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Original Article

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Neural representations of non-symbolic magnitudes show familial specificity in the right intraparietal sulcus

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Parental skills strongly predict children's cognitive development. This is the case even for abilities such as non-symbolic magnitude processing, which are evolutionary old and might be expected to show relatively invariant neural architecture. However, whether this behavioral similarity reflects similar neural representations between parents and children is unknown. Here we combined fMRI with dyadic representational similarity analysis to measure mother–child neural similarity during a numerosity adaptation task. Forty-four mother–child dyads (children's mean age = 8.55 yr) viewed sequences of dot arrays where numerosity remained either constant or varied. We assessed whether neural patterns associated with the numerosity adaptation effect showed greater similarity in familial than non-familial dyads. Results revealed family-specific neural similarity in the right intraparietal sulcus, a core region for non-symbolic magnitude processing. Structural analyses revealed that cortical thickness in this region also showed family-specific similarity, suggesting that functional transmission may partly reflect shared anatomical properties. These findings indicate that even evolutionarily ancient cognitive systems like the approximate number system show intergenerational neural transmission. Together with prior evidence of familial transmission in regions associated with executive functions during mental arithmetic, the present study highlights multiple pathways through which math skills may be transmitted from parents to children.

Keywords **fMRI, intergenerational neuroimaging, intraparietal sulcus, non-symbolic magnitude, representational searchlight similarity analyses**

Introduction

Parents substantially shape children's cognitive and academic development. This influence is demonstrated by research showing behavioral resemblance between parents and children in various skills (Anger and Heineck 2010; van Bergen et al. 2015; Bernabini et al. 2021), but also by neuroimaging studies exploring the relation between brain structure and function across generations (Qu et al. 2023; Constant-Varlet et al. 2024). These intergenerational studies have shown parent–child correlations of structural measures in several regions (Foland-Ross et al. 2016; Yamagata et al. 2016; Vandermosten et al. 2020; Fehlbaum et al. 2022; Minami et al. 2022, Sep 9). Functional studies have also shown parent–child resemblance in activity and connectivity (Colich et al. 2017; Kim et al. 2021; Takagi et al. 2021; Su et al. 2022), sometimes relating these similarities to behaviors (Lee et al. 2017a, 2017b). However, a limitation of intergenerational studies has often been the reliance on structural indices and resting-state measures, which cannot directly characterize cognitive processes associated with specific brain regions during task performance.

In a recent study (Constant-Varlet et al. 2025), we addressed this challenge by examining mother–child neural similarity during mental arithmetic. Using dyadic searchlight representational similarity analysis (RSA) across the whole-brain (see Fig. 1A), we assessed whether brain activity associated with mental arithmetic was more similar in familial dyads (ie mother–child dyads from the same family) than in non-familial dyads (ie mother–child dyads from different families). We found family-specific similarity in the anterior insula and precentral gyrus. These regions are more often associated with executive processing (Sridharan et al. 2008; Nee et al. 2013) than with numerical representations, which are instead thought to be supported by the intraparietal sulcus (IPS) (Dehaene et al. 2004). Therefore, the study suggests familial transmission of arithmetic-related brain activity may primarily involve executive functioning rather than numerical processing mechanisms.

Why might familial transmission involve executive regions but not the IPS? Answering this question is important because it can reveal whether intergenerational transmission occurs primarily through domain-general systems or whether it can also involve domain-specific circuits. On the one hand, there might be relative

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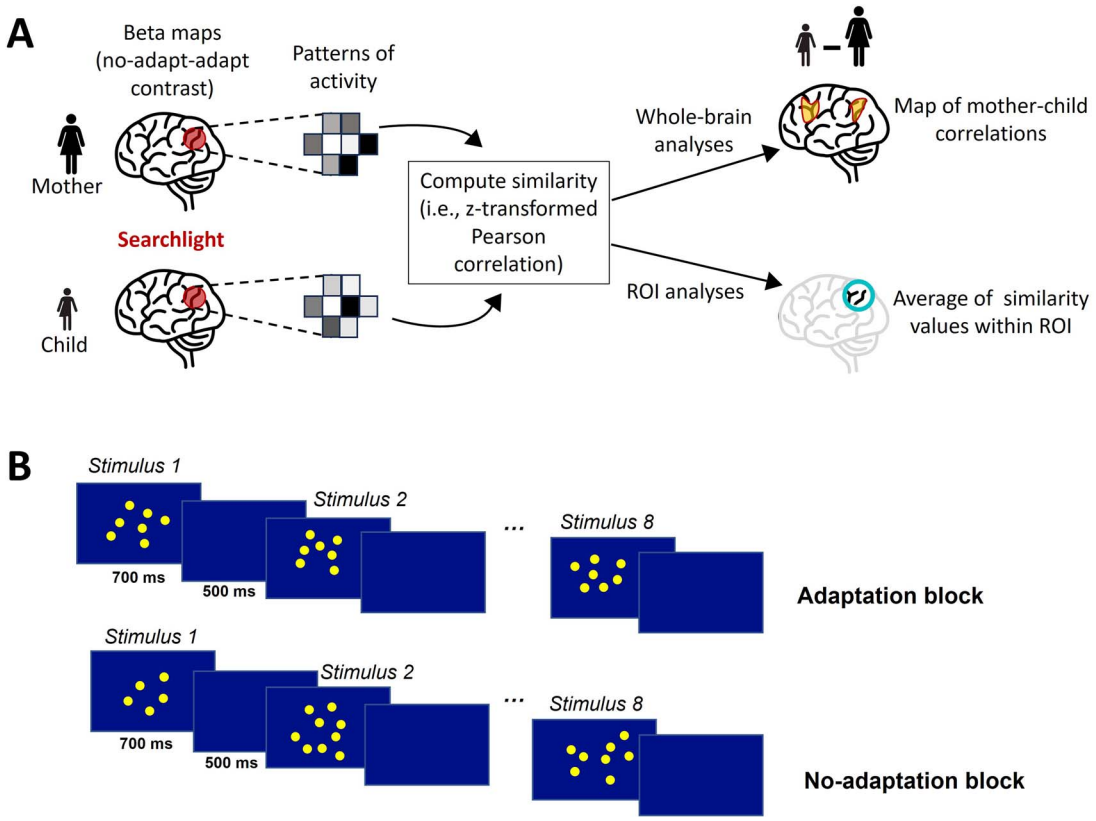


