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Gray Matter Correlates of Finger Gnosis in Children: A VBM Study

Firat Soylu,[a,*] Roy Seo,[b] Morgan Newman[c] and Sharlene D. Newman[d]

[a]The University of Alabama, Tuscaloosa, USA

[b]University of Washington, Seattle, USA

[c]Vanderbilt University, Nashville, USA

[d]Indiana University, Bloomington, USA

Abstract—Accumulating evidence relates finger gnosis (also called finger sense or finger gnosia), the ability to identify and individuate fingers, to cognitive processing, particularly numerical cognition. Multiple studies have shown that finger gnosis scores correlate with or predict numerical skills in children. Neuropsychological cases as well as magnetic stimulation studies have also shown that finger agnosia (defects in finger gnosis) often co-occurs with cognitive impairments, including agraphia and acalculia. However, our knowledge of the structural and functional correlates, and the development of finger gnosis is limited. To expand our understanding of structural brain features that are associated with finger gnosis, we conducted a voxel-based morphometry study with 42 seven- to 10-year-old children, where we investigated the correlation between finger gnosis scores and whole-brain gray matter volume (GMV). Correlations between finger gnosis and GMV were found in a set of frontoparietal, striatal, and cerebellar areas. We also found sex differences in how GMV is associated with finger gnosis. While females showed a more distributed and extensive set of frontal and parietal clusters, males showed two striatal clusters. This study provides the first findings on structural brain features that correlate with finger gnosis.

Key words: finger gnosis, voxel-based morphometry, gray matter volume, sexual dimorphisms.

INTRODUCTION

Finger gnosis (also referred to as finger sense, finger localization or gnosia) denotes the presence of a finger schema and the ability to identify, individuate, and mentally represent one's own fingers (Fayol et al., 1998; Noel, 2005; Penner-Wilger and Anderson, 2013). Due to its relevance to cognition in general, poor finger gnosis has been used as an indicator of brain dysfunction and learning disability for several decades (Gerstmann, 1940; Critchleey, 1953; Benton, 1979). The scientific study of the relation between finger gnosis and its relation to cognitive processing goes back to 1924 when Josef Gerstmann diagnosed an adult patient showing four impairments: difficulty naming her own fingers and pointing to her fingers on request (finger agnosia), differentiating between her own or another person's left and right hands, writing, and performing arithmetic calculations. These impairments were due to a lesion in the left angular gyrus (Gerstmann, 1940). After his initial discovery Gerstmann studied a series of patients with inferior parietal brain damage in the dominant hemisphere, each showing a subset of the tetrad of symptoms, and less often all four (Gerstmann, 1957). Gerstmann claimed that an impairment of the body image, particularly to the finger schema, underlay all four symptoms.

*Corresponding author at: The University of Alabama, Box 870231, Tuscaloosa, AL 35487, USA.
E-mail address: fsoylu@ua.edu (Firat Soylu).

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Later case studies (Mayer et al., 1999; Carota et al., 2004) and magnetic stimulation studies (Rusconi et al., 2005) offered supporting evidence for Gerstmann's syndrome. More recently the common origin for these four symptoms was claimed to be an impairment in mental manipulation of images (Mayer et al., 1999; Carota et al., 2004; Ardila, 2014) and a subcortical disconnection affecting parietal networks (Rusconi et al., 2009).

