± standard error. These features are colored by sulcus (legend). Metrics are in standardized units. **b.** Radial plot displaying the connectivity fingerprints of these three sulci: the Dice Coefficient overlap (values from 0-1) between each component and individual-level functional connectivity parcellations (Kong et al., 2019).

We further found that the three caudal STS rami (Petrides, 2019; Segal & Petrides, 2012) and intermediate parietal sulci (aipsJ and pips) (Petrides, 2019; Zlatkina & Petrides, 2014) are morphologically, architecturally, and functionally distinct structures for the first time (to our knowledge), which empirically supports their distinctions with separate sulcal labels (Supplementary Results and Supplementary Fig. 8).

The morphology of LPC/LPOJ sulci, including the slocs-v, is related to cognitive performance

Finally, leveraging a data-driven approach of cross-validated LASSO feature selection, we sought to determine whether sulcal depth, a main defining feature of sulci, related to cognitive performance (**Methods**). To do so, we primarily focused on spatial orientation and reasoning given that these abilities recruit multiple subregions of lateral parietal and/or occipital cortices (Gur et al., 2000; Karnath, 1997; Vendetti & Bunge, 2014; Wendelken, 2014). As in prior work (Voorhies et al., 2021; Willbrand et al., 2024; Willbrand, Ferrer, et al., 2023; Willbrand, Voorhies, et al., 2022; Yao et al., 2022), we chose the model at the alpha that minimized MSE_{cv}. Participants with a slocs-v in both hemispheres and all behavioral metrics were included (N = 69). Due to their rarity (being in less than 70% of hemispheres at most), we did not include the slocs-d or pAng components in this analysis.

This method revealed an association between spatial orientation scores and normalized sulcal depth in the left hemisphere (MSE_{cv} = 25.63, alpha = 0.05; **Fig. 3a**), but not in the right hemisphere (MSE_{cv} = 26.41, alpha = 0.3). Further, we found that no LPC/LPOJ sulci were selected for reasoning in either hemisphere (right: alpha = 0.3, MSE = 24.01; left: alpha = 0.3, MSE = 24.01). Six left hemisphere LPC/LPOJ sulci were related to spatial orientation task performance (**Fig. 3a, b**). Four of these sulci were positioned ventrally: cSTS3 (β = −9.77), slocs-v (β = −3.36), lTOS (β = −4.91), and mTOS (β = −0.06), whereas two were positioned dorsally: pips (β = 5.02), and SPS (β = 4.30; **Fig. 3a, b**). Using LooCV to construct models that predict behavior, the LASSO-selected model explained variation in spatial orientation score (R^2_{cv} = 0.06, MSE_{cv} = 23.99) above and beyond a model with all left hemisphere sulci (R^2 < 0.01, MSE_{cv} = 27.12). This model also showed a moderate correspondence (r_s = 0.29, p = .01; **Fig. 3c**) between predicted and actual measured scores. We then tested for anatomical and behavioral specificity using the AIC, which revealed two primary findings. First, we found that the LASSO-selected sulcal depth model outperformed a model using the cortical thickness of the six LASSO-selected sulci (R^2_{cv} < .01, MSE_{cv} = 26.02, $AIC_{cortical\ thickness} - AIC_{sulcal\ depth}$ = 2.19). This model also showed task specificity as these sulci outperformed a model with processing speed (R^2_{cv} < .01, MSE_{cv} = 254.65, $AIC_{processing\ speed} - AIC_{spatial\ orientation}$ = 63.57). Thus, our data-driven model explains a significant amount of variance on a spatial orientation task and shows behavioral and morphological specificity.

Discussion

Overview

In the present study, we examined the relationship between LPC/LPOJ sulcal morphology, functional connectivity fingerprints, and cognition. We report five main findings. First, while manually defining sulci in LPC/LPOJ across 144 hemispheres, we uncovered four small and shallow sulci that are not included in present or classic neuroanatomy atlases or neuroimaging software packages. Second, we found that the most common of these structures (the slocs-v; identifiable 98.6% of the time) was morphologically, architecturally, and functionally differentiable from nearby sulci. Third, using a model-based, data-driven approach quantifying the relationship between sulcal morphology and cognition, we found a relationship between the depths of six LPC/LPOJ sulci and performance on a spatial orientation processing task. Fourth, the model identified distinct dorsal and ventral sulcal networks in LPC/LPOJ: ventral sulci had

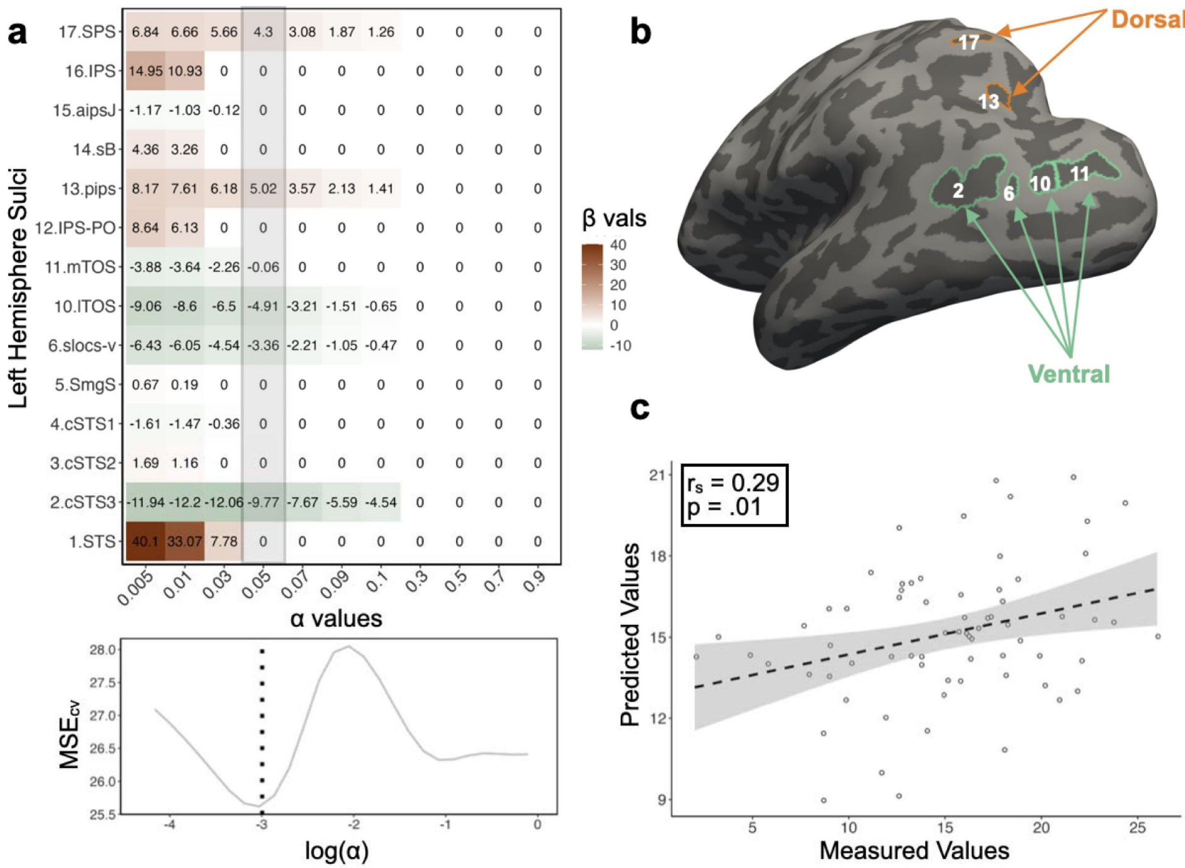


Fig. 3.

The morphology of LPC/LPOJ sulci, including the slocs-v, is related to cognitive performance.

a. Beta-coefficients for each left hemisphere LPC/LPOJ sulcus at a range of shrinking parameter values [alpha (α)]. Highlighted gray bar indicates coefficients at the chosen α-level. Bottom: Cross-validated mean-squared error (MSE_{CV}) at each α level. By convention, we selected the α that minimized the MSE_{CV} (dotted line). **b.** Inflated left hemisphere cortical surface from an example participant highlighting the two groups of sulci—*dorsal positive* (orange) and *ventral negative* (green)— related to spatial orientation performance. **c.** Spearman's correlation (r_s) between the measured and the predicted spatial orientation scores from the LASSO-selected model is shown in a.

negative weights while dorsal sulci had positive weights (**Fig. 3b**). These findings are consistent with previous neuroimaging work from Gur et al. (Gur et al., 2000) who demonstrated separate functional activations in dorsal parietal and the more ventrally situated occipital-parietal cortices for the judgment of line orientation task used in the present study. Fifth, the model identified that the slocs-v is cognitively relevant, further indicating the importance of this neuroanatomical structure. In the sections below, we discuss (i) the slocs-v relative to modern functional and cytoarchitectonic parcellations in the LPC/LPOJ, as well as anatomical connectivity to other parts of the brain, (ii) underlying anatomical mechanisms relating sulcal morphology and behavior more broadly, and (iii) limitations of the present study. Implications for future studies are distributed throughout each section.

The slocs-v relative to modern functional and cytoarchitectonic parcellations in the LPC/LPOJ, as well as anatomical connectivity to other parts of the brain

To lay the foundation for future studies relating the newly-described slocs-v to different anatomical and functional organizational features of LPC/LPOJ, we situate probabilistic predictions of slocs-v relative to probabilistic cortical areas identified using multiple modalities. For example, when examining the correspondence between the slocs-v and modern multimodal (HCP-MMP) (Glasser et al., 2016) and observer-independent cytoarchitectural (Julich-Brain atlas) (Amunts et al., 2020) areas (**Methods**), the slocs-v is located within distinct areas. In particular, the slocs-v aligns with the multimodally- and cytoarchitecturally-defined area PGp bilaterally and cytoarchitecturally-defined hIP4 in the right hemisphere (**Fig. 4**). In classic neuroanatomical terms (Cunningham, 1892), this indicates that the slocs-v is a putative “axial sulcus” for these regions, which future work can assess with analyses in individual participants.