Figure 1 Dyadic analysis strategy and task. A) Dyadic searchlight RSA and group-level analyses. Activity associated with the contrast of interest is first estimated at every voxel in the brain for each participant in a dyad (eg mother and child). Mother–child correlations between beta maps are then computed using searchlights either across the whole brain or averaged within ROIs. Group-level analyses are then conducted at the whole-brain or ROI level. B) Example blocks of the numerosity adaptation task presented in the scanner. No-adaptation blocks consisted of 8 dot arrays that contained different number of dots. Adaptation blocks consisted of 8 dot arrays that contained the same numbers of dots.

invariance in neural representations of numbers across families. This is consistent with the idea that symbolic numbers are a recent invention that may "recycle" evolutionarily conserved circuits dedicated to non-symbolic quantity processing in the IPS (Dehaene and Cohen 2007). This "approximate number system" (ANS) is early-emerging (Xu et al. 2005) and shared with non-human animals (Odic and Starr 2018), suggesting relatively invariant architecture. Genetic differences between individuals also explain little variation in ANS acuity compared to executive functions (Friedman et al. 2008; Tosto et al. 2014), suggesting reduced genetic variance in ANS architecture. On the other hand, ANS acuity varies across individuals (Halberda et al. 2008; Piazza et al. 2010), develops throughout the lifespan (Halberda et al. 2012), relates to math achievement (Halberda et al. 2008; Libertus et al. 2011), and shows intergenerational transmission, with correlations observed between parents and children (Braham and Libertus 2017; Navarro et al. 2018; Bernabini et al. 2021). Moreover, the ability to measure familial similarity in the IPS may critically depend on the task used to probe numerical processing. In our previous study (Constant-Varlet et al. 2025), we found that neural similarity in a symbolic arithmetic task was observed primarily in executive regions (ie anterior insula, precentral gyrus). However, symbolic arithmetic is well-known for placing substantial demands on domain-general cognitive control processes, particularly in children (Vogel and De Smedt 2021). Thus, the absence of IPS similarity in that study may reflect task-specific demands rather than a general lack of familial transmission of numerical representations in the IPS per se.

The present study has two goals. First, we aimed to assess whether it would be possible to detect familial transmission of representations of numerical quantity in the IPS, using a numerical processing task making minimal executive demands. We measured functional MRI (fMRI) activity while mothers and children passively viewed series of dot arrays where numerosity was either constant (adaptation blocks) or varied (no-adaptation blocks) (see Fig. 1B). Because repeated stimuli reduce neural responses in feature-sensitive regions (Grill-Spector and Malach 2001), areas sensitive to numerosity processing should show reduced activity in adaptation versus no-adaptation blocks. Using dyadic RSA, we assessed whether neural adaptation to numerosity showed greater similarity in familial than non-familial dyads in the IPS. This was done using a searchlight analysis ran across the whole brain as in our previous study (Constant-Varlet et al. 2025), but also by averaging searchlight similarity within hypothesis-driven region-of-interests (ROIs) in the left and right IPS to increase statistical sensitivity given the passive nature of the task (see Fig. 1A). Second, to test whether functional similarity may be explained (at least in part) by structural similarity, we also measured parent–child resemblance in cortical thickness and surface area within the IPS.

Material and methods

Participants

The participants analyzed in this study were drawn from the same cohort described in our previous study (Constant-Varlet et al. 2025). The recruitment involved 119 individuals from 59 families, comprising 60 eight-year-old children (mean age = 8.52, standard deviation [SD] = 0.25, range = 8.03–9.01; 31 females) and their biological mothers ($n = 59$ due to one twin pair; mean age = 40.40, SD = 4.27, range = 32.02–50.12). We focused on a narrow age range in children to reduce developmental variability in ANS precision, which undergoes changes across childhood (Halberda et al. 2012). Families were recruited through social media advertisements in the Lyon metropolitan area, France. All participants demonstrated French fluency, with all but one mother (whose native language was Arabic) being native French speakers. Maternal education level distribution suggests that participants came from a range of socioeconomic levels, though there was a bias toward higher educational attainment (see Supplementary Methods). The research protocol received approval from the regional ethics committee (Comité pour la Protection des Personnes Est IV, n°2019-A01918-49), with mothers providing written informed consent and children giving verbal assent. The experimental protocol followed the same two-session design as our previous study. An initial session involved standardized cognitive assessments and MRI familiarization for children (see details in Supplementary Methods), followed by neuroimaging data collection (see acquisition parameters in Supplementary Methods). Families received 60 euros compensation per session. Data quality screening resulted in the exclusion of several children and mothers from the fMRI and structural MRI (sMRI) datasets, such that the final fMRI sample comprised 46 children and 53 mothers, forming 44 dyads, whereas the final sMRI sample comprised 39 children and 52 mothers, forming 36 dyads. Details about participants in the final samples are provided in Supplementary Methods.

Standardized behavioral assessment

To characterize the sample, participants completed a battery of cognitive assessments as detailed in our previous study (Constant-Varlet et al. 2025). Details on the battery are provided in Supplementary Methods. Percentile ranks are presented in Table S1. Performance across the sample ranged from average to high-average levels.

fMRI task

Participants were presented with a passive numerosity adaptation task (see Fig. 1B) during a single run. The paradigm employed a block design with blocks of rest, adaptation, and no-adaptation. The complete task comprised 30 blocks of 9.6 s each (ie 10 rest blocks, 10 adaptation blocks, and 10 no-adaptation blocks). Block order was pseudorandomized with the constraint that identical block types could not occur consecutively. To ensure that participants maintained consistent attention throughout the task, they performed an orthogonal detection task, pressing a response button whenever a rocket image appeared on screen (rockets appeared 10 times during the task, always in rest blocks). During rest blocks, a yellow fixation star was shown on a blue background. During adaptation and no-adaptation blocks, participants were presented with sequences of yellow dot arrays on a blue background. Each array was presented for 700 ms followed by a 500 ms interstimulus interval. Each block contained eight sequential array presentations.

