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ORIGINAL ARTICLE

Heritability of gray matter volume and asymmetry in chimpanzees (*Pan troglodytes*) and their association to cognitive abilities and tool use

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Abstract
Genetic studies have increasingly identified key mechanisms that underlie individual and phylogenetic variation in behavioral and brain phenotypes. Here, we used quantitative genetics to estimate heritability in whole brain and region-specific variation in gray matter in a sample of captive chimpanzees. We included the contributions of sex and age to individual variation in gray matter as well as their association with cognition and motor functions and found small to moderate heritability in average gray matter volume in the majority of brain regions. By contrast, weaker estimates of heritability were found when considering asymmetries in gray matter across brain regions. Age was inversely associated with gray matter volume for the frontal lobe and the basal forebrain after accounting for sex and relatedness of the chimpanzees. Chimpanzees that had higher cognition scores were found to have greater leftward asymmetries in the regions comprising the frontal lobe and basal forebrain component. Further, chimpanzees with better performance on a tool use task had higher gray matter volumes in the frontal and basal forebrain regions. However, no genetic associations were found between tool use performance or cognition and the average frontal or basal forebrain gray matter volumes or asymmetry.

Keywords Chimpanzee · Gray Matter Volume · Heritability · Cognition · Tool Use Skill

Introduction

Comparative studies of primate brain organization have received considerable scientific attention as a means of identifying mechanisms underlying the evolution of human specific neuroanatomical and cognitive specializations (Sherwood et al. 2012; Rilling 2006). In humans, there is a growing body of evidence from quantitative and behavioral genetic analyses demonstrating the role of genetic and environmental factors on individual differences in various features of cortical organization, including gray and white matter volume and integrity, cortical thickness, and gyrification (Jansen et al. 2015; Eyler et al. 2012; Strike et al. 2015; Grasby et al. 2020). More recently, quantitative and behavioral genetic studies have also examined phylogenetic variation among nonhuman primates in behavioral and brain phenotypes. For example, total brain size, cortical surface areas and overall gyrification have been found to be significantly heritable in vervet monkeys, baboons, rhesus macaques, chimpanzees and humans (Kochunov et al. 2010; Rogers et al. 2007, 2010; Fears et al. 2009, 2011; Cheverud et al. 1990; Hopkins et al. 2015a, 2019a; Atkinson et al. 2015; Pizzagalli et al. 2016; DeCasien et al. 2020). Additional studies have shown that the surface area, lengths or shapes of selected sulci are heritable in baboons, rhesus monkeys, chimpanzees and humans (Kochunov et al. 2010; Atkinson et al. 2015; DeCasien et al. 2020; Hopkins et al. 2017, 2021b, 2023a; Foubet et al. 2024). Interestingly, the

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current collective findings generally suggest that heritability is lowest in humans compared to apes and Old World monkeys. For instance, Gomez-Robles et al. (2015) reported that relative contributions of genetic factors to within species variation in the spatial location of sulci and lobular landmarks were higher in chimpanzees compared to humans, suggesting increased plasticity in human brain development. This interpretation is consistent with evidence that the human brain, at birth, is much smaller as a proportion of its total adult size (~28%), compared to chimpanzees (~50%) and more distantly related Old World monkeys (~65%) (Leigh 2004). The general interpretation of these combined comparative findings is that reduced genetic contributions to cortical organization, coupled with increasingly longer periods of juvenile and adolescent development, provides a context for greater plasticity and allows the brain to be malleable in response to different cultural, social and environmental factors.

Recently, Vickery et al. (2020) published a macroanatomical atlas of the chimpanzee brain that included measures of gray matter volume and asymmetry from 65 brain regions in a sample of >200 individuals (referred to as DAVI130). Vickery et al. (2020) reported wide-spread region-specific age differences in gray matter volume as well as evidence of population-level asymmetry in multiple brains regions within the chimpanzee sample. In this paper, we leveraged the available pedigree information on the chimpanzee cohort included within the Vickery et al. (2020) paper to assess heritability in (1) whole brain and region-specific gray matter volume and (2) region-specific gray matter asymmetry. Based on previous studies on heritability on brain phenotypes in nonhuman primates, we hypothesized that chimpanzees would show significant heritability in whole brain and region-specific gray matter volume and hemispheric asymmetry.

In addition to the heritability findings, the contributions of sex and age to individual variation in gray matter volume was of interest in this study. As noted above, Vickery et al. (2020) reported widespread region-specific decline in gray matter volume associated with increasing age in the chimpanzees. Age-related decline in total intracranial, gray matter and white matter volume, as measured from magnetic resonance image scans, has also been reported in a multiple captive populations of nonhuman primates (Didier et al. 2016; Autrey et al. 2014; Frye et al. 2022; Phillips and Sherwood 2012; Westerhausen and Meguerditchian 2021; Westerhausen et al. 2020; Herndon et al. 1999; Koo et al. 2012; Makris et al. 2007; Wisco et al. 2008; Alexander et al. 2008; Sherwood et al. 2011; Lacreuse et al. 2020). That said, most studies on aging in nonhuman primates include young and old individuals that are part of captive breeding programs; however, seldom if ever are data on the relatedness of the subjects selected for use in the study provided in the reports. Ideally one would want to determine the relative contribution of relatedness between subjects to individual variation in morphology, independent of other factors including age and sex. This is especially the case for studies using cross-sectional designs. Thus, to assess the contribution of non-genetic factors to individual variation in each morphology outcome measure, we included age and sex and their cross-product as covariates in the heritability analysis. Of specific interest was whether the variable age or the interaction term between age and sex accounted for a significant proportion of variance in the brain phenotypes after accounting for their heritability.