Aside from recent multimodal and observer-independent cytoarchitectonic parcellations, an immediate question is: What is the relationship between the slocs-v and other functional regions at this junction between the occipital and parietal lobes, as well as potential anatomical connectivity? For example, there are over a dozen visual field maps in the cortical expanse spanning the TOS, IPS-PO, and the IPS proper (see (i), (ii), and (iii), respectively in **Fig. 5a**) (Mackey et al., 2017). When projecting probabilistic locations of retinotopic maps from over 50 individuals from Wang and colleagues (L. Wang et al., 2015) (**Methods**), the slocs-v is likely located outside of visual field maps extending into this cortical expanse (**Fig. 5a**). Nevertheless, when also projecting the map of the mean R^2 metric from the HCP retinotopy dataset from 181 participants shared by Benson and colleagues (Benson et al., 2018) (Methods), the slocs-v is in a cortical expanse that explains a significant amount of variance (left hemisphere: R^2 = 19.29, R^2_{max} = 41.73; right hemisphere: R^2_{mean} = 21.17, R^2_{max} = 44.23; **Fig. 5b**).

In terms of anatomical connectivity, as the slocs-v co-localizes with cytoarchitectonically defined PGp (**Fig. 4**) and previous studies have examined the anatomical connectivity of the probabilistically defined PGp, we can glean insight regarding the anatomical connectivity of slocs-v from these previous studies (Caspers et al., 2011; J. Wang et al., 2012). This prior work showed that PGp was anatomically connected to temporo-occipital regions, other regions in the temporal lobe, middle and superior frontal cortex, as well as the inferior frontal cortex and insula (Caspers et al., 2011; J. Wang et al., 2012). Furthermore, the slocs-v appears to lie at the junction of scene-perception and place-memory activity (a transition that also consistently co-localizes with the HCP-MMP area PGp) as identified by Steel and colleagues (Steel et al., 2021). Of course, the location of the slocs-v relative to multimodal, cytoarchitectonic, and retinotopic areas, as well as the anatomical connectivity of the slocs-v, would need to be examined in individual participants, but the present work makes clear predictions for future studies as fleshed out here. To conclude this section, as the multimodal area PGp (**Fig. 4**) was recently proposed as

Fig. 4.

The slocs-v relative to modern functional and cytoarchitectonic parcellations in LPC/LPOJ.

a. Top: Left (LH) and right (RH) hemispheres of the inflated fsaverage surface with two areas from the modern HCP multimodal parcellation (HCP-MMP; blue) (Glasser et al., 2016) relative to an MPM of the slocs-v (warm colors indicate areas with at least 20% overlap across participants; Supplementary Fig. 6). Bottom: Same as top, except for two observer-independent cytoarchitectonic regions from the Julich-Brain Atlas (Amunts et al., 2020). **b.** Overlap between the slocs-v and each area (Methods). Each dot and solid line represents the mean. The dashed lines indicate ± standard error (left: gray; right: white).

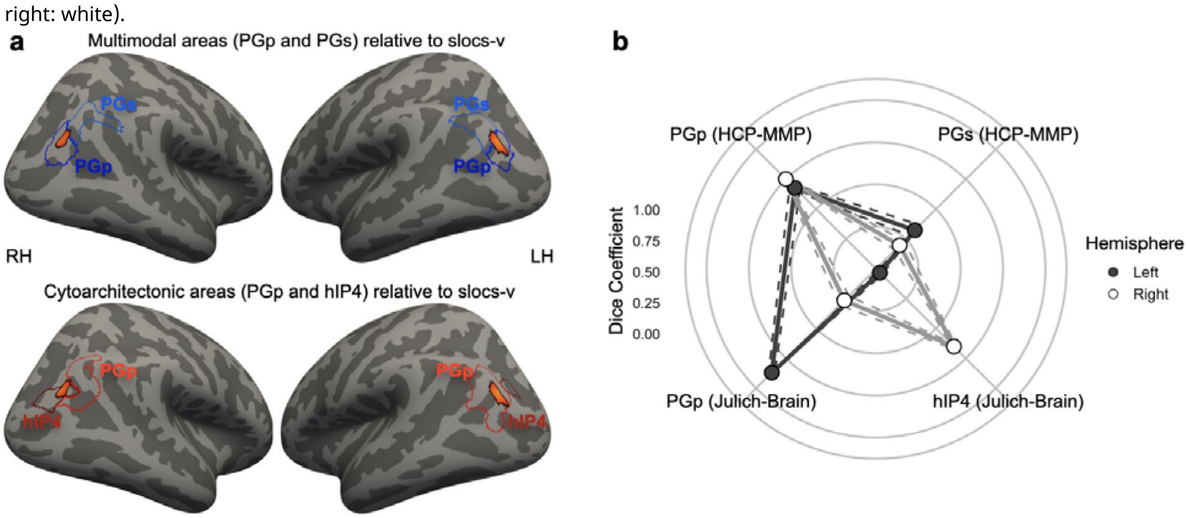
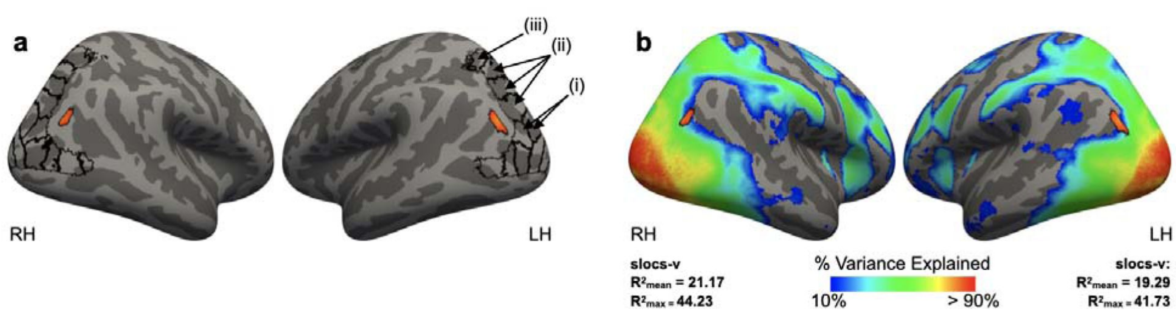


Fig. 5.

The slocs-v relative to retinotopy.

a. Top: Left (LH) and right (RH) hemispheres of the inflated fsaverage surface displaying the probabilistic locations of retinotopic maps from over 50 individuals from Wang and colleagues (L. Wang et al., 2015) (black outlines). The predicted slocs-v location from the MPMs is overlaid in orange (as in **Fig. 4**). (i), (ii), and (iii) point out the retinotopic maps in the cortical expanse spanning the TOS, IPS-PO, and IPS, respectively. **b.** Same format as in a, but with a map of the mean R^2 metric from the HCP retinotopy dataset (Benson et al., 2018) overlayed on the fsaverage surfaces (thresholded between R^2 values of 10% and 90%). This metric measures how well the fMRI time series at each vertex is explained by a population receptive field (pRF) model. The mean and max R^2 values for the slocs-v MPM in each hemisphere are included below each surface.



a “transitional area” by Glasser and colleagues (Glasser et al., 2016) (Supplementary Table 5), future studies can also further functionally and anatomically test the transitional properties of slocs-v.

Underlying anatomical mechanisms relating sulcal morphology and behavior

In this section, we discuss potential anatomical mechanisms contributing to the relationship between sulcal depth and behavior in two main ways. First, long-range white matter fibers have a gyral bias, while short-range white matter fibers have a sulcal bias in which some fibers project directly from the deepest points of a sulcus (Cottaar et al., 2021; Reveley et al., 2015; K. Schilling et al., 2018; K. G. Schilling et al., 2023; Van Essen et al., 2014). As such, recent work hypothesized a close link between sulcal depth and short-range white matter properties (Bodin et al., 2021; Pron et al., 2021; Voorhies et al., 2021; Willbrand, Ferrer, et al., 2023; Yao et al., 2022): deeper sulci would reflect even shorter short-range white matter fibers, which would result in faster communication between local, cortical regions and in turn, contribute to improved cognitive performance. This increased neural efficiency could underlie individual differences in cognitive performance. Ongoing work is testing this hypothesis which can be further explored in future studies incorporating anatomical, functional, and behavioral measures, as well as computational modeling.

Second, our model-based approach identified separate dorsal and ventral sulcal networks in which deeper sulci dorsally and shallower sulci ventrally contributed to the most explained variance on the spatial orientation task. A similar finding was identified by our previous work in the lateral prefrontal cortex (Yao et al., 2022). These previous and present findings may be explained by the classic anatomical compensation theory, which proposes that the size and depth of a sulcus counterbalance those of the neighboring sulci (Armstrong et al., 1995; Connolly, 1950; Zilles et al., 2013). Thus, a larger, deeper sulcus would be surrounded by sulci that are smaller and shallower, rendering the overall degree of cortical folding within a given region approximately equal (Armstrong et al., 1995; Connolly, 1950; Zilles et al., 2013). Future work can incorporate underlying white matter architecture into the compensation theory, as well as a recent modification that proposed to also incorporate local morphological features such as the deepest sulcal point (e.g., sulcal pit or sulcal root (Régis et al., 2005)), which has recently been shown to be related to different functional features of the cerebral cortex (Bodin et al., 2018; Leroy et al., 2015; Natu et al., 2021). Altogether, these and recent findings begin to build a multimodal mechanistic neuroanatomical understanding underlying the complex relationship between sulcal depth and cognition relative to other anatomical features.