A separate body of research with healthy children link finger gnosis with number skills (see Soylu et al., 2018a for a review). These studies show that finger gnosis scores either correlate with or predict performance in different number tasks (Fayol et al., 1998; Noel, 2005; Penner-Wilger et al., 2009; Newman, 2016; Wasner et al., 2016). However, the association between finger gnosis and number skills might be age specific. Newman (2016) reported that children five to eight failed to show a relationship between addition performance and finger gnosis, while children nine to 12 did show such a relationship. The explanation provided for the discrepancy between the two age groups on how finger gnosis relates to addition performance was that both addition skills and finger sense are still developing in the younger group. Similarly Long et al. (2016) found no correlation between finger sense skills and arithmetic performance with a group of six- to eight-year-old children. These results are in contrast to multiple studies that showed a relation between finger gnosis and mathematical ability with similar aged samples (Fayol et al., 1998; Noel, 2005; Penner-Wilger et al., 2009; Reeve and Humberstone, 2011; Wasner et al., 2016). To unfold the association of finger gnosis and arithmetic processing at the neural level Soylu et al. (2018b) studied areas of activation that correlate with finger gnosis scores during addition and subtraction with seven- to eight-year-old children. Negative correlations were found for activation in the left fusiform and bilateral precuneus for both addition and subtraction, and in the left inferior parietal lobule only for addition. They concluded that children with better finger sense skills are also better at linking finger representations to number representations, which can facilitate the access to Arabic numerals via finger representations. They further hypothesized that finger representations may also participate in numerical magnitude representation, possibly in the form of visuomotor imagery. These findings overlap with a previous fMRI study on neural correlates of finger gnosis which reported a network involving the left intra-parietal lobule (IPL) , bilateral precuneus, bilateral premotor cortex, and the left inferior frontal gyrus compared to a matching visuomotor task that did not involve fingers (Rusconi et al., 2014).

Even though there is accumulating evidence suggesting a relation between finger gnosis and cognitive processing, in particular numerical cognition, the developmental trajectory and the neural correlates of this relation is not well understood. Part of the issue is weaknesses in our understanding of how finger gnosis develops in young children and the neural systems that support it. Structural measures inform cortical maturation (through myelination & synaptic pruning), the trajectory of which tends to parallel cognitive development milestones (Sowell et al., 2003). Cortical maturation takes place earlier for primary sensory and motor systems, followed by more latent maturation for temporal and parietal association areas related to cognitive function (e.g., language, visual memory), and with higher-order association areas (e.g., prefrontal and lateral temporal), which integrate information from primary sensorimotor areas and support executive function and cognition, maturing last (Casey et al., 2005). In particular, gray matter loss (pruning) has been shown to take place earliest in sensorimotor and latest in the prefrontal areas (Sowell, 2004). Gray matter loss during development is considered a crucial part of the brain maturation process. Therefore, investigating how structural features, such as gray matter volume, associate with sensorimotor and cognitive functions in developmental populations is important in understanding the neural correlates and developmental trajectories of these functions.

To further our understanding of neural systems supporting finger gnosis in children, the current study used voxel based morphometry (VBM) to explore the relationship between finger gnosis and gray matter volume (GMV). Based on previous research, GMV in parietal areas –in particular IPL, precuneus, and motor and somatosensory regions for fingers in the pre/post central areas – was predicted to be related to finger gnosis scores. Additionally, since the finger gnosis task involves both sensory stimulus and a motor response we expected to find correlations in frontal areas related to executive control and areas in the basal ganglia and the cerebellum related to sensory and motor functions.

EXPERIMENTAL PROCEDURES

Participants

The data presented came from two fMRI studies where both T1 weighted structural images and finger gnosis data were collected. Data from 51 seven- to 10- year-old children (23 female, mean age = 8.31, SD = 1.02 years) were used in this study. Five participants were removed from the data pool due to excessive motion in the scanner (>5 mm). Data from four participants were excluded from the analysis due to left-handedness, leaving 42 right-handed participants (mean handedness = 86.67, SD = 13.61), included in the analysis.

This age group was chosen because they: 1) can understand and perform the finger gnosis task and they either have fully developed or are on the cusp of having fully developed finger gnosis (Reeve and Humberstone, 2011).

Parental consent and child assent were obtained prior to the experimental sessions, in accordance with the Indiana University Institutional Review Board and the Declaration of Helsinki.

Finger gnosis test

The finger gnosis test is a standard assessment that dates back to Benton (1955) and since has been used in a number of studies (Noel, 2005; Berteletti and Booth, 2015). During the test participants sat with both hands palm down on the table in front of them. They were instructed to close their eyes and to keep them closed during the entire procedure (eyes were checked regularly). There were two phases of the test. During the first phase, the experimenter, with a pointer, touched a single finger of the left hand in a pre-determined order, touching each finger (five trials). After each finger touch the subject was instructed to indicate which finger was touched, by moving the corresponding finger of the other hand (one point per trial). During the second phase the experimenter touched a combination of two fingers in succession (five trials), and the participant was instructed to indicate which two fingers were touched and the order that they were touched, by moving the corresponding fingers of the other hand (two points per trial; one point for the correct fingers and one point for the correct order). The score was the total number of points earned divided by the total possible points. There were 15 possible points. The scores were normalized by scaling between 0 and one.