Finally, cognition and motor skill performance data were available in many of the chimpanzees that were subjects in the Vickery et al. (2020) paper. Specifically, 191 chimpanzees within the Vickery et al. sample have been tested on the Primate Cognition Test Battery, a set of tasks developed to assess physical and social cognition in human children and nonhuman primates (Herrmann et al. 2007, 2010; Schmitt et al. 2011; Fichtel et al. 2020). Motor skill as measured by a tool use task were also available in 201 of these same chimpanzees (Hopkins et al. 2009). Previous studies have reported that chimpanzees show age-related decline in performance on the PCTB tasks (Hopkins et al. 2021a) and that age-mediates associations between cognitive performance, gray matter covariation as well as cortical thickness (Mulholland et al. 2021; Hopkins et al. 2023b). Similarly, previous studies have reported that older chimpanzees perform more slowly on tool use tasks compared to middle-aged and young apes (Hopkins et al. 2009) and that variation in performance is associated with gray matter covariation in premotor and superior parietal cortex (Hopkins et al. 2019a). Because the Vickery et al. (2020) data represent a more granular, region-specific assessment of gray matter volumetric variation, here we examined whether individual differences in cognition and tool use skill were phenotypically or genetically related to region-specific measures of gray matter volume or asymmetry after adjustment for sex and age. We hypothesized that significant associations would be found between chimpanzee cognition, tool use skill and gray matter volume or asymmetry in one or more brain regions.

Methods and materials

Subjects and archived gray matter volume data

As described in Vickery et al. (2020), magnetic resonance images (MRI) were obtained from 222 captive chimpanzees housed at the Yerkes National Primate Research Center (YNPRC, $n=87$) and National Center for Chimpanzee Care

(NCCC, $n = 135$) of the University of Texas MD Anderson Cancer Center. There were 135 females and 87 males ranging from 6 to 54 years of age (Mean = 26.64 years, $SD = 10.4$). All the NCCC chimpanzees as well as 11 YNPRC chimpanzees were scanned on a 1.5T scanner. The remaining 76 chimpanzees were all housed at the YNPRC and were scanned on a 3 T scanner. Details on the scanner type, scan sequences and post-image processing can be found in Vickery et al. (2020). For each chimpanzee, the 130 region (65 regions X 2 hemispheres) DAVI atlas maps were applied to the processed gray matter modulated volumes and the average gray matter volume per voxel was computed for the left and right hemispheres within each region (see Fig. 1 for atlas map description and legend).

Cognition assessment

Briefly, the PCTB data used in this study have been previously described in Hopkins et al. (2014b); Russell et al. (2011). In these studies, 191 chimpanzees were tested on 12 tasks that measure different aspects of physical and social cognition. Within the sample, individual performance data on each task were converted to standardized *z*-scores. The *z*-scores were then averaged across all 12 tasks to create a unit weighted average (UWA) score (Woodley et al. 2015). Chimpanzees were subsequently classified as performing higher (HTA, UWA scores > 0) or lower than average (LTA, UWA < 0) (we note here that there were no chimpanzees with a UWA score = 0). Using this classification criteria, there were 89 HTA and 102 LTA chimpanzees in the sample. The PCTB tests were most frequently administered within 1 to 3 years of the acquisition of the MRI scans (Mean difference in age = 2.33 years, SD = 1.90).

Tool use performance

Tool use performance data was available in 201 chimpanzees and was tested using a task designed to simulate termite fishing or ant dipping in wild chimpanzees (Bogart et al. 2012; Hopkins et al. 2009, 2015b; Boesch and Boesch