Limitations

The main limitation of our study is that presently, the most accurate methodology to define sulci — especially the small, shallow, and variable PTS—requires researchers to manually trace each structure on the cortical surface reconstructions. This method is limited due to the individual variability of cortical sulcal patterning (**Fig. 1**, Supplementary Fig. 5), which makes it challenging to identify sulci without extensive experience and practice. However, we anticipate that our probabilistic maps will provide a starting point and hopefully, expedite the identification of these sulci in new participants. This should accelerate the process of subsequent studies confirming the accuracy of our updated schematic of LPC/LOPJ. This manual method is also arduous and time-consuming, which, on the one hand, limits the sample size in terms of number of participants, while on the other, results in thousands of precisely defined sulci. This push-pull relationship reflects a broader conversation in the human brain mapping and cognitive neuroscience fields between a balance of large N studies and “precision imaging” studies in individual participants (Allen et al., 2022; Gratton et al., 2022; Naselaris et al., 2021; Rosenberg & Finn, 2022). Though our sample size is comparable to other studies that produced reliable results relating sulcal morphology to brain function and cognition (e.g., (Cachia et al., 2021; Garrison et al., 2015; Lopez-Persem et al., 2019; Miller et al., 2021; Roell et al., 2021; Voorhies et al., 2021; Weiner, 2019; Willbrand, Parker, et al., 2022; Willbrand, Voorhies, et al., 2022; Yao et al., 2022), ongoing work that uses deep learning algorithms to automatically define sulci should result in much larger sample sizes in future studies (Borne et al., 2020; Lyu et al., 2021). The time-consuming manual definitions of primary, secondary, and PTS also limit the cortical expanse explored in each study, thus restricting the present study to LPC/LPOJ.

It is also worth noting that the morphological-behavioral relationship identified in the present study explains a modest amount of variance; however, the more important aspect of our findings is that multiple sulci identified in our model-based approach are recently-characterized sulci in LPC/LOPJ identified by our group and others (Petrides, 2019), and thus, the relationship would have been overlooked or lost if these sulci were not identified. Finally, although we did not focus on the relationship between the other three PTS (slocs-d, pAngs-v, and pAngs-d) to anatomical and functional features of LPC and cognition, given that variability in sulcal incidence is cognitively (Amiez et al., 2018; Cachia et al., 2021; Garrison et al., 2015; Willbrand et al., 2024; Willbrand, Voorhies, et al., 2022), anatomically (Amiez et al., 2021; Vogt et al., 1995), functionally (Lopez-Persem et al., 2019), and translationally (Clark et al., 2010; Le Provost et al., 2003; Meredith et al., 2012; Nakamura et al., 2020; Yücel et al., 2002, 2003) relevant, future work can also examine the relationship between the more variable slocs-d, pAngs-v, and pAngs-d and these features.

Conclusion

In conclusion, we uncovered four previously-undefined sulci in LPC/LPOJ and quantitatively showed that the slocs-v is a stable sulcal landmark that is morphologically, architecturally, and functionally differentiable from surrounding sulci. We further used a data-driven, model-based approach relating sulcal morphology to behavior, which identified different relationships of ventral and dorsal LPC/LPOJ sulcal networks contributing to the perception of spatial orientation. The model identified the slocs-v, further indicating the importance of this newly-described neuroanatomical structure. Altogether, this work provides a scaffolding for future “precision imaging” studies interested in understanding how anatomical and functional features of LPC/LPOJ relate to cognitive performance at the individual level.

Methods

Participants

Data for the young adult human cohort analyzed in the present study were from the Human Connectome Project (HCP) database (*https://www.humanconnectome.org/study/hcp-young-adult/overview*). Here, we used 72 randomly-selected participants, balanced for gender (following the terminology of the HCP data dictionary), from the HCP database (50% female, 22-36 years old, and 90% right-handed; there was no effect of handedness on our behavioral tasks; Supplementary Methods) that were also analyzed in several prior studies (Hathaway et al., 2023; Miller et al., 2020, 2021; Willbrand, Ferrer, et al., 2023; Willbrand, Maboudian, et al., 2023; Willbrand, Parker, et al., 2022). HCP consortium data were previously acquired using protocols approved by the Washington University Institutional Review Board (Mapping the Human Connectome: Structure, Function, and Heritability; IRB # 201204036). Informed consent was obtained from all participants.

Neuroimaging data acquisition

Anatomical T1-weighted (T1-w) MRI scans (0.8 mm voxel resolution) were obtained in native space from the HCP database. Reconstructions of the cortical surfaces of each participant were generated using FreeSurfer (v6.0.0), a software package used for processing and analyzing human brain MRI images (*surfer.nmr.mgh.harvard.edu*) (Dale et al., 1999; Fischl et al., 1999). All subsequent sulcal labeling and extraction of anatomical metrics were calculated from these native space reconstructions generated through the HCP's version of the FreeSurfer pipeline (Glasser et al., 2013).

Behavioral data

In addition to structural and functional neuroimaging data, the HCP also includes a wide range of behavioral metrics from the NIH toolbox (Barch et al., 2013). To relate LPC/LPOJ sulcal morphology to behavior, we leveraged behavioral data related to spatial orientation (Variable Short Penn Line Orientation Test), relational reasoning (Penn Progressive Matrices Test), and processing speed (Pattern Completion Processing Speed Test; Supplementary Methods for task details). We selected these tasks as previous functional neuroimaging studies have shown the crucial role of LPC/LPOJ in relational reasoning and spatial orientation (Gur et al., 2000; Karnath, 1997; Vendetti & Bunge, 2014; Wendelken, 2014), while our previous work relating sulcal morphology to cognition uses processing speed performance as a control behavioral task (Voorhies et al., 2021; Willbrand, Voorhies, et al., 2022).

Anatomical analyses

Manual labeling of LPC sulci

Sulci were manually defined in 72 participants (144 hemispheres) guided by the most recent atlas by Petrides (Petrides, 2019), as well as recent empirical studies (Drudik et al., 2023; Segal & Petrides, 2012; Zlatkina & Petrides, 2014), which together offer a comprehensive definition of cerebral sulcal patterns, including PTS. For a historical analysis of sulci in this cortical expanse, please refer to Segal & Petrides (Segal & Petrides, 2012) and Zlatkina & Petrides (Zlatkina & Petrides, 2014). Our cortical expanse of interest was bounded by the following sulci and gyri: (i) the postcentral sulcus (PoCS) served as the anterior boundary, (ii) the superior temporal sulcus (STS) served as the inferior boundary, (iii) the superior parietal lobule (SPL) served as the superior boundary, and (iv) the medial and lateral transverse occipital sulci (mTOS and lTOS) served as the posterior boundary. We also considered the following sulci within this cortical expanse: the three different branches of the caudal superior temporal sulcus (posterior to anterior: cSTS3, 2, 1), the supramarginal sulcus (SmgS), posterior intermediate parietal sulcus (pips), sulcus of Brissaud (sB), anterior intermediate parietal sulcus of Jensen (aipsJ), paroccipital intraparietal sulcus (IPS-PO), intraparietal sulcus (IPS), and the superior parietal sulcus (SPS). Of note, the IPS-PO is the portion of the IPS extending ventrally into the occipital lobe. The IPS-PO was first identified as the paroccipital sulcus by Wilder (1886). There is often an annectant gyrus separating the horizontal portion of the IPS proper from the IPS-PO (Roell et al., 2021; Zlatkina & Petrides, 2014).

Additionally, we identified as many as four previously uncharted and variable LPC/LPOJ PTS for the first time: the supralateral occipital sulcus (slocs; composed of ventral (slocs-v) and dorsal (slocs-d) components) and the posterior angular sulcus (pAngs; composed of ventral (pAngs-v) and dorsal (pAngs-d) components). In the Supplementary Methods and Supplementary Figs. 1-4, we discuss the slocs and pAngs within the context of modern and historical sources.

For each participant in each hemisphere, the location of each sulcus was confirmed by first trained independent raters (Y.T. and T.G.), then confirmed by a trained expert (E.H.W.), and finally, finalized by a neuroanatomist (K.S.W.). All LPC sulci were then manually defined in FreeSurfer using tksurfer tools, as in previous work (Hathaway et al., 2023; Miller et al., 2020, 2021; Parker et al., 2023; Voorhies et al., 2021; Willbrand, Ferrer, et al., 2023; Willbrand, Maboudian, et al., 2023; Willbrand, Parker, et al., 2022; Willbrand, Voorhies, et al., 2022; Yao et al., 2022), from which morphological and anatomical features were extracted. We defined LPC/LPOJ sulci for each participant based on the most recent schematics of sulcal patterning by Petrides (2019) as well as pial, inflated, and smoothed white matter (smoothwm) FreeSurfer cortical surface reconstructions of each individual. In some cases, the precise start or end point of a sulcus can be difficult to determine on a surface (Borne et al., 2020); however, examining consensus across multiple surfaces allowed us to clearly determine each sulcal boundary in each individual. For four example hemispheres with these 13-17 sulci identified, see **Fig. 1a** (Supplementary Fig. 5 for all hemispheres). The specific criteria to identify the slocs and pAngs are outlined in **Fig. 1b**.

To test whether the incidence rates of the slocs and pAngs components were statistically different, we implemented a binomial logistic regression GLM with sulcus (slocs-v, slocs-d, pAngs-v, and pAngs-d) and hemisphere (left and right), as well as their interaction, as predictors for sulcal presence [0 (absent), 1 (present)]. Additional GLMs were run relating the incidence of the more variable sulci (slocs-d, pAngs-v, and pAngs-d) to demographic features (gender and age) were also run. GLMs were carried out with the glm function from the built-in stats R package. ANOVA $\chi 2$ tests were applied to each GLM with the Anova function from the car R package, from which results were reported.

Probability maps

Sulcal probability maps were generated to show the vertices with the highest alignment across participants for a given sulcus. To create these maps, the label file for each sulcus was transformed from the individual to the fsaverage surface with the FreeSurfer mri_label2label command (*https://surfer.nmr.mgh.harvard.edu/fswiki/mri_label2label*). Once each label was transformed into this common template space, we calculated the proportion of participants for which each vertex was labeled as the given sulcus with custom Python code (Miller et al., 2021; Voorhies et al., 2021). For vertices with overlap between sulci, we employed a “winner-take-all” approach such that the sulcus with the highest overlap across participants was assigned to that vertex. Alongside the thresholded maps, we also provide constrained maps [maximum probability maps (MPMs)] at 20% participant overlap to increase interpretability (20% MPMs shown in Supplementary Fig. 6). To aid future studies interested in investigating LPC/LPOJ sulci, we share these maps with the field (**Data availability**).