Imaging parameters

Participants underwent MRI scanning using a 12-channel head coil and a Siemens 3T TIM Trio MRI scanner. T1-weighted anatomical scans were collected for each subject. An MPRAGE sequence (192 sagittal slices; FOV = 256 mm, matrix = 256 × 256, TR = 1800 ms, TE = 2.67 ms, TI = 900 ms, flip angle = 9°, slice thickness = 1 mm, resulting in 1-mm × 1-mm × 1-mm voxels) was used.

Data analysis

The origins of all structural images were manually set to the anterior commissure using the display tool in SPM12 (Wellcome Trust Centre for Neuroimaging; http://www.fil.ion.ucl.

ac.uk/spm), and segmented into GMV and WMV using the Computational Anatomy Toolbox (CAT12; http://dbm.neuro.uni-jena.de/cat12/) segmentation tool. CAT12 provides image quality ratings (IQR), based on noise (e.g., motion) and spatial resolution. The structural images for the 42 participants included in the analysis had a mean IQR of 0.83 (STD = 0.024, range 0.77–0.86). The IQR for all images were above the C+ (0.75) threshold (Karavasilis et al., 2017). A customized age- and sex-matched Tissue Probability Map, generated using the Template-O-Matic toolbox (Wilke et al., 2008) was used during the segmentation. A custom DARTEL template was created using the segmented images, then the images were warped to this template and normalized to the Montreal Neurological Institute (MNI) template with 1.5 mm isotropic voxels. GMV images were then smoothed with an 8 mm^3 Gaussian kernel. The homogeneity check showed no outliers.

First, a multiple regression analysis was performed to test for the whole-brain GMV and finger gnosis correlations, followed by an F-test, where males and females were separated into two groups, to test for areas where sex interacted with GMV and finger gnosis correlations.

Across all analyses finger gnosis scores were entered as a covariate of interest and total cranial volume (TIV) as a nuisance variable. An absolute threshold mask of 0.1 was used to exclude voxels outside of the brain. AFNI 3dFWHMx (https://afni.nimh.nih.gov) was used to estimate noise smoothness values for the design specification using the "-acf" (spatial autocorrelation function) option, and using the ResMS (estimated residual variance image) file as the input. The ACF values were used as inputs for 3dClustSim to calculate (using Monte Carlo simulations) the whole brain cluster thresholds, separately for each contrast, that would be appropriate to control for type I errors for an uncorrected $p < .001$, which corresponds to a $p < .01$ corrected for the multiple comparisons in the whole brain volume analysis.

Approaches that assume constant spatial smoothness in (f)MRI data was found to lead to an increased rate of type I errors (Eklund et al., 2016). The approach used here addresses this problem, and is shown to better control for type I errors (Cox et al., 2017). The results were visualized using the ITK-SNAP (http://www.itksnap.org) and ParaView (https://www.paraview.org) software.

Data availability

The raw structural MRI and behavioral data is publicly available in the Harvard Dataverse public data repository (Soylu and Newman, 2019).

RESULTS

Finger gnosis scores

The average for the normalized finger gnosis scores was 0.87 (range between 0.35 and 1, SD = 0.14). The finger gnosis scores did not significantly correlate with age ($r = 0.204$, $p = .195$), or with handedness ($r = -0.28$, $p = .073$). Males and females (females N = 23, males N = 19) did not differ in finger gnosis scores (females M = 0.88, SD = 0.12, males M = 0.85, SD = 0.16), $t(40) = 0.74$, $p = .463$, in age (females M = 8.35, SD = 1.03, males M = 8.26, SD = 1.05), $t(40) = 0.26$, $p = .793$, or in handedness (females M = 79.69, SD = 16.47, males M = 85.59, SD = 17.56), $t(40) = 1.12$, $p = .27$.