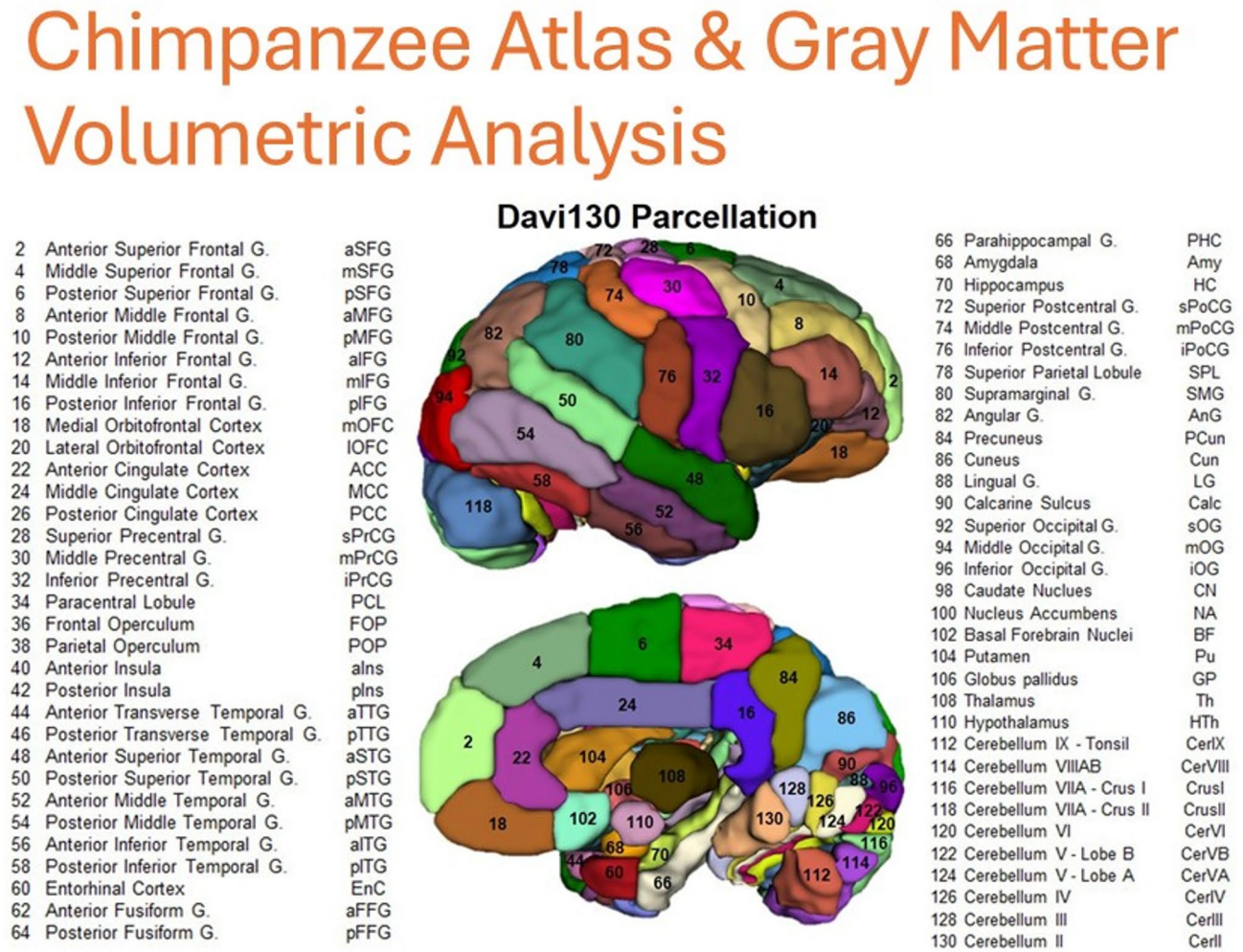

Fig. 1 3D -rendering of the Juna template and the DAVI 130 parcellation of the atlas labels map projected on the surface

1990; Boesch et al. 2017; Whiten et al. 1999; Marchant and McGrew 2007; Sanz et al. 2016). Briefly, a PVC pipe was attached to the subject's home cage that was blocked at one end and had a small opening on the opposite end. Food with an adhesive quality was placed inside the PVC pipe and in order to obtain the food, the chimpanzee had to insert a small lollipop stick into the hole, then extract the stick and consume the food that adhered to the stick. Hand use and the latency to successfully insert the stick was recorded on 50 responses for each chimpanzee (measured from the time the subject initiated an attempt to insert the tool with one hand and ended when the chimpanzee successfully inserted and removed the tool; Hopkins et al. 2015b, 2019c). The average latency of the 50 responses served as one outcome measure of interest. Because the two chimpanzee cohorts had different experiences with this tool use device, within the NCCC and YNPRC cohorts, the average latency scores were converted to standardized *z*-scores. Based on the *z*-scores, chimpanzees were classified as performing better (BTA, *z*-score < 0) or worse (WTA, *z*-score = > 0) than average (note that there were no chimpanzees with an exact z-score value = 0). The majority of the tool use performance data were obtained within 2 to 4 years of the acquisition of the MRI scans (Mean difference in age = 3.69 years, SD = 2.87). We also recorded the frequency hand use across the 50 trials. Using binomial *z*-scores, chimpanzees were classified as strongly-left handed (*z*-score <= −1.96, $n = 70$), weakly-left-handed (*z*-score between >−1.96 and 0, $n = 32$), weakly right-handed (*z*-score between 0 and +1.95, $n = 31$) and strongly right-handed (*z*-score >= +1.96, $n = 68$).

Data and heritability analyses

Whole brain gray matter was computed for each chimpanzee. Additionally, for each 65 DAVI regions, we computed the average gray matter volume per voxel for each subject. Lastly, asymmetry quotients (AQ) were computed following the formula [(AQ = (R – L)/((R + L) *0.5)] where R and L represent the right and left hemisphere gray matter values for each brain region. Positive AQ values indicated rightward biases and negative values indicated leftward asymmetries. Because magnetic resonance scans were acquired on different scanner platforms and protocols, as has been done in studies in human subjects (Orlhac et al. 2022; Tassi et al. 2024), we used the program Combat Harmonization to adjust the whole brain and 64 region specific gray matter volume values for variation due to scanner magnet strength (see Supplemental Fig. 1).

Consistent with previous work, to estimate heritability, we used the software package SOLAR (Almasy and Blangero 1998). SOLAR uses a variance components approach to estimate the polygenic component of variance when considering the entire pedigree (see Fears et al. 2009, 2011; Rogers et al. 2007; Hopkins et al., 2014a, b, 2018). Total additive genetic variance (h^2) is the amount overall phenotypic variance that is attributable to all genetic sources. Total phenotypic variance attributable to genetic and non-genetic variables is constrained to a value of 1; therefore, all non-genetic contributions to the phenotype are equal to 1 - h^2.

We initially used SOLAR to determine heritability in estimates of whole brain gray matter. Following on from the initial analysis, rather than consider all brain regions, we reduced the 65 DAVI regions to 8 dimensions or components of brain organization including frontal, parietal, temporal, visual, cingulate_insula, motor-sensory, basal forebrain, and cerebellar by averaging the gray matter values within each component. We adopted this approach to (1) to reduce the number of statistical tests and thereby limit Type I error and (2) simplify the comparison of the findings to results from other species. The specific brain regions from the DAVI atlas that were included in the computation of the values within each dimension is shown in Fig. 2. The mean gray matter and AQ values for the 8 components were the outcome measures in the SOLAR heritability analyses. Sex, age, and the sex by age interaction term were covariates. Because the AQ data did not meet the assumptions for normality, non-parametric tests were used to test for associations with cognition, tool use skill and handedness. For all analyses, alpha was set to $p < .05$.

For the analyses assessing the associations between cognition and average gray matter values, mixed model analysis of co-variance (ANCOVA) was used with region as the repeated measure (8 levels) while sex and cognition group were the between group factors The difference in age of the chimpanzees between PCTB testing and MRI scan acquisition as well as the chimpanzee relatedness coefficients were the covariates. Similarly, an ANCOVA was used to examine the effect of tool use skill and sex on average gray matter values. Region was the repeated measure (8 levels) while sex and tool use group were the between group factors. The difference in age of the chimpanzees between tool use testing and MRI scan acquisition as well as their relatedness coefficients were the covariates. Because the AQ values were not normally distributed, we used non-parametric tests (Mann-Whitney U, Kruskall-Wallis) to test for their association with cognition, tool use skill and hand preference.