Adaptation blocks included the sequential presentation of dot arrays with the exact same number of dots across all eight presentations within the block. The spatial configuration of the dots was randomized across successive presentations, ensuring that identical visual patterns were never repeated. No-adaptation blocks included the sequential presentation of dot arrays with different number of dots across all eight presentations within the block (consecutive arrays differed by ratios ranging from 1:2 to 1:8). Dot arrays contained between 6 and 60 elements, beyond the subitizing range (typically 1 to 4 items). Thus, subitization or counting were highly unlikely given the time constrain. The dot stimuli were generated using the MATLAB script by Gebuis and Reynvoet (2011), which systematically controls multiple visual properties that covary with numerosity. As demonstrated by Gebuis and Reynvoet (2011), this algorithm ensures that for numerosities in the range we used (6 to 60 dots), the controlled visual properties (convex hull area, aggregate surface area, density, average item diameter, and total contour length) explain only a negligible proportion of variance in numerical distance (R^2 values ranging from < 0.01 to 0.08 in their validation analyses for comparable numerosity ranges and designs). Therefore, neural responses in our task most likely reflect numerical rather than visual processing.

The task was coded and presented using PsychoPy (Peirce 2007), with stimuli projected onto a screen positioned at the end of the scanner bore. Participants viewed stimuli via a 45° angled mirror mounted above the head coil. Head stabilization was achieved using fitted cushions to minimize motion artifacts during data acquisition.

MRI data quality control

Quality control of fMRI and sMRI data was performed using MRIQC (see Supplementary Methods). From the initial sample of 109 participants (56 children and 53 mothers forming 54 complete dyads) who completed the numerosity adaptation task, 10 children (including one twin) demonstrated excessive motion artifacts and were excluded from subsequent analyses. Thus, analyses of familial dyads were conducted on a total of 44 dyads. We examined whether participants included in the fMRI analyses differed from those excluded due to missing or low-quality fMRI data on the cognitive assessments reported in Table S1. No significant differences were observed for children on any cognitive measure (Vocabulary: $t(58) = 0.84$, $P = 0.40$; Working memory: $t(58) = -1.32$, $P = 0.19$; Math: $t(58) = 0.41$, $P = 0.68$; Reading: $t(54) = -0.49$, $P = 0.63$). For mothers, participants included showed higher scores on working memory and math compared to excluded participants (Working memory: $t(57) = 2.36$, $P = 0.02$; Math: $t(57) = 2.19$, $P = 0.03$), whereas no difference was observed for vocabulary ($t(57) = 0.07$, $P = 0.94$). Thus, the included maternal sample was slightly biased toward higher math and working memory performance. Moreover, out of the 109 participants for whom we collected T1-weighted images (56 children and 53 mothers, forming 54 dyads), data from 17 dyads were excluded because either the child ($n = 16$) or the mother ($n = 1$) was classified as outlier. Note that both twins had valid T1-w data, but to avoid imbalance with other familial dyads, one of the twins was randomly excluded from analyses. Thus, analyses of familial dyads were conducted on a total of 36 dyads.

fMRI data processing

fMRI data were preprocessed using fMRIPrep version 20.2.5 (see details in Supplementary Methods). Using Nilearn, a general linear model characterized the neural responses associated with no-adaptation and adaptation blocks across the whole brain (see Supplementary Methods). Whole-brain beta maps corresponding to the contrast between the no-adaptation and adaptation regressors were calculated for each participant. These maps were then submitted to univariate one sample t-tests across all participants to examine whether adaptation effects were generally measured in clusters consistent with prior studies, particularly in the IPS (Escobar-Magariño et al. 2022).

A searchlight RSA approach was used to assess similarity in the neural representations of the numerosity adaptation effect between all mothers and all children (Fig. 1A). Specifically, we measured the mother–child correlation between beta maps across all possible dyadic permutations within the entire sample (eg parent A correlated with child A, parent A correlated with child B, etc.). This was done by calculating a Pearson correlation of the multivariate pattern of activity around each voxel of the brain using spherical searchlights with a 5-voxel (10-mm) radius (Etzel et al. 2013). Note that, to preserve fine-grained spatial patterns, non-smoothed beta maps were used in these analyses. Pearson correlation coefficients were then converted to z-values using a Fisher transformation. The Fisher-transformed correlation coefficient for each searchlight was associated with the central voxel of that searchlight. For each possible dyad, this led to a z-map representing, at each voxel, the mother–child similarity (ie the multivariate correlation) in the patterns of activity associated with the adaptation effect around that voxel.

To evaluate the familial specificity of mother–child similarity, we compared the Fisher-transformed correlation coefficients obtained in familial dyads ($n = 44$) (eg Adult A correlated with Child A, Adult B correlated with Child B, etc.) to coefficients obtained in "non-familial" dyads, ie dyads created by associating mothers with children from other families ($n = 2{,}394$) (eg Adult A correlated with Child B, Adult B correlated with Child A, etc.). This was done using two-sample t-tests conducted across the whole-brain as well as within ROIs in the left and right IPS (averaging the Fisher-z transformed correlations across all voxels within each ROI). These ROIs, which were defined using the Anatomy Toolbox (Version 2.2; Eickhoff et al. 2005), consisted of voxels with at least 50% probability of belonging to one of the IPS subdivisions (hIP1, hIP2, and hIP3). The exact same IPS ROIs were used in several of our previous studies (Schwartz et al. 2018, 2020; Girard et al. 2022; Viesel-Nordmeyer and Prado 2023). One sample t-tests were also used to test whether pattern similarity between mothers and children was significant overall (ie greater than 0), either across the whole brain or in the ROIs.