Extracting and comparing the morphological and architectural features from sulcal labels

Morphologically, we compared sulcal depth and surface area across sulci, as these are two of the primary morphological features used to define and characterize sulci (Armstrong et al., 1995; Chi et al., 1977; Leroy et al., 2015; Lopez-Persem et al., 2019; Miller et al., 2020, 2021; Natu et al., 2021; Sanides, 1964; Voorhies et al., 2021; Weiner, 2019; Welker, 1990; Willbrand, Ferrer, et al., 2023; Willbrand, Parker, et al., 2022; Yao et al., 2022). As in our prior work (Voorhies et al., 2021; Yao et al., 2022), mean sulcal depth values (in standard FreeSurfer units) were computed in native space from the .sulc file generated in FreeSurfer (Dale et al., 1999) with custom Python code (Voorhies et al., 2021). Briefly, depth values are calculated based on how far removed a vertex is from what is referred to as a “mid-surface,” which is determined computationally so that the mean of the displacements around this “mid-surface” is zero. Thus, generally, gyri have negative values, while sulci have positive values. Each depth value was also normalized by the deepest point in the given hemisphere. Surface area (mm^2) was calculated with the FreeSurfer mris_anatomical_stats function (*https://surfer.nmr.mgh.harvard.edu/fswiki/mris_anatomical_stats*). The morphological features of all LPC/LPOJ sulci are documented in Supplementary Fig. 7.

Architecturally, we compared cortical thickness and myelination, as in our prior work in other cortical expanses (Miller et al., 2021; Voorhies et al., 2021; Willbrand, Ferrer, et al., 2023; Willbrand, Parker, et al., 2022). Mean gray matter cortical thickness (mm) was extracted using the FreeSurfer mris_anatomical_stats function. To quantify myelin content, we used the T1-w/T2-w maps for each hemisphere, an in vivo myelination proxy (Glasser & Van Essen, 2011). To generate the T1-w/T2-w maps, two T1-w and T2-w structural MR scans from each participant were registered together and averaged as part of the HCP processing pipeline (Glasser et al., 2013). The averaging helps to reduce motion-related effects or blurring. Additionally, and as described by Glasser and colleagues (Glasser et al., 2013), the T1-w/T2-w images were bias-corrected for distortion effects using field maps. We then extracted the average T1-w/T2-w ratio values across each vertex for each sulcus using custom Python code (Miller et al., 2021). The architectural features of all LPC/LPOJ sulci are documented in Supplementary Fig. 7.

To assess whether these four metrics differed between the slocs-v and surrounding sulci (cSTS3 and lTOS), we ran a repeated measure analysis of variance (rm-ANOVA) with the within-participant effects of sulcus (slocs-v, cSTS3, and lTOS), metric (surface area, depth, cortical thickness, and myelination), and hemisphere (left and right). Rm-ANOVAs (including sphericity correction) were implemented with the aov_ez function from the afex R package. Effect sizes for the ANOVAs are reported with the partial eta-squared metric ($\eta 2$). Post-hoc analyses were computed with the emmeans function from the emmeans R package (*p*-values corrected with Tukey's method). We also repeated these analyses for the three cSTS components (Petrides, 2019; Segal & Petrides, 2012) and the two intermediate parietal sulcal components (ips: aipsJ and pips (Petrides, 2019; Zlatkina & Petrides, 2014); detailed in the Supplementary Results and Supplementary Fig. 8) as these components, to our knowledge, have not been quantitatively compared in previous work.

Functional analyses

To determine if the slocs-v is functionally distinct from surrounding sulci, we generated functional connectivity profiles using recently developed analyses (Miller et al., 2021; Willbrand, Bunge, et al., 2023; Willbrand, Parker, et al., 2022). First, we used resting-state network parcellations for each individual participant from Kong and colleagues (Kong et al., 2019), who generated individual network definitions by applying a hierarchical Bayesian network algorithm to produce maps for each of the 17 networks in individual HCP participants. Importantly, this parcellation was conducted blind to both cortical folding and our sulcal definitions. Next, we resampled the network profiles for each participant onto the fsaverage cortical surface, and then to each native surface using CBIG tools (*https://github.com/ThomasYeoLab/CBIG*). We then calculated the spatial overlap between a sulcus and each of the 17 individual resting-state networks via the Dice coefficient (*Equation 1*):

$$(1)\quad DICE\,(X,Y) = \frac{2\,|X \cap Y|}{|X| + |Y|}$$

This process of calculating the overlap between each sulcus and the 17-network parcellation generated a "connectivity fingerprint" for each sulcus in each hemisphere of each participant. We then ran an rm-ANOVA with within-participant factors of sulcus (slocs-v, cSTS3, and lTOS), network (17 networks), and hemisphere (left and right) to determine if the network profiles (i.e., the Dice coefficient overlap with each network) of the slocs-v was differentiable from the surrounding sulci (i.e., cSTS3 and lTOS). Here we discuss effects related to networks that at least showed minor overlap with one sulcus (i.e., Dice ≥ .10). As in the prior analysis, we also repeated these analyses for the three cSTS components and the two intermediate parietal sulcal components (Supplementary Results and Supplementary Fig. 8).

Behavioral analyses

Model selection

The analysis relating sulcal morphology to spatial orientation and/or reasoning consisted of using a cross-validated (CV) least absolute shrinkage and selection operator (LASSO) regression to select the sulci that explained the most variance in the data and determined how much variance is explained by sulcal depth as a predictor of behavior, as implemented in our previous work (Maboudian et al., 2023; Voorhies et al., 2021; Willbrand, Ferrer, et al., 2023; Yao et al., 2022). A LASSO regression is well suited to address our question since it facilitates the model selection process and increases the generalizability of a model by providing a sparse solution that reduces coefficient values and decreases variance in the model without increasing bias (Heinze et al., 2018). Further, regularization is recommended in cases where there are many predictors (X > 10), as in this study, because this technique guards against overfitting and increases the likelihood that a model will generalize to other datasets. A LASSO performs L1 regularization by applying a penalty, or shrinking parameter (alpha, α), to the absolute magnitude of the coefficients. In this manner, low coefficients are set to zero and eliminated from the model. Therefore, LASSO affords data-driven variable selection that results in simplified models containing only the most predictive features, in this case, sulci predicting cognitive performance. This methodology improves model interpretability and prediction accuracy, as well as protects against overfitting, which improves generalizability (Ghojogh & Crowley, 2019; Heinze et al., 2018).

The depths of all LPC/LPOJ sulci were included as predictors in the LASSO regression model (Supplementary Methods for details on demographic control variables). We used nested CV to optimize the shrinking parameter for the LASSO regression. By convention (Heinze et al., 2018), we selected the model parameters that minimized the CV mean squared error (MSE_{cv}). Optimization was performed with the GridSearchCV function from the SciKit-learn package in Python. This function allowed us to determine the model parameters minimizing the MSE_{cv} by performing an exhaustive search across a range of α values. Nested CV was done as non-nested CV leads to biased performance (Cawley & Talbot, 2010; Vabalas et al., 2019).

To evaluate the performance of the model selected by the LASSO regression and verify the result of our feature selection, we used linear regression with leave-one-out CV (LooCV) to fit these selected models and to compare various models. Specifically, we measured the model performance for the relevant behavioral task using nested model comparison. With LooCV, we compared the LASSO-selected model with the predictors to a model with all left hemisphere sulci as predictors. All regression models were implemented with functions from the SciKit-learn Python package.

Assessing morphological and behavioral specificity

To assess whether our findings generalized to other anatomical features, we considered cortical thickness, which is consistently studied in cognitive neuroscience studies relating morphology to cognition (Dickerson et al., 2008; Gogtay et al., 2004; Voorhies et al., 2021; Willbrand, Ferrer, et al., 2023; Yao et al., 2022). To do so, we replaced sulcal depth with cortical thickness as the predictive metric in our LASSO-selected model. As with depth, the model was fit to the data with LooCV. To compare the thickness model to the depth model, we used the Akaike Information Criterion (AIC), which provides an estimate of in-sample prediction error and is suitable for non-nested model comparison. By comparing AIC scores, we are able to assess the relative performance of the two models. If the ΔAIC is > 2, it suggests an interpretable difference between models. If the ΔAIC is > 10, it suggests a strong difference between models, with the lower AIC value indicating the preferred model (Wagenmakers & Farrell, 2004). To also ascertain whether the relationship between LPC/LPOJ sulcal depth and cognition is specific to spatial orientation performance, or transferable to other general measures of cognitive processing, we investigated the generalizability of the sulcal-behavior relationship to another widely used measure of cognitive functioning: processing speed (Kail & Salthouse, 1994). Specifically, we used LooCV to predict processing speed instead of spatial orientation score. As with thickness, we compared the two models with the AIC.

Situating the slocs-v within modern group-level cortical parcellations

To putatively relate the slocs-v to modern multimodal (HCP multimodal parcellation, HCP-MMP (Glasser et al., 2016)) and cytoarchitectural (Julich-Brain atlas (Amunts et al., 2020)) regions of the cerebral cortex located in fsaverage template space, we quantified the Dice coefficient overlap between the slocs-v of each participant (resampled to fsaverage space) and the individual regions of interest comprising the HCP-MMP and Julich-Brain parcellations.

Retinotopic response mapping of LPC/LPOJ sulci

To assess whether any of the LPC/LPOJ sulci related to retinotopic representations, we leveraged population receptive field mapping data (Benson et al., 2018). For each sulcal MPM (as the retinotopic data were only available in this template space), we extracted the mean R^2 values (i.e., the percentage of variance in each vertex explained by the population receptive field model) for vertices that showed meaningful retinotopic responses across participants (thresholded at $R^2 >$ 10%) (Mackey et al., 2017).

Competing interests

The authors declare no competing financial interests.

Data availability

The processed data required to perform all statistical analyses and reproduce all Figures, as well as the probability maps, are available on GitHub (*https://github.com/cnl-berkeley/stable_projects*). Anonymized HCP neuroimaging data are publicly available on ConnectomeDB (*db.humanconnectome.org*). Raw data will be made available from the corresponding author upon request.

Code availability

The code is available on GitHub (*https://github.com/cnl-berkeley/stable_projects*) and Open Science Framework (*https://osf.io/7fwqk/*).