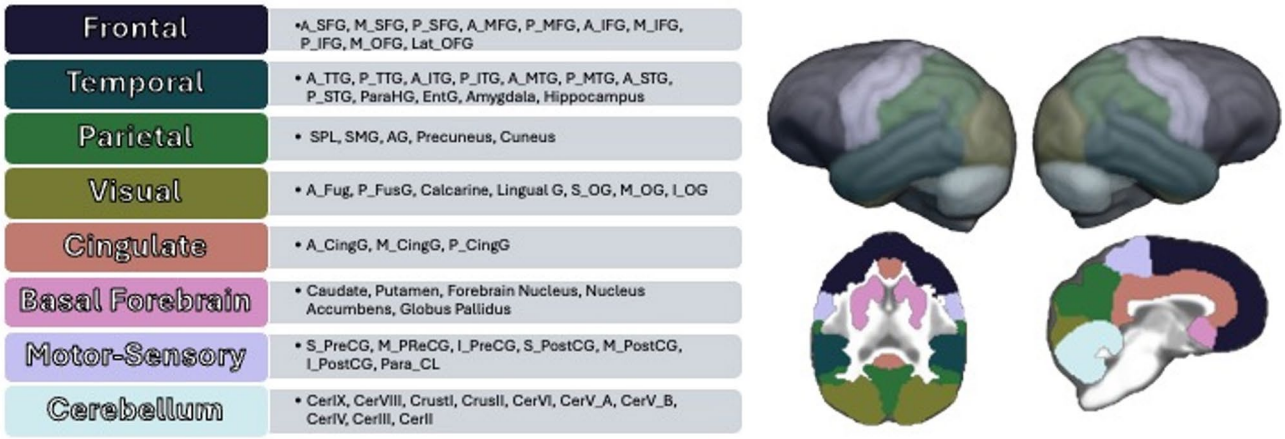

Fig. 2 Depiction of the regions within the DAVI 130 parcellation collapsed into the macrostructural organizational components used in this study

Table 1 Results of stepwise regression analyses and best fit line in chimpanzees linear quadratic

	Linear F-value	r2	*p*	Quadratic F-Value	r2	*p*
Mean Gray Matter						
Frontal	27.593	0.135	0	0.111	0.136	0.74
Temporal	32.793	0.147	0	1.469	0.153	0.227
Parietal	16.537	0.074	0	0.578	0.076	0.448
Visual	24.051	0.106	0	3.467	0.12	0.064
Cingulate-Insula	19.642	0.092	0	0.939	0.086	0.334
Motor-Sensory	11.592	0.07	0.001	0.001	0.07	0.97
Basal Forebrain	23.973	0.106	0	1.503	0.112	0.222
Cerebellum	27.471	0.118	0	5.601	0.14	0.019
Asymmetry						
Frontal	0.175	0.015	0.676	0.832	0.019	0.363
Temporal	0.005	0.016	0.944	0.868	0.02	0.352
Parietal	2.793	0.02	0.096	2.353	0.03	0.127
Visual	0.489	0.008	0.485	3.861	0.025	0.051
Cingulate-Insula	1.737	0.019	0.189	0.047	0.019	0.828
Motor-Sensory	17.008	0.124	0.001	2.455	0.134	0.119
Basal Forebrain	1.473	0.022	0.226	2.13	0.032	0.146
Cerebellum	0.365	0.003	0.546	1.608	0.01	0.206

Results

Age effects

Prior to the heritability analyses, we determined whether age showed a significant linear or quadratic associations with the whole brain and region-specific gray matter volume data. This was done as a means of determining which model of age association (i.e., linear or quadratic) to include as a covariate in the SOLAR heritability analyses. For these tests, we used stepwise multiple regression analysis. Sex, linear age and quadratic age were entered in that order and the *F*-value associated with the change in R with the inclusion of the linear and quadratic age variable was used to determine the best fit line. These findings are shown in Table 1. For 7 of the 8 components, age showed significant linear associations with gray matter volume. For the cerebellum (and borderline for the visual component), the quadratic association between age and gray matter volume was the best fit. For the AQ measures, age showed a significant linear association with the motor-sensory component. No significant linear or quadratic associations were found between age and the remaining 7 components.

Heritability in whole brain and region-specific gray matter volumes

For the whole brain analyses, significant heritability was found for gray matter volume ($h^2 = 0.340$, s.e. = 0.164, $p = .012$). Sex and the interaction between sex and linear age were found to be significant covariates (variance accounted

for = 0.189) (see Fig. 3). As can be seen, the slope in change between age and whole brain gray matter was stronger in the males compared to females. Significant heritability was also evident for 7 of the 8 components (the lone exception was the cingulate_insula component) (See Fig. 4; Table 2). Linear age was a significant covariate for the frontal and basal forebrain regions with increasing age associated with lower gray matter volumes (see Fig. 5a and b). The interaction between sex and age was a significant covariate for the temporal (linear) and visual (quadratic) components. For both components, males showed a higher change in slope value compared to females (see Fig. 5c and d). For completeness, the heritability estimates for all 65 regions within the DAVI atlas can be found in Supplemental Table 1. We note there that of the 65 regions within the DAVI atlas, 49 were significantly heritable at $p < .05$. In light of these findings, the significant heritability in 7 of 8 of the combined brain regions is not surprising.

We next considered heritability in the AQ values for the 8 components. No significant heritability was found for any of the components (see Table 2). Sex was a significant covariate for the visual and motor_sensory regions with females having greater rightward biases than males. As with the region-specific gray matter volume data, for completeness, the heritability estimates and proportion of variance accounted for by the covariates for the AQ values in all 65 DAVI atlas can be found in Supplemental Table 2. Of the 64 regions, only four showed significant heritability at $p < .05$.