Whole-brain analysis

Whole sample analysis

The regression analysis for the correlation between finger gnosis scores and whole brain GMV revealed no clusters showing positive correlations and eight significant clusters negatively correlating with finger gnosis (Fig. 1, Table 1). These included bilateral clusters in the cerebellum and putamen, and a left precuneus, precentral, fusiform, and a medial superior frontal gyrus (SFG) cluster. Bilateral cerebellar clusters (the left one being larger) covered the posterior lobe of cerebellum and in particular the inferior semilunar lobule (lobules simplex).

Effects of sex

There was an interaction (F-test) between sex and the correlation between finger gnosis scores and GMV in two clusters, one in the right superior frontal gyrus (rSFG) and another in the left lingual gyrus. To make sense of this interaction the correlation between finger gnosis and GMV was tested separately for males and females. These two separate one sample t-tests showed mutually exclusive clusters for females (seven clusters) and males (two clusters) (Fig. 2, Table 2). The interaction in the rSFG was driven by GMV correlating with finger gnosis in this area only for females; the interaction cluster overlapping with the cluster for the female group, while there was no significant correlation in this area for the male group. Neither the female nor the male group showed a significant cluster in the left lingual area.

DISCUSSION

Finger gnosis is an important construct that has been used to diagnose brain dysfunction and disabilities for decades (e.g., Sauguet et al., 1971; Benton, 1979). Recent research has also shown that finger gnosis correlates with and predicts mathematical abilities (Noel, 2005; Penner-Wilger and Anderson, 2013; Wasner et al., 2016) and there is some evidence showing that finger sense training can improve mathematical skills in children (Gracia-Bafalluy and Noel, 2008; Jay and Betenson, 2017). In spite of the relevance of finger gnosis to cognition, there has been only one study on the neural correlates of finger gnosis (Rusconi et al., 2014) and no studies so far on its structural correlates. In this study we partially addressed this gap by investigating the relation between GMV and finger gnosis in children and exploring sex differences in this relation.

The results presented here show that finger gnosis was negatively correlated with GMV in the precuneus, the medial frontal gyrus, the basal ganglia and the cerebellum; areas previously linked to finger, spatial and motor processing. Additionally, sex differences were observed such that finger gnosis scores negatively correlated with a wider distribution of frontal and parietal regions in females, while the