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Editors

Reviewing Editor
Jason Lerch
University of Oxford, Oxford, United Kingdom

Senior Editor
Michael Frank
Brown University, Providence, United States of America

Reviewer #1 (Public Review):

Summary:
Ever-improving techniques allow the detailed capture of brain morphology and function to the point where individual brain anatomy becomes an important factor. This study investigated detailed sulcal morphology in the parieto-occipital junction. Using cutting-edge methods, it provides important insights into local anatomy, individual variability, and local brain function. The presented work advances the field and will stimulate future research into this important area.

Strengths:
Detailed, very thorough methodology. Multiple raters mapped detailed sulci in a large cohort. The identified sulcal features and their functional and behavioural relevance are then studied using various complementary methods. The results provide compelling evidence for the importance of the described sulcal features and their proposed relationship to cortical brain function.

Comments on revised version:

The revised manuscript addresses all my concerns.

https://doi.org/10.7554/eLife.90451.2.sa3

Reviewer #2 (Public Review):

Summary:
After manually labelling 144 human adult hemispheres in the lateral parieto-occipital junction (LPOJ), the authors 1) propose a nomenclature for 4 previously unnamed highly variable sulci located between the temporal and parietal or occipital lobes, 2) focus on one of these newly named sulci, namely the ventral supralateral occipital sulcus (slocs-v) and compare it to neighbouring sulci to demonstrate its specificity (in terms of depth, surface area, gray matter thickness, myelination, and connectivity), 3) relate the morphology of a subgroup of sulci from the region including the slocs-v to the performance in a spatial orientation task, demonstrating behavioural and morphological specificity. In addition to these results, the authors propose an extended reflection on the relationship between these newly named landmarks and previous anatomical studies, a reflection about the slocs-v related to functional and cytoarchitectonic parcellations as well as anatomic connectivity and an insight about potential anatomical mechanisms relating sulcation and behaviour.

Strengths:
- To my knowledge, this is the first study addressing the variable tertiary sulci located between the superior temporal sulcus (STS) and intra-parietal sulcus (IPS).
- This is a very comprehensive study addressing altogether anatomical, architectural, functional and cognitive aspects.

- The definition of highly variable yet highly reproductible sulci such as the slocs-v feeds the community with new anatomo-functional landmarks (which is emphasized by the provision of a probability map in supp. mat., which in my opinion should be proposed in the main body).
- The comparison of different features between the slocs-v and similar sulci is useful to demonstrate their difference.
- The detailed comparison of the present study with state of the art contextualises and strengthens the novel findings.
- The functional study complements the anatomical description and points towards cognitive specificity related to a subset of sulci from the LPOJ
- The discussion offers a proposition of theoretical interpretation of the findings
- The data and code are mostly available online (raw data made available upon request).

Weaknesses:
- While the identification of the sulci has been done thoroughly with expert validation, the sulci have not been labelled in a way that enables the demonstration of the reproducibility of the labelling.

The proposed methodology is convincing in identifying and studying the relationship between highly variable sulci and cognition. This improves our refined understanding of the general anatomical variability in the LPOJ and its potential functional/cognitive correlates. This work is important to the understanding of sulcal variability and its implications on functional and cognitive aspects.

Comments on revised version:

Thank you for the elegant and informative work.

https://doi.org/10.7554/eLife.90451.2.sa2

Reviewer #3 (Public Review):

Summary:
72 subjects, and 144 hemispheres, from the Human Connectome Project had their parietal sulci manually traced. This identified the presence of previous undescribed shallow sulci. One of these sulci, the ventral supralateral occipital sulcus (slocs-v), was then demonstrated to have functional specificity in spatial orientation. The discussion furthermore provides an eloquent overview of our understanding of the anatomy of the parietal cortex, situating their new work into the broader field. Finally, this paper stimulates further debate about the relative value of detailed manual anatomy, inherently limited in participant numbers and areas of the brain covered, against fully automated processing that can cover thousands of participants but easily misses the kinds of anatomical details described here.

Strengths:
- This is the first paper describing the tertiary sulci of the parietal cortex with this level of detail, identifying novel shallow sulci and mapping them to behaviour and function.
- It is a very elegantly written paper, situating the current work into the broader field.
- The combination of detailed anatomy and function and behaviour is superb.

Weaknesses:
- the numbers of subjects are inherently limited both in number as well as in being typically developing young adults.
- while the paper begins by describing four new sulci, only one is explored further in greater detail.
- there is some tension between calling the discovered sulci new vs acknowledging they have

already been reported, but not named.
- the anatomy of the sulci, as opposed to their relation to other sulci, could be described in greater detail.

Overall, to summarize, I greatly enjoyed this paper and believe it to be a highly valued contribution to the field.

https://doi.org/10.7554/eLife.90451.2.sa1

Author response:

The following is the authors' response to the original reviews.

> ***Public Reviews:***
>
> ***Reviewer #1 (Public Review):***
>
> *Summary:*
>
> *Ever-improving techniques allow the detailed capture of brain morphology and function to the point where individual brain anatomy becomes an important factor. This study investigated detailed sulcal morphology in the parieto-occipital junction. Using cutting-edge methods, it provides important insights into local anatomy, individual variability, and local brain function. The presented work advances the field and will stimulate future research into this important area.*
>
> *Strengths:*
>
> *Detailed, very thorough methodology. Multiple raters mapped detailed sulci in a large cohort. The identified sulcal features and their functional and behavioural relevance are then studied using various complementary methods. The results provide compelling evidence for the importance of the described sulcal features and their proposed relationship to cortical brain function.*

We thank the Reviewer for highlighting the strengths of our methods and findings.

> *Weaknesses:*
>
> *A detailed description/depiction of the various sulcal patterns is missing.*

We agree that adding these details for the newly described sulci is necessary and have now done so. These details are included in the Results (Page 6):

"Beyond characterizing the incidence of sulci, it is also common in the neuroanatomical literature to qualitatively characterize sulci on the basis of fractionation and intersection with surrounding sulci (termed "sulcal types"; for examples in other cortical expanses, see Chiavaras & Petrides, 2000; Drudik et al., 2023; Miller et al., 2021; Paus et al., 1996; Weiner et al., 2014; Willbrand, Parker, et al., 2022). All four sulci most commonly did not intersect with other sulci (see Supplementary Tables 1-4 for a summary of the sulcal types of the slocs and pAngs dorsal and ventral components). The sulcal types were also highly comparable between hemispheres (rs > .99 , ps < .001)."

And in four new Supplementary Tables.

> *A possible relationship between sulcal morphology and individual demographics might provide more insight into anatomical variability.*

We have conducted additional analyses to relate sulcal incidence to demographic features (age and gender). These results are included on Pages 5-6:

"Given that sulcal incidence and patterning is also sometimes related to demographic features (Cachia et al., 2021; Leonard et al., 2009; Wei et al., 2017), subsequent GLMs relating the incidence and patterning of the three more variable sulci (slocs-d, pAngs-v, and pAngs-d) to demographic features (age and gender) revealed no associations for any sulcus (ps > .05)."

> *The unique dataset offers an opportunity to provide insights into laterality effects that should be explored.*

We included hemisphere as a factor in all models for this exact reason. Throughout the paper, we have edited the text to ensure that these laterality effects are more apparent to readers.

Further, we have a Supplementary Results section on hemispheric effects regarding the slocs-v, cSTS3, and lTOS:

"Hemispheric asymmetries in morphological, architectural, and functional features with regards to the slocs-v, cSTS3, and lTOS comparison

We observed a sulcus x metric x hemisphere interaction on the morphological and architectural features of the slocs-v ($F(4.20, 289.81) = 4.16$, $\eta2 = 0.01$, $p = .002$; the cSTS3 is discussed in the next section). Post hoc tests showed that this interaction was driven by the slocs-v being cortically thinner in the left than the right hemisphere ($p < .001$; Fig. 2a).

There was also a sulcus x network x hemisphere interaction on the functional connectivity profiles (using functional connectivity parcellations from (Kong et al., 2019)) of the slocs-v and lTOS ($F(32, 2144) = 3.99$, $\eta2 = 0.06$, $p < .001$; the cSTS3 is discussed in the next section). Post hoc tests showed that this interaction was driven by three effects: (i) the slocs-v overlapped more with the Default C subnetwork in the left than the right hemisphere ($p = .013$), (ii) the lTOS overlapped more with Visual A subnetwork in the right than the left hemisphere ($p = .002$), and (iii) the lTOS overlapped more with the Visual B subnetwork in the left than the right hemisphere ($p = .002$; Fig. 2b)."

As well as the other STS rami on morphology:

"It is also worth noting that there was a sulcus x metric x hemisphere interaction ($F(4, 284.12) = 6.60$, $\eta2 = 0.08$, $p < .001$). Post hoc tests showed that: (i) the cSTS3 was smaller ($p < .001$) and thinner ($p = .025$) in the left than the right hemisphere (Supplementary Fig. 8a), (ii) the cSTS2 was shallower ($p = .004$) and thicker ($p < .001$) in the right than left hemisphere (Supplementary Fig. 8a), and (iii) the cSTS1 was shallower ($p < .001$), smaller ($p = .002$), thinner ($p = .001$), and less myelinated ($p < .001$) in the left than the right hemisphere (Supplementary Fig. 8a)."

And functional connectivity of the STS rami:

"There was also a sulcus x network x hemisphere interaction ($F(32, 2208) = 12.26$, $\eta2 = 0.15$, $p < .001$). Post hoc tests showed differences for each cSTS component. Here, the cSTS1 overlapped more with the Auditory network ($p < .001$), less with the Control B subnetwork ($p < .001$), more with the Control C subnetwork ($p < .001$), less with the Default B subnetwork ($p < .001$), more with the Default C subnetwork ($p < .001$), more with the Ventral Attention B subnetwork ($p < .001$), and more with the Visual A subnetwork ($p = .024$) in the right than in the left hemisphere (Supplementary Fig. 8b). In addition, the cSTS2 overlapped more with the Control B subnetwork ($p < .001$), more with the Control C subnetwork ($p < .001$), less with the Default B subnetwork ($p < .001$), and less with the Temporal-Parietal network ($p = .011$) in the right than in the left hemisphere (Supplementary Fig. 8b). Finally, the cSTS3 overlapped more with the Control B subnetwork (p = .002), less with the Default B subnetwork (p = .014), more with the Default C subnetwork (p = .022), less with the Ventral Attention B subnetwork (p = .029) in the right than in the left hemisphere (Supplementary Fig. 8b)."