Cognitive correlates of gray matter volume and asymmetry

For the average GM values, we performed a mixed model analysis of variance with region as the repeated measure (8 levels) while sex and cognition group (HTA, LTA) were the between group factors. The difference in age of the

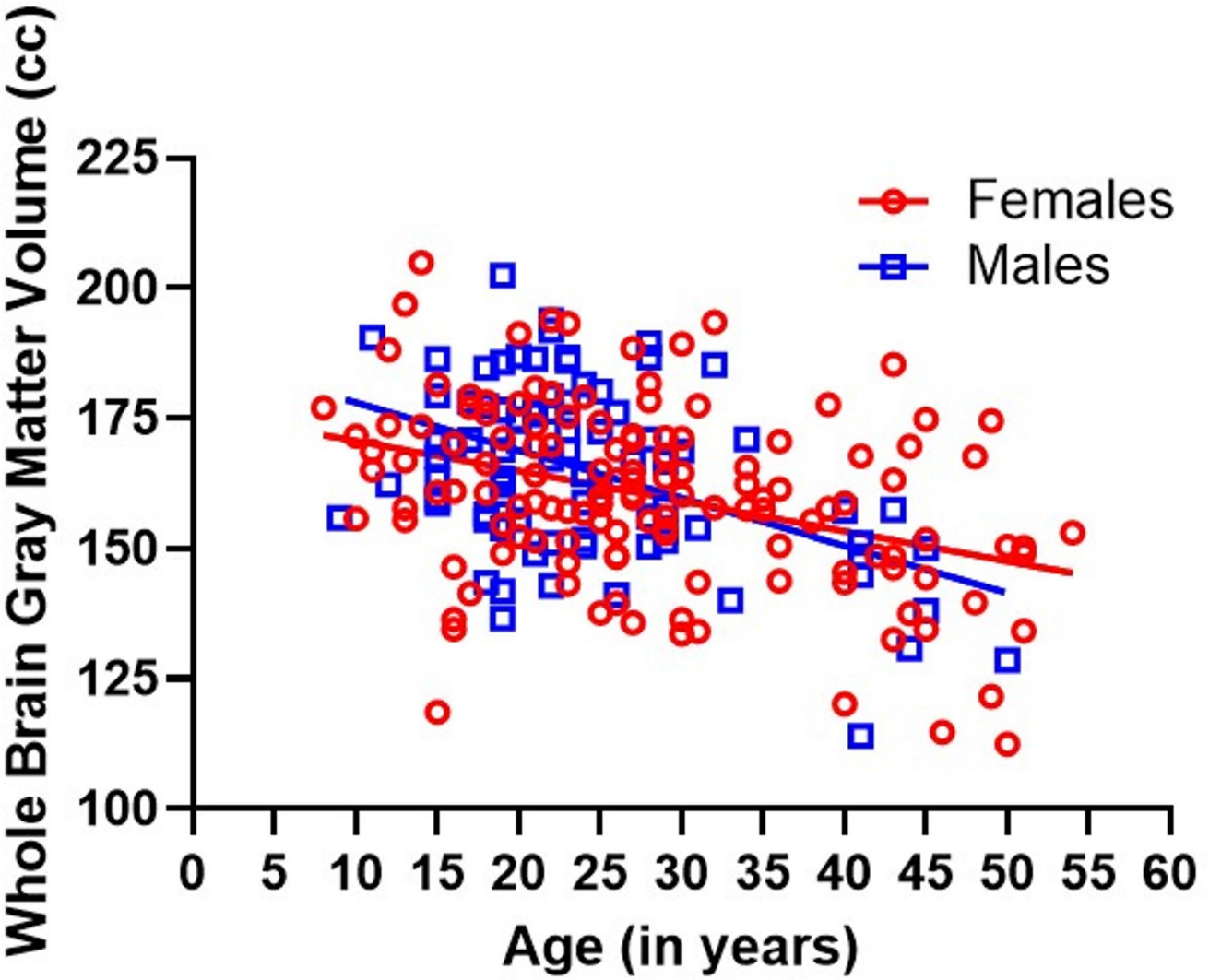

Fig. 3 (A) Scatterplot of the association between age and whole brain gray matter volume for males (blue) and females (red)