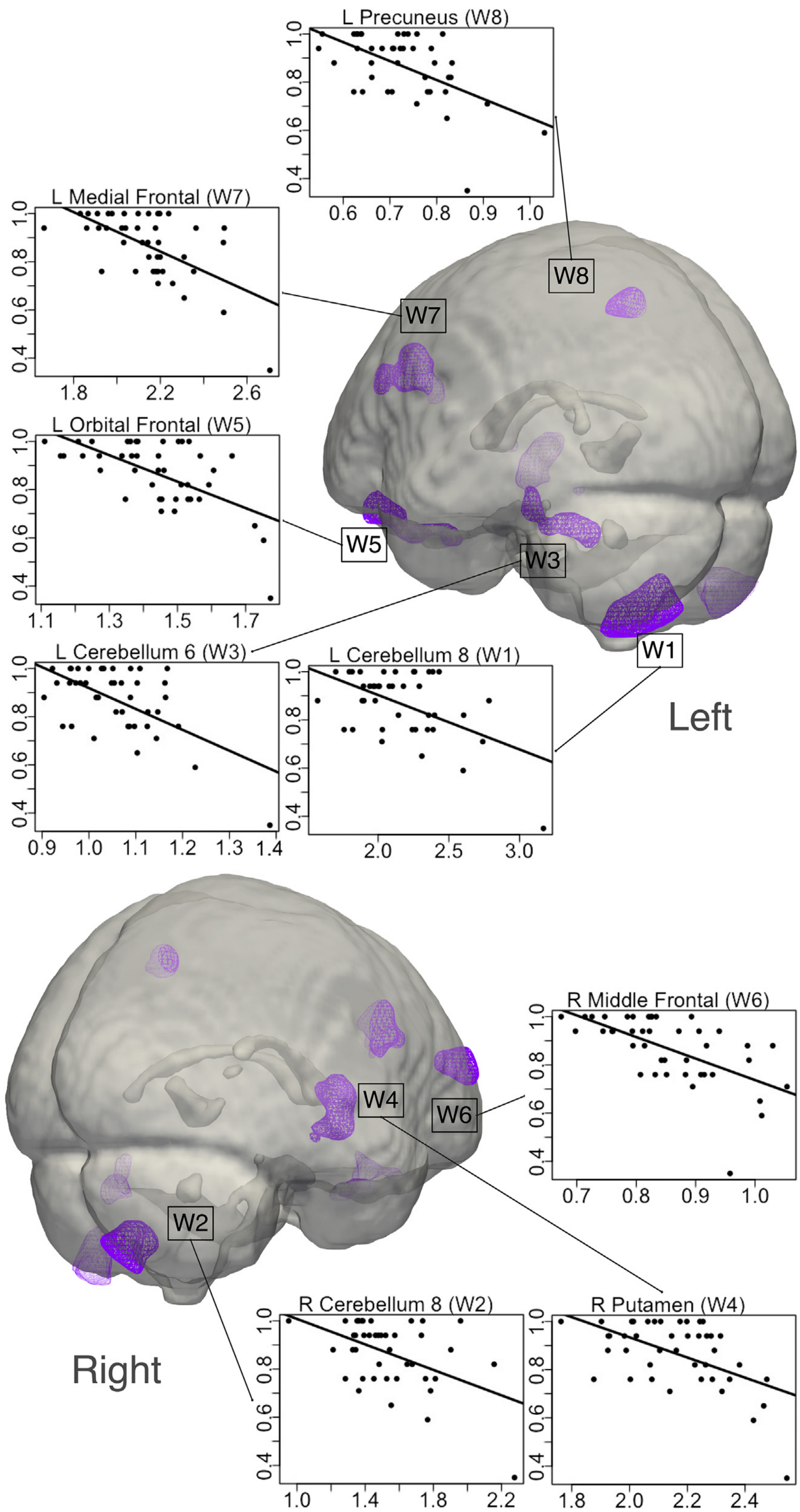

Fig. 1. Areas showing showing significant negative correlations between finger gnosis and GMV for the whole-sample (left hemisphere at the top, right hemishpere at the bottom). The scatter plots show the correlations between regional GMV (x-axis) and finger gnosis scores (y-axis).

correlations were limited to two areas in the basal ganglia for males. Given that GMV volume decreases with maturation during development (Brain Development Cooperative Group, 2012), the reported negative correlations between GMV and finger gnosis are interpreted as earlier maturation of these areas in children with higher finger gnosis abilities. Because of the low variance in age, lack of a correlation between age and finger gnosis scores within this sample, and lack of an age difference between males and females, the effects observed are not driven by age differences and are likely to be related to the differences in the developmental trajectories for males and females.

The finger gnosis task variant used in this study involves a set of sensory and cognitive processes that include the perception of somatosensory stimulation, mapping that stimulation to a mental representation of fingers, relating the mental representation of one's own body to the output representation, as well as the generation of a motor response. Rusconi et al. (2014) examined the neural correlates of finger gnosis in adults using an fMRI paradigm, where subjects went through the finger gnosis test during scanning. The finger gnosis task variant used in this study involved verbal responses in two sub-tasks; first, whether the distance between the two stimulated fingers was the same or different across the two hands and, second, whether fingers received stimulation of equal or different intensity between the hands. The reported finger gnosis network included the left inferior parietal lobule (IPL), left inferior frontal gyrus (IFG), bilateral precuneus, and the bilateral premotor cortex. Ruscaoni et al. argued that the IPL provides the primary substrate for body-structure representations for fingers and that the connections between the IPL and the precuneus are critical to finger gnosis because together they provide an interface for visuospatial finger schema processing. The precuneus participates in a range of multimodal, integrated tasks that involve visuospatial processing (see Cavanna and Trimble, 2006 for a review), including visuospatial imagery, episodic memory retrieval, encoding and retrieval of spatial locations (Frings et al., 2006), and in regeneration of contextual associations (e.g., word-picture associations; Lundstrom et al., 2003). Outside of the parietal cortex, the principal corticocortical connections of the precuneus are with the frontal lobes, particularly with the premotor cortex (Brodmann areas 8, 9 & 46) (Cavanna and Trimble, 2006). Studies with non-human primates provide evidence for a crucial role for the corticocortical projections from the precuneus to the

Table 1. Clusters showing significant negative correlations between GMV and finger gnosis scores for the whole-sample.