Following our previous study (Constant-Varlet et al. 2025), second-level whole-brain maps resulting from univariate and multivariate analyses were corrected for multiple comparisons using a false discovery rate (FDR) correction at the voxel-level (Genovese et al. 2002). Because our hypotheses are systematically directional (ie we are only interested in testing whether neural similarity is greater in familial than non-familial dyads and not the other way around), whole-brain maps were one-sided and the significance level was set at $P < 0.05$, one-tailed (voxel-level FDR-corrected, see above). One-tailed P values were also reported for the ROI analyses (P values less than 0.05 were considered to be significant).

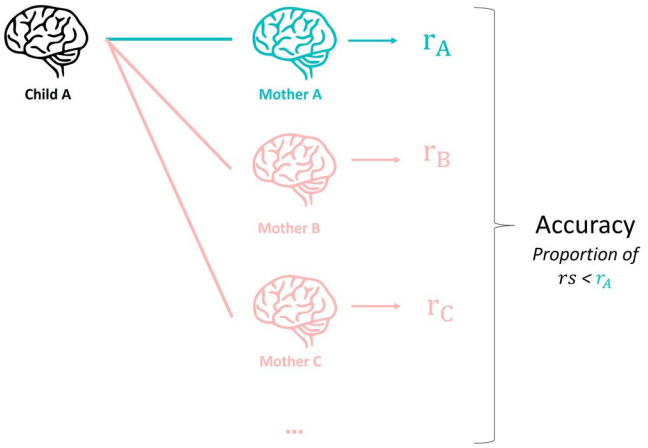


Figure 2 Accuracy analysis procedure adapted from Takagi et al. (2021). For each child, we identified the relative position of the familial dyad (ie dyad in blue) among the distribution of all other possible non-familial dyads involving the same child (ie dyads in pink) in terms of neural similarity. An "accuracy" score was calculated as the percentage of non-familial dyads with a lower similarity than the familial dyad.

Finally, following Takagi et al. (2021) (see Fig. 2), we quantified, for each familial dyad, the relative position of their mother–child neural similarity within the distribution of randomly paired mother–child combinations. Specifically, we calculated for each familial dyad a pairwise comparison "accuracy" score in each ROI (left and right IPS), defined as the proportion of non-familial dyads that exhibited lower mother–child similarity than that specific familial dyad. For each of the 44 familial dyads, we counted how many non-familial dyads involving the "same child" showed lower Fisher z-transformed correlation coefficients. This count was expressed as a percentage, which therefore represents the percentile rank of each familial dyad within the distribution of non-familial dyads. An accuracy of 50% indicates that the similarity of a familial dyad is at the median of the non-familial distribution (ie chance level), while accuracies above 50% indicate that the familial dyad exhibits greater similarity than the majority of non-familial dyads. One-sample t-tests were used to test whether mean accuracy across the 44 familial dyads was significantly greater than 50% in each ROI. One-tailed P-values less than 0.05 were considered significant.

sMRI data processing

To anticipate, results of intergenerational RSA analyses revealed family-specific mother–child similarity in brain activity patterns in the IPS (see Results). Therefore, we explored whether that increased similarity could be due to some anatomical similarity between mothers and children in that region. T1-weighted anatomical images underwent cortical reconstruction using the recon-all command in FreeSurfer (version 6.0.1). Following standard tissue segmentation and surface identification procedures, cortical thickness was calculated as the distance between gray-white matter and pial surfaces, while surface area was measured from the reconstructed pial surface. Vertex-wise cortical measures were converted to volumetric maps using the mri_surf2vol command in FreeSurfer. The resulting individual volumes for cortical thickness and surface area underwent identical searchlight RSA procedures as the fMRI data. In other words, mother–child correlations across all possible dyadic permutations

within the entire sample were computed within 5-voxel radius searchlights and Fisher z-transformed. For cortical thickness as well as for surface area, we tested whether mother–child correlations in familial dyads ($n = 36$) were significantly greater than correlations in non-familial dyads ($n = 2{,}028$, considering 39 children and 52 mothers) using two-sample t-tests conducted within the same left and right IPS as the fMRI analyses. The significance level was set at $P < 0.05$ (one-tailed).

Following the same pairwise comparison approach as described above for fMRI data (Takagi et al. 2021) (see Fig. 2), we also calculated accuracy scores for structural measures in each ROI (left and right IPS). For each of the 36 familial dyads in the sMRI sample, we computed the proportion of non-familial dyads with the same child that exhibited lower similarity in cortical thickness and surface area. Mean accuracy scores were tested against the 50% chance level using one-sample t-tests for each structural measure and ROI (one-tailed, $P < 0.05$).

Results

fMRI results

Before examining neural similarity between mothers and children using multivariate analyses, we first ensured that the univariate contrast between no-adaptation and adaptation blocks was associated with overall activity across participants in regions of the bilateral IPS that have been repeatedly identified in similar tasks in prior studies (Escobar-Magariño et al. 2022). After correction for multiple comparisons using voxel-level FDR correction, we identified several clusters in which univariate activity was greater in no-adaptation than in adaptation blocks across all mothers and children (see Table S2). As expected, this was notably the case in the bilateral IPS (Left IPS: $x = -52$, $y = -40$, $z = 58$, Z-value = 4.48; Right IPS: $x = 44$, $y = -42$, $z = 64$, Z-value = 4.11) (see Fig. 3A). That bilateral IPS cluster showing greater activity for no-adaptation than adaptation blocks remained significant when only mothers were considered (Left IPS: $x = -50$, $y = -40$, $z = 58$, Z-value = 4.79; Right IPS: $x = 42$, $y = -42$, $z = 64$, Z-value = 4.61) (see Fig. 3B). However, it did not survive correction for multiple comparisons in children. Activity in the right IPS at the peak coordinates identified in adults was numerically greater in no-adaptation than adaptation blocks, but this difference did not reach statistical significance (Left IPS: $t(45) = 1.10$, $P = 0.139$, $d = 0.16$; Right IPS: $t(45) = 1.32$, $P = 0.097$, $d = 0.19$).