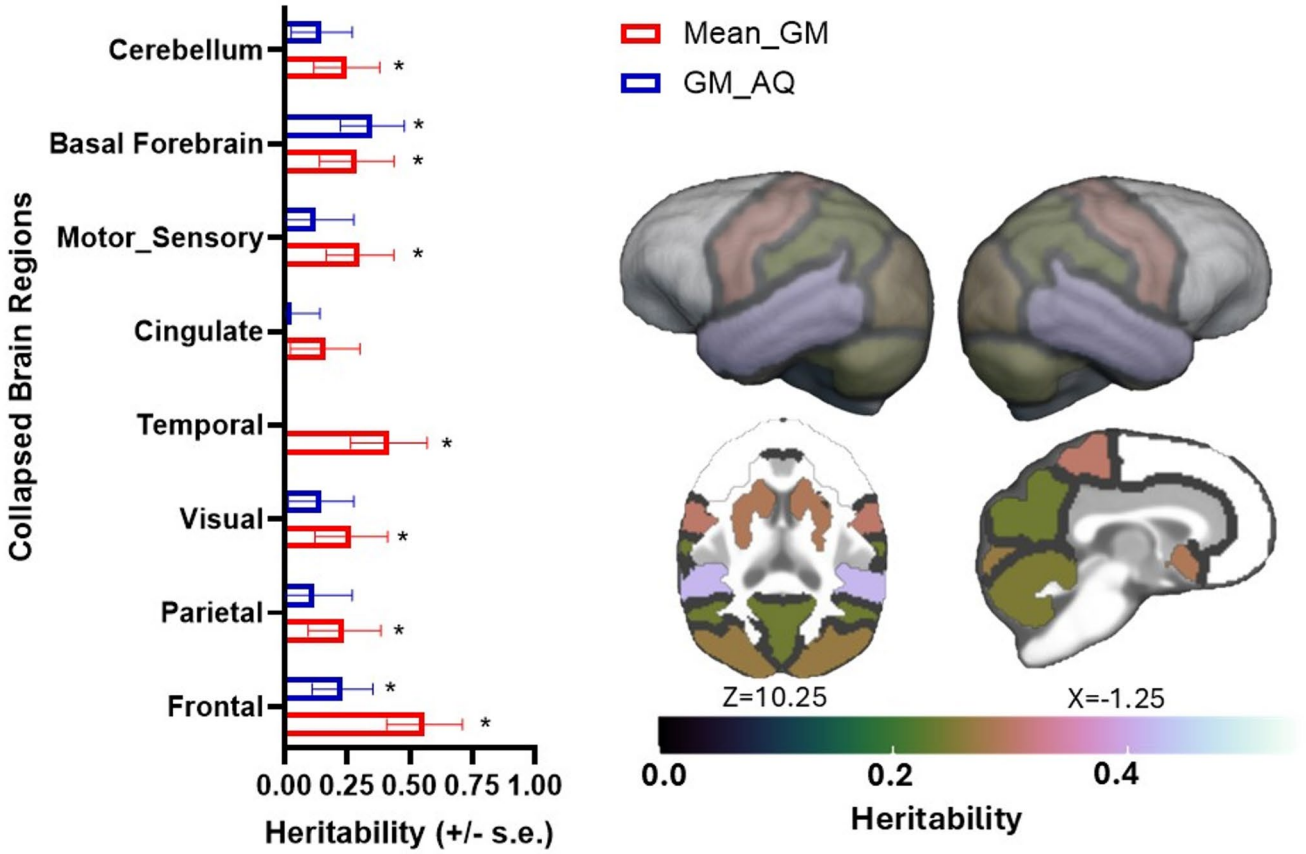

Fig. 4 Left panel) Heritability estimates (+/- s.e.) for average gray matter volume and asymmetry for each component. Right panel) 3D rendering with color coded indicators of heritability in gray matter volume

Table 2 Heritability estimates of each component for the average Gray matter volume and asymmetry measures

	h2	se	*p*	Covariates	Variance
Mean Gray Matter					
Frontal	0.572	0.154	0.000005	Age	0.117
Temporal	0.43	0.143	0.0004	Sex * Age	0.166
Parietal	0.245	0.141	0.0236	None	
Visual	0.251	0.142	0.023	Sex * Age	0.162
Cingulate-Insula	0.139	0.135	0.131	None	
Motor-Sensory	0.341	0.137	0.0017	None	
Basal Forebrain	0.297	0.141	0.0082	Age	0.106
Cerebellum	0.281	0.126	0.006	None	
Asymmetry					
Frontal	0.023	0.125	0.426	None	
Temporal	0	–	0.5	None	
Parietal	0.175	0.152	0.106	None	
Visual	0	–	0.5	Sex, Sex * Age	0.012
Cingulate-Insula	0.004	0.116	0.486	None	
Motor-Sensory	0.003	0.171	0.492	Sex	0.063
Basal Forebrain	0.126	0.14	0.164	None	
Cerebellum	0	–	0.5	None	

chimpanzees between PCTB testing and MRI scan acquisition as well as the chimpanzee relatedness coefficients were the covariates. No significant main effects or interactions were found. For the AQ analysis, Mann-Whitney U-tests revealed significant differences between the LTA and HTA chimpanzees for the frontal ($U=3596$, $p=.003$) and basal forebrain components ($U=3761$, $p=.041$). For both regions, LTA apes had greater rightward asymmetries than HTA individuals (see Fig. 6a).

Motor correlates of gray matter volume and asymmetry

For the average GM values, we performed a mixed model analysis of variance with region as the repeated measure (8 levels) while sex and tool use performance group (BTA, WTA) were the between group factors. The difference in age of the chimpanzees at the time of tool use performance data and MRI scan as well as their relatedness coefficient were the covariates. Significant two-way interactions were found between tool use skill and component $F(7, 1351)=2.773$, $p=.007$ as well as between tool use skill and sex $F(1, 193)=5.173$, $p=.024$. For the tool use

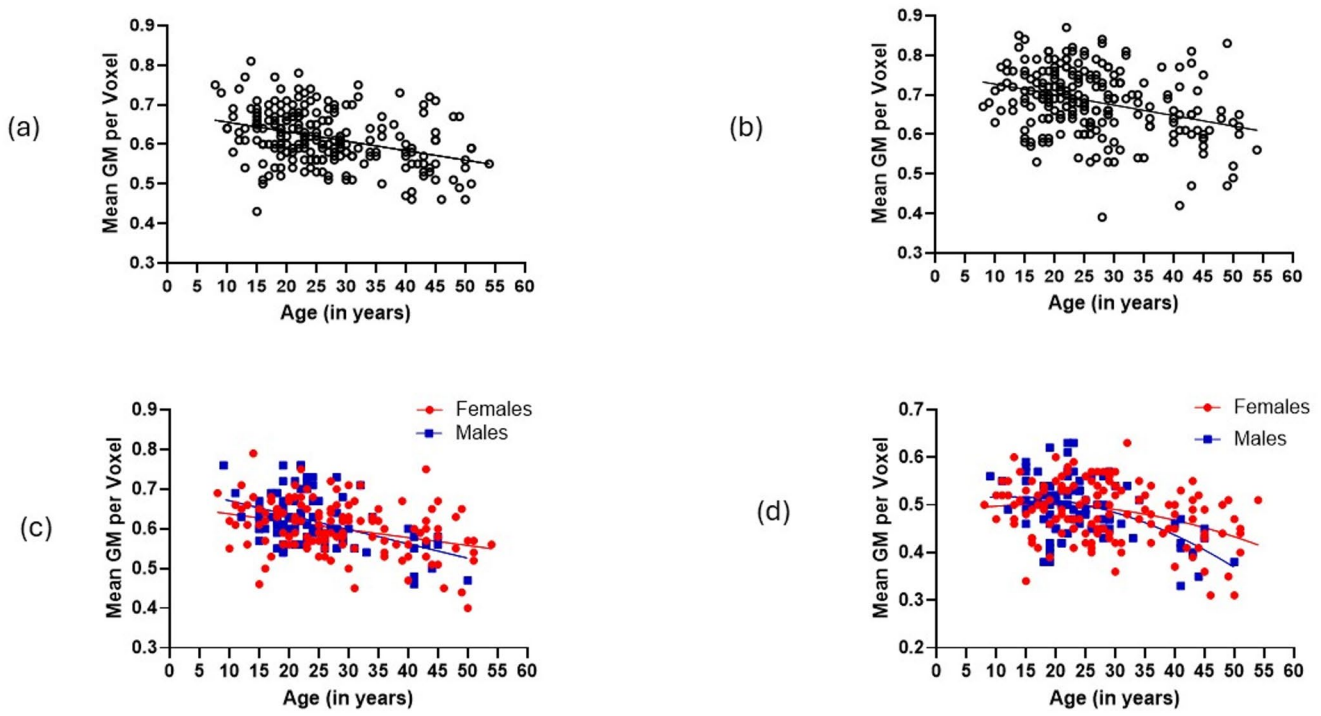

Fig. 5 Scatterplot of the association between age and **a** frontal gray matter volume **b** basal forebrain volume **c** temporal lobe components for males (blue) and females (red) and **d** visual regions for males (blue) and females (red)