	Region	Extent	t	MNI, x y z		
W1	L Cerebellum (8)	1062	4.139	−15	−70	−51
W2	R Cerebellum (8)	750	3.805	12	−79	−55
W3	L Cerebellum (6)	366	4.037	−36	−51	−28
W4	R Putamen	789	4.017	21	4	4
W5	L Orbital Frontal	813	4.853	−17	56	−17
W6	R Mid. Frontal Gyrus	480	5.599	43	43	18
W7	Med. Frontal Gyrus	1056	4.791	−1	49	42
W8	L Precuneus	293	4.305	−8	−54	50

premotor cortex in visually guided hand movements (Caminiti et al., 1999). The left precuneus cluster found in the whole-sample analysis is therefore likely to be related to the visuospatial processing involved in matching finger somatosensory stimulation with a visuospatial representation for fingers. Precuneus activation has also been consistently reported in arithmetic tasks and is thought to be related to visuospatial transformations involved in arithmetic calculation (Arsalidou and Taylor, 2011). In an fMRI study involving an arithmetic task with seven to eight-year-old children, Soylu et al. (2018b) reported a negative correlation between finger gnosis scores and the BOLD response in the bilateral precuneus during addition and subtraction, and in the left IPL only during addition. They argued that the negative correlation in the precuneus may be due to either an indirect relation between finger gnosis and arithmetic processing, mediated through visuospatial skills, or direct involvement of precuneus in mental representation of fingers. Even though the exact function of the precuneus in finger gnosis is not clear, the findings reported here overlap with previous neuroimaging findings on the involvement of precuneus in finger gnosis.

The current study failed to show a correlation between IPL GMV and finger gnosis. This result may appear to be at odds with those reported by Rusconi et al. (2014), who suggested that the IPL is a core component of the finger gnosis network. However, it is important to remember that this study is exploring individual variance in GMV as a function of finger gnosis. Therefore, it may be that IPL GMV, while a core component of finger gnosis processing, does not vary within this subject group and that there are other component processes that account for the individual differences in finger gnosis performance.

Sex differences

Even though the finger gnosis scores between females and males did not differ, we found considerable sexual dimorphisms in brain areas where GMV correlates with finger gnosis scores. While the females showed seven frontal and parietal clusters, males showed two clusters, one in the left putamen and the other in the right putamen, both of them overlapping with the clusters found in the whole-sample analysis (Fig. 3).

One explanation for the observed sex differences is based on differences in spatial abilities between males and females. Sex differences have been found in many spatial ability tasks, including a male advantage on mental rotation tasks (see Levine et al., 2016 for a review). However, given that finger gnosis scores did not differ between male and female participants and the strong influence of spatial processing on the finger gnosis task, the groups are unlikely to have large spatial ability differences. Therefore, spatial ability differences alone cannot explain the sex differences observed in the GMV correlations.

An alternative explanation is sex differences in strategy. Previous studies have suggested that males and females use different strategies to perform spatial tasks. For example, Heil and Jansen-Osmann (2008) showed that the mental rotation speed of males did not increase with the complexity of the shapes (measured as the number of the vertices on the shape), where the speed decreased with females. The authors argued that this difference is due to divergences in strategies used; while males use a holistic rotation strategy, females use a piecemeal, analytic one. The piecemeal strategy is more affected by the complexity of the shapes since it requires encoding, rotating, and comparing a higher number of features. Geiser et al. (2006) also showed strategy differences between males and females, and reported that females are more likely to use non-rotation based analytic strategies. In the current study males showed a correlation between finger gnosis and GMV in the bilateral putamen. The putamen has been implicated in motor imagery (Jeannerod, 2001; Higuchi et al., 2007). Motor imagery can be characterized as a dynamic state where an action is mentally simulated without any overt behavior (Decety and Jeannerod, 1995). Motor imagery uses most of the visual and motor systems that are involved in the execution of the action mentally simulated (Meister et al., 2004). Therefore, motor imagery involves both visuospatial and motor processing. In a recent fMRI study on mental rotation of hands Berneiser et al. (2018) found pre/post-modulation of activity in the putamen with training. They argued that the putamen might be a critical area for motor imagery and processing of egocentric spatial orientation during mental rotation of hands. They also reported an overall decrease in visual imagery in conjunction with increased involvement of motor-related areas before and after training, indicating a shift from visual to motor imagery with increasing skill. These studies suggest that the differences observed in our study might be due to males relying more heavily on motor imagery to perform the finger gnosis task than females. For female participants we see no correlation with finger gnosis and GMV in the putamen or the cerebellum. Instead, a relationship was found in regions more strongly tied to visuospatial processing,