> ***Reviewer #2 (Public Review):***
>
> *Summary: After manually labeling 144 human adult hemispheres in the lateral parieto-occipital junction (LPOJ), the authors 1) propose a nomenclature for 4 previously unnamed highly variable sulci located between the temporal and parietal or occipital lobes, 2) focus on one of these newly named sulci, namely the ventral supralateral occipital sulcus (slocs-v) and compare it to neighboring sulci to demonstrate its specificity (in terms of depth, surface area, gray matter thickness, myelination, and connectivity), 3) relate the morphology of a subgroup of sulci from the region including the slocs-v to the performance in a spatial orientation task, demonstrating behavioral and morphological specificity. In addition to these results, the authors propose an extended reflection on the relationship between these newly named landmarks and previous anatomical studies, a reflection about the slocs-v related to functional and cytoarchitectonic parcellations as well as anatomic connectivity and an insight about potential anatomical mechanisms relating sulcation and behavior.*
>
> *Strengths:*
>
> *- To my knowledge, this is the first study addressing the variable tertiary sulci located between the superior temporal sulcus (STS) and intraparietal sulcus (IPS).*
>
> *- This is a very comprehensive study addressing altogether anatomical, architectural, functional and cognitive aspects.*
>
> *- The definition of highly variable yet highly reproducible sulci such as the slocs-v feeds the community with new anatomo-functional landmarks (which is emphasized by the provision of a probability map in supp. mat., which in my opinion should be proposed in the main body).*
>
> *- The comparison of different features between the slocs-v and similar sulci is useful to demonstrate their difference.*
>
> *- The detailed comparison of the present study with state of the art contextualizes and strengthens the novel findings.*
>
> *- The functional study complements the anatomical description and points towards cognitive specificity related to a subset of sulci from the LPOJ*
>
> *- The discussion offers a proposition of theoretical interpretation of the findings*
>
> *- The data and code are mostly available online (raw data made available upon request).*

We thank the Reviewer for highlighting the strengths of our methods, analyses, and applications of our findings.

> *Weaknesses:*
>
> *- While three independent raters labeled all hemispheres, one single expert finalized the decision. Because no information is reported on the inter-rater variability, this somehow equates to a single expert labeling the whole cohort, which could result in biased labellings and therefore affect the reproducibility of the new labels.*

Our group does not use an approach amenable to calculating inter-rater agreements to expedite the process of defining thousands of sulci at the individual level in multiple regions. Our method consists of a two-tiered procedure. Here, authors YT and TG defined sulci which were then checked by a trained expert (EHW). These were then checked again by senior author (KSW) . We emphasize that this process has produced reproducible anatomical results in other regions such as posteromedial cortex (Willbrand et al., 2023 Science Advances; Willbrand et al., 2023 Communications Biology; Maboudian et al., 2024 The Journal of Neuroscience), ventral temporal cortex (Weiner et al., 2014 NeuroImage; Miller et al., 2020 Scientific Reports; Parker et al., 2023 Brain Structure and Function), and lateral prefrontal cortex (Miller et al., 2021 The Journal of Neuroscience; Voorhies et al., 2021 Nature Communications; Yao et al., 2022 Cerebral Cortex; Willbrand et al., 2022 Brain Structure and Function; Willbrand et al., 2023 The Journal of Neuroscience) across age groups, species, and clinical populations. Further, in the Supplemental Materials we provide post mortem images showing that these sulci exist outside of cortical reconstructions, supporting this updated sulcal schematic of the lateral parieto-occipital junction. For the present study, by the time the final tier of our method was reached, we emphasize that a very small percentage (~2%) of sulcal definitions were actually modified. We will include an exact percentage in future publications in LPC/LOPJ.

> *- 3 out of the 4 newly labeled sulci are only described in the very first part and never reused. This should be emphasized as it is far from obvious at first glance of the article.*

We have edited the Abstract (shown below, on Page 1) and paper throughout to emphasize the emphasis on the slocs-v over the other three sulci.

“After defining thousands of sulci in a young adult cohort, we revised the previous LPC/LPOJ sulcal landscape to include four previously overlooked, small, shallow, and variable sulci. One of these sulci (ventral supralateral occipital sulcus, slocs-v) is present in nearly every hemisphere and is morphologically, architecturally, and functionally dissociable from neighboring sulci. A data-driven, model-based approach, relating sulcal depth to behavior further revealed that the morphology of only a subset of LPC/LPOJ sulci, including the slocs-v, is related to performance on a spatial orientation task.”

It is worth noting that we have added additional analyses that include the other three newly-characterized sulci in response to Reviewer 1. We first described the relationship between these sulci and demographic features, alongside analyses on the patterning of these sulci, which are included in the Results (Page 6):

“Beyond characterizing the incidence of sulci, it is also common in the neuroanatomical literature to qualitatively characterize sulci on the basis of fractionation and intersection with surrounding sulci (termed “sulcal types”; for examples in other cortical expanses, see Chiavaras & Petrides, 2000; Drudik et al., 2023; Miller et al., 2021; Paus et al., 1996; Weiner et al., 2014; Willbrand, Parker, et al., 2022). All four sulci most commonly did not intersect with other sulci (see Supplementary Tables 1-4 for a summary of the sulcal types of the slocs and pAngs dorsal and ventral components). The sulcal types were also highly comparable between hemispheres (rs > .99 , ps < .001). Though we characterize these sulci in this paper for the first time, the location of these four sulci is consistent with the presence of variable “accessory sulci” in this cortical expanse mentioned in prior modern and classic studies (Supplementary Methods). We could also identify these sulci in post-mortem hemispheres (Supplementary Figs. 2, 3), ensuring that these sulci were not an artifact of the cortical reconstruction process.

Given that sulcal incidence and patterning is also sometimes related to demographic features (Cachia et al., 2021; Leonard et al., 2009; Wei et al., 2017), subsequent GLMs relating the incidence and patterning of the three more variable sulci (slocs-d, pAngs-v, and pAngs-d) to demographic features (age and gender) revealed no associations for any sulcus (ps > .05). Finally, to help guide future research on these newly- and previously-classified LPC/LPOJ sulci, we generated probabilistic maps of each of these 17 sulci and share them with the field with the publication of this paper (Supplementary Fig. 6; Data availability)."

> *- The tone of the article suggests a discovery of these 4 sulci when some of them have already been reported (as rightfully highlighted in the article), though not named nor studied specifically. This is slightly misleading as I interpret the first part of the article as a proposition of nomenclature rather than a discovery of sulci.*

We have toned down our language throughout the paper, emphasizing that this paper is updating the sulcal landscape of LPC/LOPJ taking into account these sulci that have not been comprehensively described previously. For example, in the Abstract (Page 1), we now write:

"After defining thousands of sulci in a young adult cohort, we revised the previous LPC/LPOJ sulcal landscape to include four previously overlooked, small, shallow, and variable sulci. One of these sulci (ventral supralateral occipital sulcus, slocs-v) is present in nearly every hemisphere and is morphologically, architecturally, and functionally dissociable from neighboring sulci. A data-driven, model-based approach, relating sulcal depth to behavior further revealed that the morphology of only a subset of LPC/LPOJ sulci, including the slocs-v, is related to performance on a spatial orientation task. "

> *- The article never mentions the concept of merging of sulcal elements and the potential effect it could have on the labeling of the newly named variable sulci.*

We emphasize that we use multiple surfaces (pial, inflated, smoothwm) to help distinguish intersecting sulci from one another. We include extra text in the Methods (Page 21):

"We defined LPC/LPOJ sulci for each participant based on the most recent schematics of sulcal patterning by Petrides (2019) as well as pial, inflated, and smoothed white matter (smoothwm) FreeSurfer cortical surface reconstructions of each individual. In some cases, the precise start or end point of a sulcus can be difficult to determine on a surface (Borne et al., 2020); however, examining consensus across multiple surfaces allowed us to clearly determine each sulcal boundary in each individual. "

Further, upon quantifying the patterning of these variable sulci, a majority of the time they are independent (described in the Results on Page 6):

"Beyond characterizing the incidence of sulci, it is also common in the neuroanatomical literature to qualitatively characterize sulci on the basis of fractionation and intersection with surrounding sulci (termed "sulcal types"; for examples in other cortical expanses, see (Chiavaras & Petrides, 2000; Drudik et al., 2023; Miller et al., 2021; Paus et al., 1996; Weiner et al., 2014; Willbrand, Parker, et al., 2022). All four sulci most commonly did not intersect with other sulci (see Supplementary Tables 1-4 for a summary of the sulcal types of the slocs and pAngs dorsal and ventral components). The sulcal types were also highly comparable between hemispheres (rs > .99 , ps < .001)."

Thus, merging sulcal elements likely had a minimal impact on the present definitions.

> *- The definition of the new sulci is solely based on their localization relative to other sulci which are themselves variable (e.g. the 3rd branch of the STS can show different locations and different orientation, potentially affecting the definition of the slocs-v). This is not addressed in the discussion.*

As displayed in our probabilistic maps of these sulci (Supplementary Fig. 6), the cSTS components (2-4) are actually relatively consistent between individuals, and thus, future investigators can utilize these maps to help define these sulci in new hemispheres.

Nevertheless, there is, of course, individual variability in the location of these sulci, and we do agree that this point brought up by the Reviewer is important. We have now added text to the Limitations section of the Discussion (Pages 15-16):

"The main limitation of our study is that presently, the most accurate methodology to define sulci —especially the small, shallow, and variable PTS—requires researchers to manually trace each structure on the cortical surface reconstructions. This method is limited due to the individual variability of cortical sulcal patterning (Fig. 1, Supplementary Fig. 5), which makes it challenging to identify sulci, let alone PTS, without extensive experience and practice. However, we anticipate that our probabilistic maps will provide a starting point and hopefully, expedite the identification of these sulci in new participants. This method is also arduous and time-consuming—which, on the one hand, limits the sample size in terms of number of participants, while on the other, results in thousands of precisely defined sulci. This push-pull relationship reflects a broader conversation in the human brain mapping and cognitive neuroscience fields between a balance of large N studies and "precision imaging" studies in individual participants (Allen et al., 2022; Gratton et al., 2022; Naselaris et al., 2021; Rosenberg and Finn, 2022)."