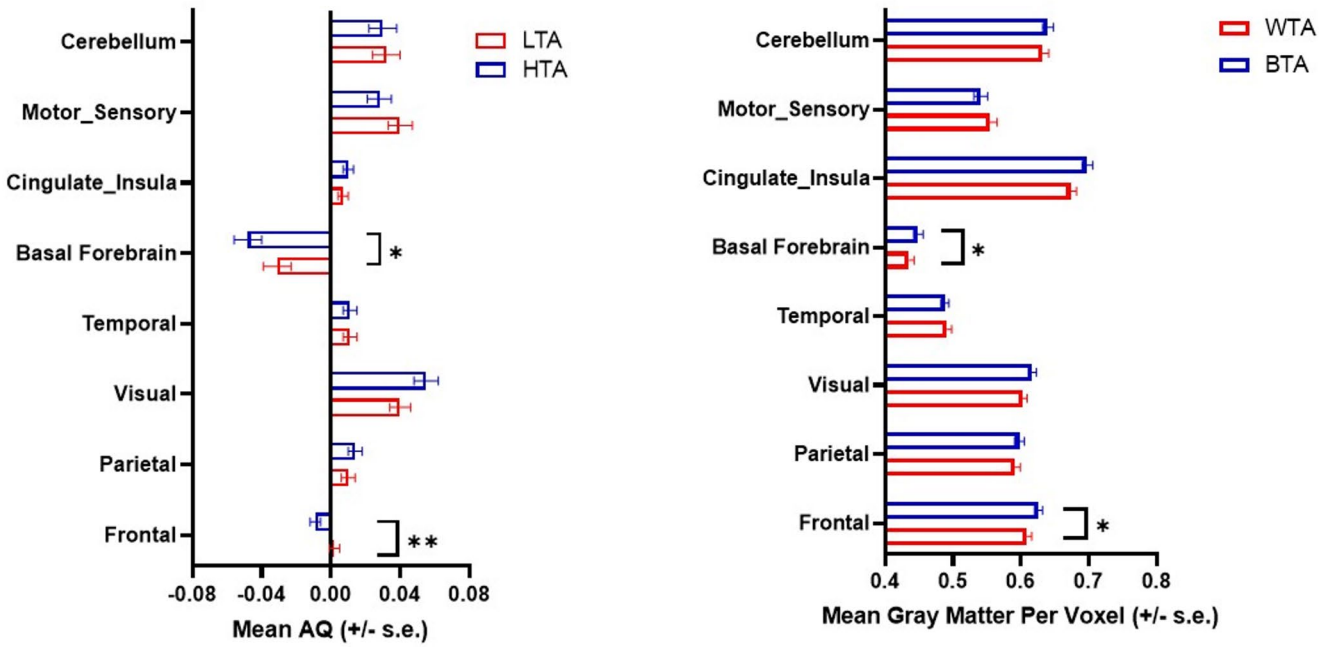

Fig. 6 **a** Mean AQ values (+/- s.e) for each component in HTA and LTA chimpanzees assessed on the PCTB task **b** Mean gray matter volumes (+/- s.e.) for each component in BTA and WTA as measured from the tool use task

by component interaction, post-hoc analysis revealed that WTA had lower gray matter values than BTA individuals for the frontal and basal forebrain regions (see Fig. 6b). For the sex by tool use performance group interaction, among females, BTA chimpanzees (*Mean* = 0.584, *se* = 0.007) had higher values compared to WTA (*Mean* = 0.555, *se* = 0.010) individuals. Among males, no significant difference was found between BTA (*Mean* = 0.580, *se* = 0.010) and WTA

(*Mean* = 0.592, *se* = 0.010) chimpanzees. For the AQ values, Kruskal-Wallis tests revealed no significant differences between handedness groups for any of the components. Because both the tool use performance data and the frontal and basal forebrain region values are significantly heritable and phenotypically associated with each other, we used SOLAR to test whether there was a significant genetic correlation between them. This analysis also failed to reveal a significant genetic correlation between these variables, suggesting that common genetic factors do not underlie their phenotypic association.

Discussion

This study is the largest ever to quantify individual difference in gray matter volume and asymmetry in chimpanzee brains. As was hypothesized, in general, whole brain and region-specific variation in gray matter volume was significantly heritable. Heritability for the 8 components ranged between 0.16 and 0.55 suggesting small to moderate genetic effects, which is consistent with previous reports on heritability in different aspects of shape and size of chimpanzee sulci (Hopkins 2013; Hopkins et al. 2017; Gomez-Robles et al. 2015). Furthermore, the estimates of heritability in our chimpanzee sample are within the range of values from previously reported findings in humans (e.g., van der Lee et al. 2017; Pizzagalli et al. 2020).

For whole brain gray matter volume as well as for the temporal and visual components, broadly speaking, older chimpanzees had smaller volumes but the slope in change was greater in male compared to female apes. It has been frequently though not always reported that the lifespan and health span of male chimpanzees is between 6 and 8 years shorter than females, which may be associated to their steeper decline in whole brain gray matter volume (Huber et al. 2025; Wood et al. 2017; Havercamp et al. 2019; Dyke et al. 1995; Che-Castaldo et al. 2021). We note here that, without considering the relatedness of the chimpanzees, age shows a significant negative association with gray matter volume for all 8 regions. Thus, after accounting for the proportion of individual variability in gray matter attributed to relatedness, the variance accounted for by the age of chimpanzees is substantially reduced. These findings reinforce that view that without consideration of the relatedness of subjects, the proportion of variability in gray matter volume that is accounted for by age on different brain or behavioral phenotypes may be overestimated.