We then turned to multivariate intergenerational RSA analyses. Specifically, we tested whether there was some neural similarity in the patterns of activity associated with the contrast of no-adaptation versus adaptation blocks between mothers and children, and whether that similarity would be family-specific. Therefore, we compared neural similarity in familial dyads ($n = 44$) to neural similarity in all non-familial dyads ($n = 2{,}394$) (see Methods). At the whole-brain level, no cluster survived the FDR correction for multiple comparisons ($P < 0.05$). However, because our hypothesis mainly concerned the IPS, we also used a more sensitive ROI approach to compare neural similarity between familial and non-familial dyads in both the left and right IPS (using anatomically-defined ROIs). In the left IPS (see Fig. 4A), neural patterns were not overall similar between mothers and children, either for familial dyads ($t(43) = -0.10$, $P = 0.54$, $d = -0.02$) or for non-familial dyads ($t(2{,}393) = -0.10$, $P = 0.54$, $d = -0.002$). There was also no difference between familial and non-familial dyads in that region ($t(2{,}436) = -0.09$, $P = 0.54$, $d = -0.01$). In contrast, in the right IPS (see Fig. 4B), neural patterns were overall similar between mothers and children for familial dyads ($t(43) = 2.82$, $P = 0.004$, $d = 0.43$) but not for non-familial dyads ($t(2{,}393) = -0.29$, $P = 0.61$, $d = -0.01$). Critically, there was greater neural similarity in familial dyads than in non-familial dyads in the right IPS ($t(2{,}436) = 3.07$, $P = 0.001$, $d = 0.47$).

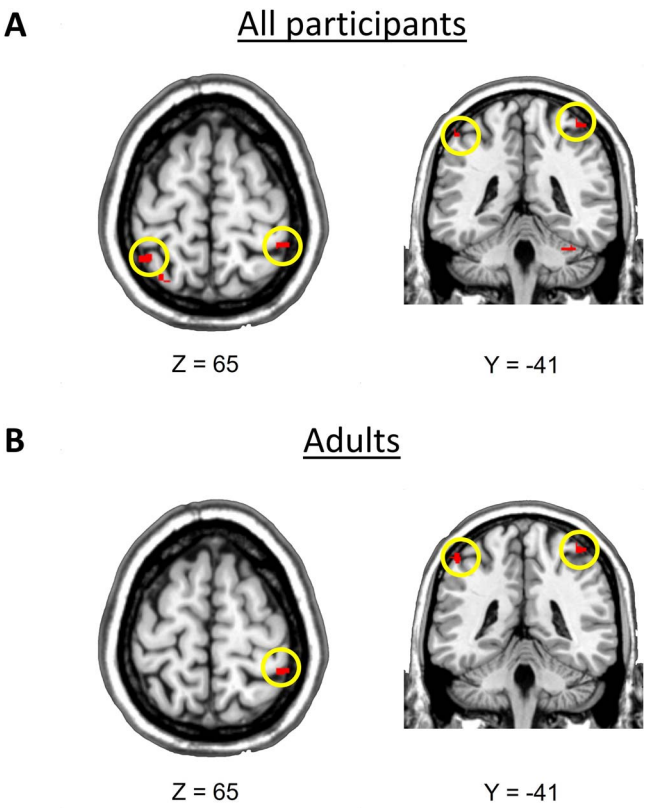


Figure 3 Univariate fMRI activity associated with the comparison of no-adaptation versus adaptation blocks. A) Greater activity in no-adaptation than adaptation blocks was observed in the bilateral IPS (circled) across all mothers and children. B) Greater activity in no-adaptation than adaptation blocks was also observed in the bilateral IPS (circled) across all mothers. Activations are overlaid on slices of the MNI-normalized anatomical brain.

We conducted three control analyses. First, a potential issue with the comparison above is that non-familial dyads included mothers who were not part of the group of familial dyads (eg because their children had to be excluded from the analyses). Therefore, it is possible that results might be confounded by differences in skills and traits between mothers in familial and non-familial dyads (eg education, math ability, age). We repeated the analysis comparing neural similarity in familial dyads to neural similarity measured from non-familial dyads that were exclusively generated with participants included in the familial dyads ($n = 1{,}892$). Results were very similar to the main analysis reported above, with greater similarity in familial than non-familial dyads in the right IPS ($t(1{,}934) = 3.07$, $P = 0.001$, $d = 0.47$), but not in the left IPS ($t(1{,}934) = -0.17$, $P = 0.57$, $d = -0.03$).

Second, because the adaptation task was passive, it remains unclear whether participants were always attentive to the stimuli throughout the run. We therefore embedded in the adaptation task a target detection task to measure sustained attention (see Methods). The average detection accuracy was high for both mothers (mean accuracy = 96.2%, SD = 14.2%) and children (mean accuracy = 88.3%,

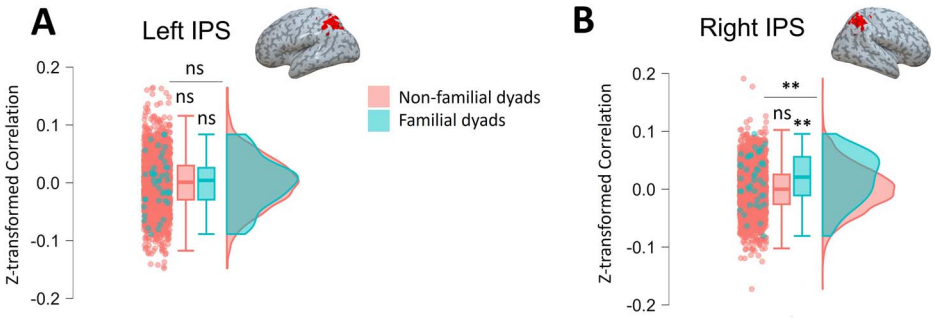


Figure 4 Functional neural similarity for familial and non-familial dyads in the left and right IPS. Neural similarity was quantified by assessing the size of Z-transformed correlations between mother and child multivariate patterns for the contrast of no-adaptation versus adaptation blocks. A) In the left IPS, neural patterns were not similar between mothers and children in either familial (blue) or non-familial (pink) dyads (ie average correlations were not greater than 0). There was also no difference in similarity between familial and non-familial dyads. B) In the right IPS, neural patterns were similar (ie average correlation was greater than 0) between mothers and children in familial dyads, but not in non-familial dyads. There was also greater similarity in familial than in non-familial dyads. $**P < 0.01$, ns: non-significant.