> *- The new sulci are only defined in terms of localization relative to other sulci, and no other property is described (general length, depth, orientation, shape...), making it hard for a new observer to take labeling decisions in case of conflict.*

To help guide future investigators, we now show these metrics for all sulci in Supplemental Figure 7 to help future groups identify these sulci with the assistance of their general morphology.

> *- The very assertive tone of the article conveys the idea that these sulci are identifiable certainly in most cases, when by definition these highly variable tertiary sulci are sometimes very difficult to take decisions on.*

The highly variable nature of ¾ of the putative tertiary sulci (slocs-v, slocs-d, pAngs-v, pAngs-d) described here is why we focused on the slocs-v (as it is identifiable in nearly all f hemispheres). However, we have edited our language throughout the text to also emphasize the variability of these sulci. For example, in the Results (Page 5), we now write:

"In previous research in small sample sizes, neuroanatomists noticed shallow sulci in this cortical expanse (Supplementary Methods and Supplementary Figs. 1-4 for historical details). In the present study, we fully update this sulcal landscape considering these overlooked indentations. In addition to defining the 13 sulci previously described within the LPC/LPOJ, as well as the posterior superior temporal cortex (Methods) (Petrides, 2019) in individual participants, we could also identify as many as four small and shallow PTS situated within the LPC/LPOJ that were highly variable across individuals and uncharted until now (Supplementary Methods and Supplementary Figs. 1-4). Macroanatomically, we could identify two sulci between the cSTS3 and the IPS-PO/lTOS ventrally and two sulci between the cSTS2 and the pips/IPS dorsally. We focus our analyses on the slocs-v since it was identifiable in nearly every hemisphere."

> *- I am not absolutely convinced with the labeling proposed of a previously reported sulcus, namely the posterior intermediate parietal sulcus.*

In defining previously-identified LPC sulci, we followed the previous labeling procedure by Petrides (2019) alongside historical definitions (detailed in Supplementary Figures 1-4). Nevertheless, future deep learning algorithms using these and others data can be used to rectify discrepancies in labeling (e.g., Borne et al., 2020 Medical Image Analysis; Lyu et al., 2021 NeuroImage). We discuss these points in the Limitations section of the Discussion (Pages 16-17):

“The main limitation of our study is that presently, the most accurate methodology to define sulci —especially the small, shallow, and variable PTS—requires researchers to manually trace each structure on the cortical surface reconstructions. This method is limited due to the individual variability of cortical sulcal patterning (Fig. 1, Supplementary Fig. 5), which makes it challenging to identify sulci without extensive experience and practice. However, we anticipate that our probabilistic maps will provide a starting point and hopefully, expedite the identification of these sulci in new participants. This should accelerate the process of subsequent studies confirming the accuracy of our updated schematic of LPC/LOPJ. This manual method is also arduous and time-consuming, which, on the one hand, limits the sample size in terms of number of participants, while on the other, results in thousands of precisely defined sulci. This push-pull relationship reflects a broader conversation in the human brain mapping and cognitive neuroscience fields between a balance of large N studies and “precision imaging” studies in individual participants (Allen et al., 2022; Gratton et al., 2022; Naselaris et al., 2021; Rosenberg & Finn, 2022). Though our sample size is comparable to other studies that produced reliable results relating sulcal morphology to brain function and cognition (e.g., (Cachia et al., 2021; Garrison et al., 2015; Lopez-Persem et al., 2019; Miller et al., 2021; Roell et al., 2021; Voorhies et al., 2021; Weiner, 2019; Willbrand, Parker, et al., 2022; Willbrand, Voorhies, et al., 2022; Yao et al., 2022), ongoing work that uses deep learning algorithms to automatically define sulci should result in much larger sample sizes in future studies (Borne et al., 2020; Lyu et al., 2021). Finally, the time-consuming manual definitions of primary, secondary, and PTS also limit the cortical expanse explored in each study, thus, restricting the present study to LPC/LPOJ. “

> *Assuming that the labelling of all sulci reported in the article is reproducible, the different results are convincing and in general, this study achieves its aims in defining more precisely the sulcation of the LPOJ and looking into its functional/cognitive value. This work clearly offers a finer understanding of sulcal pattern in this region, and lacks only little for the new markers to be convincingly demonstrated. An overall coherence of the labelling can still be inferred from the supplementary material which support the results and therefore the conclusions, yet, addressing some of the weaknesses listed above would greatly enhance the impact of this work. This work is important to the understanding of sulcal variability and its implications on functional and cognitive aspects.*

We thank the Reviewer for their positive remarks on the implications of this work.

> ***Reviewer #3 (Public Review):***
>
> *Summary: 72 subjects, and 144 hemispheres, from the Human Connectome Project had their parietal sulci manually traced. This identified the presence of previously undescribed shallow sulci. One of these sulci, the ventral supralateral occipital sulcus (slocs-v), was then demonstrated to have functional specificity in spatial orientation. The discussion furthermore provides an eloquent overview of our understanding of the anatomy of the parietal cortex, situating their new work into the broader field. Finally, this paper stimulates further debate about the relative value of detailed manual anatomy, inherently limited in participant numbers and areas of the brain covered, against fully automated processing that can cover thousands of participants but easily misses the kinds of anatomical details described here.*
>
> *Strengths:*

> *- This is the first paper describing the tertiary sulci of the parietal cortex with this level of detail, identifying novel shallow sulci and mapping them to behaviour and function.*
>
> *- It is a very elegantly written paper, situating the current work into the broader field.*
>
> *- The combination of detailed anatomy and function and behaviour is superb.*

We thank the Reviewer for their positive remarks on paper and our findings.

> *Weaknesses:*
>
> *- The numbers of subjects are inherently limited both in number as well as in typically developing young adults.*

We emphasize that the sample size is limited due to the arduous nature of manually defining sulci; however, we provide probabilistic maps with the publication of this work to help expedite this process for future investigators. Further, with improved deep learning algorithms, the sample sizes in future neuroanatomical studies should be enhanced. We discuss these points in the Limitations section of the Discussion (Pages 16-17):

"The main limitation of our study is that presently, the most accurate methodology to define sulci —especially the small, shallow, and variable PTS—requires researchers to manually trace each structure on the cortical surface reconstructions. This method is limited due to the individual variability of cortical sulcal patterning (Fig. 1, Supplementary Fig. 5), which makes it challenging to identify sulci without extensive experience and practice. However, we anticipate that our probabilistic maps will provide a starting point and hopefully, expedite the identification of these sulci in new participants. This should accelerate the process of subsequent studies confirming the accuracy of our updated schematic of LPC/LOPJ. This manual method is also arduous and time-consuming, which, on the one hand, limits the sample size in terms of number of participants, while on the other, results in thousands of precisely defined sulci. This push-pull relationship reflects a broader conversation in the human brain mapping and cognitive neuroscience fields between a balance of large N studies and "precision imaging" studies in individual participants (Allen et al., 2022; Gratton et al., 2022; Naselaris et al., 2021; Rosenberg & Finn, 2022). Though our sample size is comparable to other studies that produced reliable results relating sulcal morphology to brain function and cognition (e.g., (Cachia et al., 2021; Garrison et al., 2015; Lopez-Persem et al., 2019; Miller et al., 2021; Roell et al., 2021; Voorhies et al., 2021; Weiner, 2019; Willbrand, Parker, et al., 2022; Willbrand, Voorhies, et al., 2022; Yao et al., 2022), ongoing work that uses deep learning algorithms to automatically define sulci should result in much larger sample sizes in future studies (Borne et al., 2020; Lyu et al., 2021). The time-consuming manual definitions of primary, secondary, and PTS also limit the cortical expanse explored in each study, thus restricting the present study to LPC/LPOJ."

> *- While the paper begins by describing four new sulci, only one is explored further in greater detail.*

Due to the increased variability of three of the four newly-classified sulci, we chose to only focus on the slocs-v given that it was present in nearly all hemispheres. In response to other reviewers, we have conducted additional analyses that also describe these new sulci and potential factors related to their incidence (Page 6):

"Given that sulcal incidence and patterning is also sometimes related to demographic features (Cachia et al., 2021; Leonard et al., 2009; Wei et al., 2017), subsequent GLMs relating the incidence and patterning of the three more variable sulci (slocs-d, pAngs-v, and pAngs-d) to demographic features (age and gender) revealed no associations for any sulcus (ps > .05)."

In addition, given that sulcal variability is cognitively (e.g., Amiez et al., 2018 Scientific Reports; Cachia et al., 2021 Frontiers in Neuroanatomy; Garrison et al., 2015 Nature Communications; Willbrand et al., 2022, 2023 Brain Structure & Function), anatomically (e.g., Amiez et al., 2021 Communications Biology; Vogt et al., 1995 Journal of Comparative Neurology), functionally (e.g., Lopez Persem et al., 2019 The Journal of Neuroscience), and translationally (e.g., Yucel et al., 2002 Biological Psychiatry) relevant, future research can investigate these relationships regarding the slocs-d and pAngs components. We have added text to the Limitations section of the Discussion (Pages 17-18) to discuss this:

"Finally, although we did not focus on the relationship between the other three PTS (slocs-d, pAngs-v, and pAngs-d) to anatomical and functional features of LPC and cognition, given that variability in sulcal incidence is cognitively (Amiez et al., 2018; Cachia et al., 2021; Garrison et al., 2015; Willbrand, Jackson, et al., 2023; Willbrand, Voorhies, et al., 2022), anatomically (Amiez et al., 2021; Vogt et al., 1995), functionally (Lopez-Persem et al., 2019), and translationally (Clark et al., 2010; Le Provost et al., 2003; Meredith et al., 2012; Nakamura et al., 2020; Yücel et al., 2002, 2003) relevant, future work can also examine the relationship between the more variable slocs-d, pAngs-v, and pAngs-d and these features."