With respect to asymmetries, no significant heritability was found for any of the components (see Table 2 as well as Supplemental Table 2). These findings are also consistent with previous reports in human subjects and, to a lesser extent, chimpanzees and other nonhuman primates (Gomez-Robles et al. 2016; Sha et al. 2021; Carrion-Castillo et al. 2020; Fears et al. 2011). At present, molecular biological evidence of specific genes that code for left-right brain asymmetries in human and nonhuman primate brains is relatively weak (Pletikos et al. 2014; Muntane et al. 2017) and the results reported here, at least with respect to gray matter are consistent with these results. Indeed, Gomez-Robles et al. (2016) have reported significant population-level asymmetries in sulci length and cortical shape in both humans and chimpanzees; however, the sulcal asymmetries in both species were either not or weakly significantly heritable, reinforcing the findings from this study.

The limited contribution of genetic factors to hemispheric asymmetries in chimpanzees, suggested by the findings reported here and by Gomez-Robles et al. (2016), raise the question of what factors might contribute to the emergence of individual and population-level lateralization in human and nonhuman primates. From a human developmental standpoint, there is now good evidence of the presence of early positional and motor asymmetries that might have long-term consequences on the development of behavioral asymmetries such as *in utero* thumb-sucking, position of the fetus during the last trimester, and post-natal factors including head orientation and maternal cradling (Michel 1981; Previc 1991; Harris 2010; Hepper et al. 2005). Likewise, in nonhuman primates, there is evidence of asymmetries in neonatal thumb-sucking, head orientation, nipple preferences and in adult infant cradling (Fagot and Bard 1995; Hopkins and Bard 1993, 1995; Hopkins et al. 1993; Damerose and Hopkins 2002; Hopkins and De Lathouwers 2006; Jaffe et al. 2006; Nishida 1993; Tomaszycki et al. 1998; Zhao et al. 2008; Manning et al. 1994; Dienske et al. 1995; Hopkins 2004; Regaiolli et al. 2018). If early lateralized experiences or environmental factors influence the long term development of left-right differences in the nervous system (Collins 1975, 1985), this might explain both individual and potentially phylogenetic differences in behavioral and brain asymmetries.

Related to the discussion of asymmetry, we also found that chimpanzees with higher-than-average cognition performance scores (i.e., HTA) showed greater leftward biases in the regions comprising the frontal and basal forebrain components compared to chimpanzees performing below average (LTA). Leftward asymmetries in higher order cognitive and motor function, including language and speech, are a feature of the human brain (Hagoort 2019; Corballis 2015) but their immediate relevance to the findings reported here are not obvious. That said, we would speculate that the greater leftward biases in chimpanzees with higher "g" values may have conferred some adaptive advantage and served as an antecedent condition or preadaptation for the

emergence of more expansive left hemisphere asymmetries observed in humans after the split from the common ancestor.

With respect to tool use performance, we found that in females but not males, BTA chimpanzees had higher gray matter values compared to WTA individuals. These findings are consistent with previous studies reporting that female chimpanzees (a) learn to use tools at an earlier age (Kahlenberg and Wrangham 2010; Lonsdorf et al. 2004) (b) perform significantly better on tool use tasks than males (Hopkins et al. 2009, 2019b) and (3) have higher gray matter volumes in premotor cortex compared to males (Hopkins et al. 2019a, 2025). Our findings also revealed BTA chimpanzees on the tool use performance task (as indicated by shorter latencies) had higher gray matter values in the frontal lobe compared to WTA apes. These results are also consistent with findings in humans implicating frontal and basal forebrain regions in motor learning as well as higher order motor and praxic functions (Lewis 2006; Johnson-Frey 2004; Thibault et al. 2021).

This study is not without some limitations. First, magnetic resonance scans were acquired on different scanner platforms and protocols. Ideally, all the images would have been obtained on the same machine and protocol, but this was not possible for a variety of pragmatic reasons. Second, the lags in time between MRI scan acquisition and collection of the cognition and tool use data varied across subjects. Though this was not a contributing factor, ideally, the collection of the cognition and tool use data would have been obtained more closely in time to the acquisition of the scans. Lastly, though not a limitation, we would point out that the wide-spread heritability found in the 65 DAVI regions is not attributable to the observed heritability for whole brain gray matter volume. Recall that the average gray matter per voxel values measured from the DAVI atlas maps were derived from the volumes that were modulated or adjusted for whole gray matter volumes for each subject.

In summary, chimpanzees showed significant heritability in whole brain and region-specific measures of gray matter volume. Significant heritability coefficients were small to moderate in their effect size and were consistent with previous findings in chimpanzees and other primate species. We also found that chimpanzees with better tool use skill had larger gray matter volumes in frontal and basal forebrain regions. Moreover, chimpanzees with higher cognition values, as assessed by the PCTB tasks, were found to have greater leftward asymmetries in brain regions within frontal and basal forebrain components. These collective findings further our understanding of the role of genetic contributions to individual, and potentially phylogenetic variation, in cortical morphology and their phenotypic associations with cognitive and motor functions. The findings also provide invaluable data on shared and potentially divergent neurobiological foundations of higher order motor and cognitive functions that distinguish chimpanzees and other primates from humans (van den Heuvel et al. 2023).

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Author contributions W.D.H. analyzed data, wrote the main text, and prepared figures. A.A. performed statistical analyses. C.F. performed harmonization analyses. S.V. created atlas maps, assisted in figure creation, and edited manuscript. F.H. edited manuscript.

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Data availability Data from this study are available upon request.

Declarations

Conflict of interest The authors declare no competing interests.

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