SD = 20.7%). However, there was a relatively high variability that was mainly due to one child and one mother who did not respond to any target, and to a child who only responded to one target. Because it remains unclear whether these participants did not understand the instructions or were truly inattentive, we ran another set of control analyses in which we excluded the familial and non-familial dyads with these participants. The results were largely similar to what is reported above. That is, in the right IPS, neural patterns remained overall similar between mothers and children for familial dyads ($t(40) = 2.73$, $P = 0.005$, $d = 0.43$) but not for non-familial dyads ($t(2,246) = -0.01$, $P = 0.50$, $d < 0.01$). Critically, there was still greater neural similarity in familial dyads than in non-familial dyads in the right IPS ($t(2,286) = 2.93$, $P = 0.002$, $d = 0.46$). Results were also similar with respect to the left IPS (ie no similarity for familial dyads, $t(40) = -0.54$, $P = 0.71$, $d = -0.08$, and no difference between familial and non-familial dyads, $t(2,286) = -0.50$, $P = 0.69$, $d = -0.08$) and the whole brain results (no cluster survived the FDR correction for multiple comparisons in the contrast of familial versus no-familial dyads). Therefore, removing these participants from the main analyses does not change any conclusion.

Third, the present findings appear to suggest that brain regions showing familial similarity in numerical processing may depend on the task demands, as we found here similarity in the IPS but not in the insula and precentral gyrus as in our previous study (Constant-Varlet et al. 2025). However, the whole-brain searchlight analysis may also have lacked power to detect familial similarity in these regions, given the passive nature of the numerosity adaptation task used here (compared to the mental arithmetic task used in Constant-Varlet et al. 2025). Therefore, we performed additional ROI analyses examining familial similarity in the exact brain regions identified by Constant-Varlet et al. (2025) (defined as spheres of 10 mm radius around the coordinates x = −36, y = 16, z = 0 for the left insula, x = 34, y = 28, z = −2 for the right insula, and x = −40, y = −2, z = 36 for the left precentral gyrus). Neural patterns were not similar between mothers and children in familial dyads (left insula: $t(43) = 0.91$, $P = 0.18$, $d = 0.14$; right insula: $t(43) = -0.96$, $P = 0.82$, $d = -0.15$; left precentral: $t(43) = -0.26$, $P = 0.60$, $d = -0.04$). There was also no difference between familial and non-familial dyads in these brain regions (left insula: $t(2,436) = 0.48$, $P = 0.32$, $d = 0.07$; right insula: $t(2,436) = -1.21$, $P = 0.89$, $d = -0.18$; left precentral: $t(2,436) = -0.41$, $P = 0.66$, $d = -0.06$). Therefore, familial neural similarity in numerical processing may be dependent upon the task demands, with the executive demands of the mental arithmetic task driving the similarity observed in the insula and precentral gyrus in Constant-Varlet et al. (2025).

Finally, following Takagi et al. (2021), we also quantified the relative position of each familial dyad within the distribution of non-familial dyads in terms of neural similarity by computing pairwise comparison accuracy scores (see Methods). In the left IPS, mean accuracy across the 44 familial dyads was 50.37% (SD = 29.44%), which was not significantly different from the 50% chance level ($t(43) = 0.08$, $P = 0.47$, $d = 0.01$). In contrast, in the right IPS, mean accuracy was 63.79% (SD = 31.04%), which was significantly greater than chance ($t(43) = 2.95$, $P = 0.003$, $d = 0.44$). This indicates that, for each child, the familial mother–child dyad typically showed higher similarity than about 63.79% of that child's non-familial dyads.

sMRI results

Overall, the results from the functional RSA analyses that are described above reveal family-specific similarity in the right IPS. We then tested whether that functional similarity could be due to some structural similarity between mothers and children in that region. Therefore, we extracted indices of cortical thickness and surface area in both the left and right IPS and tested whether similarity was greater in familial dyads ($n = 36$) than non-familial dyads ($n = 1,992$) with respect to these indices.

For cortical thickness (see Fig. 5), neural patterns in the left IPS were overall similar between mothers and children, both for familial dyads ($t(35) = 2.49$, $P = 0.01$, $d = 0.415$) and for non-familial dyads ($t(1,991) = 17.7$, $P < 0.0001$, $d = 0.396$). Most critically, however, there was no difference of similarity between familial and non-familial dyads in that region ($t(2,026) = 0.50$, $P = 0.31$, $d = 0.08$). In the right IPS, neural patterns were also overall similar between mothers and children for familial dyads ($t(35) = 3.20$, $P = 0.001$, $d = 0.53$) and for non-familial dyads ($t(1,991) = 15.0$, $P < 0.0001$, $d = 0.336$). Critically, there was greater neural similarity in familial dyads than in non-familial dyads in that region ($t(2,026) = 1.67$, $P = 0.048$, $d = 0.28$). Pairwise comparison accuracy scores revealed that, in the left IPS, mean accuracy across the 36 familial dyads was 52.70% (SD = 34.86%), which was not significantly different from chance ($t(35) = 0.46$, $P = 0.32$, $d = 0.08$). In

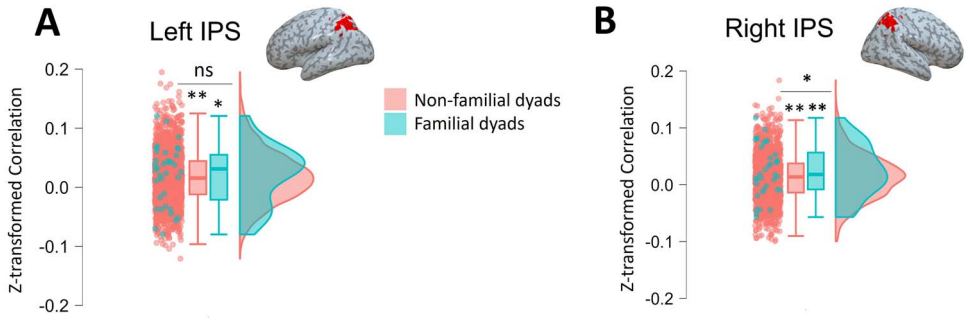


Figure 5 Neural similarity in cortical thickness for familial and non-familial dyads in the left and right IPS. A) In the left IPS, neural patterns were similar between mothers and children in both familial (blue) or non-familial (pink) dyads (ie average correlations were greater than 0). There was no difference in similarity between familial and non-familial dyads. B) In the right IPS, neural patterns were also similar between mothers and children in both familial and non-familial dyads. In that region, however, there was greater similarity in familial than in non-familial dyads. $*P < 0.05$, $**P < 0.01$, ns: non-significant.

the right IPS, mean accuracy was 58.89% (SD = 31.74%), showing a trend toward being greater than the 50% chance level ($t(35) = 1.68$, $P = 0.051$, $d = 0.28$).