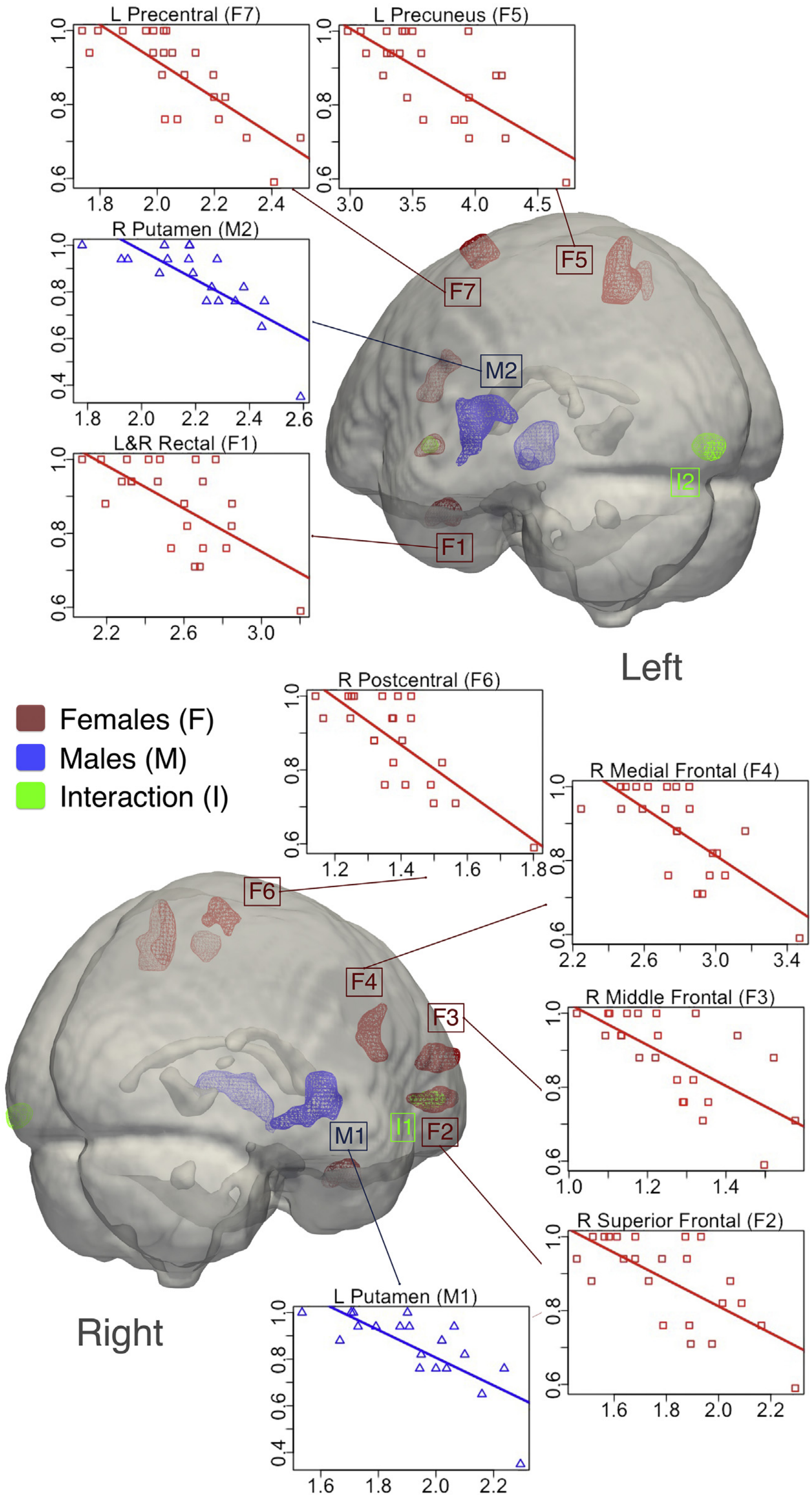

Fig. 2. Areas showing significant negative correlations between finger gnosis and GMV for females and males (left hemisphere at the top, right hemishpere at the bottom). The scatter plots show the correlations between regional GMV (x-axis) and finger gnosis scores (y-axis). See Table 2 for detailed information on the clusters.

suggesting greater variance in visuospatial processing skill in female participants than in male participants, and less reliance on motor imagery for females. To be clear, we do not argue here that visuospatial processing is also not used by male participants or that motor imagery is not used by female participants. That cannot be determined with a VBM study alone. The hypothesis proposed is preliminary and a VBM analysis along with an fMRI study that identifies the brain regions activated by the task is necessary to test the validity of this hypothesis.

If the sex differences observed are not simply due to differences in the variance of spatial ability within each group, and instead due to strategy differences between males and females, and differential recruitment of cortical and subcortical areas for finger gnosis, traces of these more fundamental differences, not confounded by uncontrolled factors like variance in spatial ability, should be found in other sensorimotor tasks related to finger gnosis. Such evidence comes from a study with adults where sex differences were found in the neural correlates of finger tapping (Lissek et al., 2007). While females showed larger activation in a set of frontal, parietal, and finger related pre & post-central areas than males, males showed larger activation in the basal ganglia, in particular the caudate nucleus and the putamen. The authors explained the higher activation of parietal areas in females based on higher reliance of females on motor imagery in learning and remembering the tapping sequences, and the higher activation in the caudate and putamen for males, based on males' higher reliance and ability to automatize motor sequences. The males in the study were found to have higher tapping rates, which the authors argued to be related to the