> *- There is some tension between calling the discovered sulci new vs acknowledging they have already been reported, but not named.*

We have edited the manuscript throughout to emphasize our primary focus on revising the LPC/LOPJ sulcal landscape to include these often overlooked small, shallow, and variable putative tertiary sulci, rather than using the terms "discovered sulci" and "new."

> *- The anatomy of the sulci, as opposed to their relation to other sulci, could be described in greater detail.*

Beyond the radar plots in the main text which compare specific groupings of sulci, we now show the morphological metrics for all sulci investigated in the present work in Supplemental Figure 7.

> *Overall, to summarize, I greatly enjoyed this paper and believe it to be a highly valued contribution to the field.*

We are glad the Reviewer enjoyed reading our paper and thank them for their positive thoughts on the potential impact of this work on the field.

> ***Recommendations for the authors:***
>
> ***Reviewer #1 (Recommendations For The Authors):***
>
> *(1) The slocs-v is found in 71 subjects left and right. Is that the same subject?*

No, these are different subjects.

> *(2) How were the 72 subjects chosen?*

The subjects were randomly selected from the HCP database as describe in the methods (Page 18):

"Here, we used 72 randomly-selected participants, balanced for gender (following the terminology of the HCP data dictionary), from the HCP database (50% female, 22-36 years old, and 90% right-handed; there was no effect of handedness on our behavioral tasks;

Supplementary materials) that were also analyzed in several prior studies (Hathaway et al., 2023; Miller et al., 2021, 2020; Willbrand et al., 2023b, 2023c, 2022a)."

> *(3) Are there effects of laterality on sulcal pattern? Table?*

We now include sulcal pattern results in the Results section and Supplementary Materials; although there were no laterality effects regarding the sulcal pattern .

> *(4) Depiction/description of common sulcal patterns*

We now include sulcal pattern results in the Results section and Supplementary Materials.

> *(5) Is there a relationship between sulcal patterns and demographic features?*

We now include analyses on this in the Results section. There is no relationship between sulcal patterns and demographic features.

> *(6) Just for clarity, the sulcal features are studied and extracted in native space?*

Yes, sulcal features are studied and extracted in native space, as described in the Methods section (Page 19):

"Anatomical T1-weighted (T1-w) MRI scans (0.8 mm voxel resolution) were obtained in native space from the HCP database. Reconstructions of the cortical surfaces of each participant were generated using FreeSurfer (v6.0.0), a software package used for processing and analyzing human brain MRI images (surfer.nmr.mgh.harvard.edu) (Dale et al., 1999; Fischl et al., 1999). All subsequent sulcal labeling and extraction of anatomical metrics were calculated from these native space reconstructions generated through the HCP's version of the FreeSurfer pipeline (Glasser et al., 2013)."

> *(7) The authors use "Gender". Are they referring to biological sex (female/male) or socially defined characteristics (man/woman etc.)?*

The term gender is referred to socially defined characteristics, as used by the HCP data dictionary (Methods page 18):

"Here, we used 72 randomly-selected participants, balanced for gender (following the terminology of the HCP data dictionary), from the HCP database (50% female, 22-36 years old, and 90% right-handed; there was no effect of handedness on our behavioral tasks; Supplementary materials) that were also analyzed in several prior studies (Hathaway et al., 2023; Miller et al., 2021, 2020; Willbrand et al., 2023b, 2023c, 2022a)."

> *(8) Fig 2. Grey is poorly visible compared to green and blue.*

The shade of gray has been edited to be more distinguishable.

> *(9) The relationship between behavior and sulcal features is significant but weak.*

We acknowledge that the morphological-behavioral relationship identified in the present study explains a modest amount of variance; however, the more important aspect of the finding is that multiple sulci identified in the model are recently-characterized sulci in LPC/LOPJ identified by our group and others (Petrides, 2019), and thus, the relationship would have been overlooked or lost if these sulci were not identified. We have added text to the Limitations section of the Discussion (Pages 17-18) to emphasize this point:

“It is also worth noting that the morphological-behavioral relationship identified in the present study explains a modest amount of variance; however, the more important aspect of our findings is that multiple sulci identified in our model-based approach are recently-characterized sulci in LPC/LOPJ identified by our group and others (Petrides, 2019), and thus, the relationship would have been overlooked or lost if these sulci were not identified. “

> *(10) The Limitation section could be expanded.*

We have added additional text to flesh out the Limitations section of the Discussion (Pages 17-18):

“It is also worth noting that the morphological-behavioral relationship identified in the present study explains a modest amount of variance; however, the more important aspect of our findings is that multiple sulci identified in our model-based approach are recently-characterized sulci in LPC/LOPJ identified by our group and others (Petrides, 2019), and thus, the relationship would have been overlooked or lost if these sulci were not identified. Finally, although we did not focus on the relationship between the other three PTS (slocs-d, pAngs-v, and pAngs-d) to anatomical and functional features of LPC and cognition, given that variability in sulcal incidence is cognitively (Amiez et al., 2018; Cachia et al., 2021; Garrison et al., 2015; Willbrand, Jackson, et al., 2023; Willbrand, Voorhies, et al., 2022), anatomically (Amiez et al., 2021; Vogt et al., 1995), functionally (Lopez-Persem et al., 2019), and translationally (Clark et al., 2010; Le Provost et al., 2003; Meredith et al., 2012; Nakamura et al., 2020; Yücel et al., 2002, 2003) relevant, future work can also examine the relationship between the more variable slocs-d, pAngs-v, and pAngs-d and these features. “

> ***Reviewer #2 (Recommendations For The Authors):***
>
> *First, I would like to thank the authors for their important contribution to the field of sulcal studies and anatomo-functional correlates. My main comments about the work are treated in the public review, and I will only address details in this section. I have detected a number of typos which are harder to report from a document in which lines are not numbered. Could you please submit a numbered document for the next iteration?*
>
> *- p2. "hominoid-specific, shallow indentations, or sulci" - can lead to misunderstanding that sulci are hominoid-specific and shallow*

Sentence has been rewritten:

“Of all the neuroanatomical features to target, recent work shows that morphological features of the shallower, later developing, hominoid-specific indentations of the cerebral cortex (also known as putative tertiary sulci, PTS) are not only functionally and cognitively meaningful, but also are particularly impacted by multiple brain-related disorders and aging (Amiez et al., 2019, 2018; Ammons et al., 2021; Cachia et al., 2021; Fornito et al., 2004; Garrison et al., 2015; Harper et al., 2022; Hathaway et al., 2023; Lopez-Persem et al., 2019; Miller et al., 2021, 2020; Nakamura et al., 2020; Parker et al., 2023; Voorhies et al., 2021; Weiner, 2019; Willbrand et al., 2023b, 2023c, 2022a, 2022b; Yao et al., 2022).”

> *- p2. next sentence (starting with "The combination [...]": not clear that you are addressing tertiary sulci here, maybe introduce the concept beforehand?*

The previous sentence (just above) has been edited to introduce putative tertiary sulci beforehand.

> *- p5. error in numbering of sulci relative to Fig1. (5,6,7,8 -> 6,7,8,9)*

Sulcal numbering has been fixed.

> *-p5. reference to supp mat -> I would have expected the nomenclature used in Borne et al. 2020 to be discussed alongside with the state of the art. How would you relate F.I.P.r.int.1 and F.I.P.r.int.2 to the sulci you describe?*

We thank the Reviewer for bringing up this relevant literature. The F.I.P.r.int. 1 and 2 are described as rami of the IPS, whereas the slocs and pAngs are independent, small indentations near the IPS, but not part of the complex. Nevertheless, future work should integrate these two schematics together to establish the most comprehensive sulcal map of LPC/LOPJ. We have added text to the Supplementary Methods detailing the differences between the F.I.P.r.int.1 and F.I.P.r.int.2 and slocs-/pAngs:

"slocs/pAng vs. F.I.P.r.int.1 and F.I.P.r.int.2

Recent work (Borne et al., 2020; Perrot et al., 2011) identified two intermediate rami of the IPS (F.I.P.r.int.1 and F.I.P.r.int.2) that were not defined in the present investigation. Crucially, the newly classified sulci here (slocs and pAngs) are distinguishable from the two F.I.P.r.int. in that the F.I.P.r.int. are branches coming off the main body of the IPS (Borne et al., 2020; Perrot et al., 2011), whereas the slocs/pAngs are predominantly non-intersecting ("free") structures that never intersected with the IPS (Supplementary Tables 1-4)."

> *- p6. Fig 1.a. labelling discrepancy between line 1 and 2, column 4: the labels 10 and 11 from the inflated hemisphere do not match the labels 10 and 11 in the pial surface. Fig 1.b. swapped label 2 and 3 in the 4th hemisphere*

These aspects of Figure 1 have been edited accordingly.

> *- p7. "(iii) the slocs-v was thicker than both the cSTS3 and lTOS" -> the slocs-v showed thicker gray matter?*

The sentence has been adjusted (Page 7):

"(iii) the slocs-v showed thicker gray matter than both the cSTS3 and lTOS (ps < .001), "

> *- p9. Six left hemisphere LPC/LPOJ sulci were related to spatial orientation task performance -> missing*

Fixed (Page 9):

"Six left hemisphere LPC/LPOJ sulci were related to spatial orientation task performance (Fig. 3a, b). "

> *- p14. "Steel and colleagues" -> missing space*

Fixed (Page 14):

"Furthermore, the slocs-v appears to lie at the junction of scene-perception and place-memory activity (a transition that also consistently co-localizes with the HCP-MMP area PGp) as identified by Steel and colleagues (2021)."

> *- p20. Probability maps "we share these maps with the field" -> specify link to data availability*

The link to data availability has been added (Page 21):

"To aid future studies interested in investigating LPC/LPOJ sulci, we share these maps with the field (Data availability). "

> ***Reviewer #3 (Recommendations For The Authors):***
>
> *No detailed recommendations not already present in the rest of the review.*

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