For surface area (see Fig. S1), neural patterns were overall similar between mothers and children in the left and right IPS. This was the case for familial dyads (Left: $t(35) = 3.25$, $P = 0.001$, $d = 0.54$; Right: $t(35) = 1.59$, $P = 0.06$, $d = 0.26$) and for non-familial dyads (Left: $t(2{,}043) = 22.9$, $P < 0.00001$, $d = 0.51$; Right: $t(2{,}043) = 16.2$, $P < 0.00001$, $d = 0.36$). However, there was no significant difference between familial and non-familial dyads in either the left or right IPS (Left: $t(2{,}026) = 0.006$, $P = 0.50$, $d = 0.001$; Right: $t(2{,}026) = 0.29$, $P = 0.61$, $d = 0.05$). Consistent with the two-sample t-test results, pairwise comparison accuracy scores were not significantly different from chance in either the left IPS (M = 50.87%, SD = 30.18%, $t(35) = 0.17$, $P = 0.43$, $d = 0.03$) or the right IPS (M = 48.41%, SD = 33.41%, $t(35) = -0.29$, $P = 0.61$, $d = -0.05$).

Overall, we found greater family-specific mother–child similarity for cortical thickness in the right IPS. We then performed the same control analysis as for fMRI RSA analyses to rule out the possibility that results might be confounded by differences in skills and traits between adults in familial and non-familial dyads. Specifically, for cortical thickness, we compared similarity in familial dyads to similarity measured from non-familial dyads that were exclusively generated with participants included in the familial dyads ($n = 1{,}260$). Results were very similar to the analysis reported above, with greater similarity in familial than in non-familial dyads for cortical thickness in the right IPS ($t(1{,}294) = 1.68$, $P = 0.047$, $d = 0.28$) but not the left IPS ($t(1{,}294) = 0.35$, $P = 0.36$, $d = 0.06$). We again found no significant difference between familial and non-familial dyads for cortical surface area (left IPS: $t(1{,}294) = 0.12$, $P = 0.45$, $d = 0.02$; right IPS: ($t(1{,}294) = -0.42$, $P = 0.66$, $d = -0.07$)).

Discussion

Recent findings suggest that mother–child similarity in mental arithmetic skills may relate to similarity in neural mechanisms subserving executive functioning (eg the anterior insula and precentral gyrus) rather than numerical processing per se (eg the IPS) (Constant-Varlet et al. 2025). However, it remained unclear how much of this pattern was due to the executive demands of the task, mental arithmetic making heavy reliance on executive functions. Here, combining fMRI with dyadic searchlight RSA, we measured mother–child neural similarity during a passive numerosity adaptation task that involves non-symbolic magnitude processing while minimizing executive demands. Our main finding was that neural representations of the numerosity adaptation effect showed greater similarity in familial than non-familial dyads in the right IPS. Moreover, there was no evidence for familial neural similarity in the brain regions that did show familial similarity in a mental arithmetic task in Constant-Varlet et al. (2025), suggesting that familial similarity in that study was driven by the executive demands of the task. These findings indicate that the neural loci of intergenerational transmission may be task-dependent, with familial similarity emerging in brain regions that are most critical for the specific cognitive processes being engaged.

This familial specificity of neural patterns in the right IPS is particularly noteworthy given that non-symbolic magnitude processing is an evolutionarily ancient cognitive skill shared with non-human animals (Odic and Starr 2018) and thought to rely on relatively invariant neural architecture (Dehaene and Cohen 2007). Indeed, the ability to process non-symbolic magnitude emerges early in human development (Xu et al. 2005) and shows relatively low genetic variance (Tosto et al. 2014). Nevertheless, behavioral studies have demonstrated familial transmission of skills associated with non-symbolic magnitude processing (Braham and Libertus 2017; Navarro et al. 2018; Bernabini et al. 2021). Our findings provide neural evidence that this behavioral transmission may be supported by family-specific patterns of IPS activity during magnitude processing. More generally, they also show that familial transmission of task-related neural patterns is not exclusive to regions supporting executive functions, but rather depends on the specific task demands.

Family-specific similarity was observed only in the right IPS and not the left IPS. This lateralization is consistent with evidence that the right IPS may show specialization for non-symbolic magnitude processing (Holloway and Ansari 2010; Escobar-Magariño et al. 2022), whereas the left IPS may be more strongly associated with symbolic number processing (Vogel et al. 2015). Therefore, the right-lateralized family-specific similarity we observed may reflect the intergenerational transmission of neural mechanisms supporting non-symbolic magnitude representations, which are particularly relevant to the passive numerosity adaptation task used here.

It should nonetheless be noted that the IPS is not exclusively involved in numerical magnitude processing but supports a range of cognitive functions, including spatial attention (Materna et al.

2008; Gillebert et al. 2011) and visual short-term memory (Xu 2007). Although our main contrast relies on a comparison between no-adaptation and adaptation blocks of dot arrays that were controlled for a number of visual confounds (see Methods), it is difficult (or even impossible, Leibovich et al. 2017) to completely control for such confounds. Therefore, the contributions of non-numerical processes to familial similarity in our adaptation task is likely minimal but cannot be entirely ruled out.

Beyond functional similarity, we found that cortical thickness in the right IPS also showed family-specific resemblance between mothers and children. This anatomical similarity raises the possibility that functional transmission may be explained, at least in part, by shared structural properties of the IPS across generations. Notably, family-specific similarity was observed specifically for cortical thickness rather than surface area. Cortical thickness and surface area show largely independent developmental trajectories in both pattern and timing (Shaw et al. 2012; Wierenga et al. 2014), with overall surface area typically peaking later in development than average cortical thickness. Although the precise biological mechanisms underlying these differences remain unclear (Winkler et al. 2010), studies have found that both measures are influenced by largely non-overlapping genetic factors, over the whole brain and at the regional level (Panizzon et al. 2009; Winkler et al. 2010). Therefore, it remains possible that the familial effects observed here in the IPS for cortical thickness but not surface area may be somewhat specific to the brain region and developmental period, though this should be demonstrated by future studies.

Nonetheless, in line with our results, previous intergenerational studies have found that cortical thickness tends to show some intergenerational similarity across various brain regions (Foland-Ross et al. 2016; Ozalay et al. 2016; Minami et al. 2022 though see Fehlbaum et al. 2022), even if the familial specificity has not been demonstrated in these studies. While the precise relationship between brain structure and function remains poorly understood (Kanai and Rees 2011), the co-occurrence of both structural and functional family-specific similarity in the right IPS may reflect shared developmental influences (whether genetic, environmental, or their interaction) that shape both the anatomy and functional organization of this region across generations. Future research may investigate whether structural similarity influences functional similarity or whether both arise independently from common underlying factors.

Our parent–child design cannot determine whether similarity emerges from genetic or environmental factors. A recent behavioral study indicates that the parent–child transmission of math skills is moderated by the quality and quantity of math-related activities at home, suggesting a role for environmental factors (Torppa et al. 2025). However, insights about the role of genes versus the environment may only come from genetically-sensitive designs (eg twin studies or genome-wide association studies). Twin studies examining the heritability of the structure and function of the parietal cortex have yielded complex results. On the one hand, unique environmental effects (rather than genetic factors) appear to account for the majority of variance in parietal cortical thickness, with estimates exceeding 80% in some studies (Lenroot et al. 2009; Yoon et al. 2010; Yang et al. 2012). On the other hand, fMRI results suggest that brain activity during arithmetic tasks in the right IPS shows substantial genetic influence, which has been interpreted as being the product of an evolutionarily conserved system for quantity representation that emerges early in development, prior to formal mathematics education (Pinel and Dehaene 2013). Functional results also suggested hemispheric differences in the relative contributions of genes and environment, with left IPS activity showing greater sensitivity to education and experience than right IPS activity. Overall, these findings suggest that the family-specific functional and structural similarity we observed in the right IPS may reflect different mixtures of genetic and environmental transmission.

It is important to consider some methodological limitations of the present study. First, we had a clear a priori hypothesis regarding family-specific similarity within the IPS and aimed to test this hypothesis through both whole-brain and ROI analyses within anatomically defined regions of the IPS. However, we were only able to detect familial similarity in ROI analyses. It remains possible that family-specific similarity exists in other brain regions not examined here, and that we might have lacked power to detect neural similarity in these brain regions using our whole-brain approach. Second, our sample consisted exclusively of mother–child dyads, which limits our ability to examine potential sex-specific patterns of transmission. Previous intergenerational neuroimaging studies have identified female-specific transmission of neural characteristics in regions associated with emotion regulation and other functions (Yamagata et al. 2016; Minami et al. 2022), raising the possibility that the transmission patterns we observed might differ in father–child or mother–child dyads. Third, the ANS develops through the lifespan, particularly in children (Halberda et al. 2012). Therefore, it is possible that familial similarity in IPS representations may be affected by the developmental period investigated. To some extent, this issue is minimized by the fact that we only investigated a narrow age range in children. However, there was more variability in the age of parents and it remains possible that age differences in parental ANS precision may have influenced mother–child similarity. Though our study does not have the power to investigate the potential effect of this variability, future studies may attempt to do so. Finally, as discussed above, our parent–child design cannot disentangle genetic from environmental contributions to the observed similarity. While this is a common limitation of two-generation studies, it means our findings should be interpreted as demonstrating familial transmission rather than specifically genetic or environmental transmission. Future studies incorporating adoption designs, or molecular genetic data would be necessary to parse these influences.

In sum, using a passive numerosity adaptation task combined with dyadic fMRI and structural neuroimaging, we demonstrate that mothers and children show family-specific similarity in both functional and structural properties of the right IPS, a core region for numerical magnitude processing. This finding is particularly striking given that the ANS is phylogenetically ancient and emerges early in development, which might have suggested relatively invariant neural architecture across individuals (even though the ANS still shows developmental changes across the lifespan, Halberda et al. 2012). Therefore, our results demonstrate that even evolutionarily conserved cognitive systems may show intergenerational neural transmission. These findings complement our previous work showing family-specific similarity in executive-related regions during mental arithmetic (Constant-Varlet et al. 2025), suggesting that skills may be transmitted from parents to children through multiple neural pathways. The fact that we observed family-specific IPS similarity only when using a task with

minimal executive demands, but not during mental arithmetic, underscores how task selection reveals different aspects of intergenerational neural transmission. By demonstrating that family-specific neural similarity in the IPS can be detected during a simple, passive task suitable for young children, this work opens new possibilities for studying the intergenerational transmission of math abilities.

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Author contributions

Charlotte Constant-Varlet (Conceptualization, Formal analysis, Investigation, Writing—original draft, Writing—review & editing), Tomoya Nakai (Conceptualization, Writing—review & editing), Lea Longo (Investigation), Honorine Bouchet (Investigation), and Jérôme Prado (Conceptualization, Formal analysis, Supervision, Writing—original draft, Writing—review & editing)

Supplementary material

Supplementary data is available at *Cerebral Cortex* online.

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Conflicts of interest

The authors declare no competing interests.

Data availability

The analyses scripts, anonymized behavioral data, and individual structural maps and functional beta maps for each participant are available from Zenodo (doi:10.5281/zenodo.17713948).

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