males' ability to automatize the finger tapping sequences. In previous studies on finger tapping, activity in the striatum was found to increase with the frequency of the tapping and the complexity of the tapping sequences (Lehéricy et al., 2006). In the only neuroimaging study on finger gnosis to date, Rusconi et al. (2014) did not report on the sex differences. Even though finger tapping and finger gnosis tasks differ, the former having more emphasis on the motoric component and the latter sensory, both require mental representation of fingers and execution of a motor program to meet the task related goals. Differential activation during finger tapping has been tied to strategy and processing differences. Similar processing differences can explain the results reported here. If males and females rely on different systems during finger sensorimotor tasks then structural changes

Table 2. Clusters showing significant negative correlations between GMV and finger gnosis scores for females and males.

Region		Extent	t/F	MNI, x y z		
Females (F)						
F1	L&R Rectal Gyrus	276	4.634	−2	30	−29
F2	R Sup. Frontal Gyrus	357	5.359	24	62	5
F3	R Mid. Frontal Gyrus	321	7.073	38	41	17
F4	R Med. Frontal Gyrus	436	5.269	11	41	38
F5	L Precuneus	679	5.764	−3	−54	57
F6	R Postcentral Gyrus	204	5.546	24	−47	63
F7	L Precentral Gyrus	279	5.844	−35	−14	68
Males (M)						
M1	L Putamen	855	5.338	−20	−2	6
M2	R Putamen	885	5.252	14	2	−6
Interaction						
I1	R Sup. Frontal Gyrus	141	24.290	21	62	5
I2	L Lingual Gyrus	162	22.229	−23	−98	−11

during development will affect the performance across the two sexes differently.

Sexual dimorphisms in the development of striatal structures have also been previously reported. The putamen and globus pallidus were found to be larger for males than females in studies both with children (Giedd et al., 1997; Brain Development Cooperative Group, 2012) and adults (Rijpkema et al., 2012), when controlled for total brain volume. One large-scale study marked the sexual dimorphism in putamen volume, compared to other areas, as "especially striking, with the male volume larger by >5%" (Brain Development Cooperative Group, 2012, pg.8). The larger putamen in adult males was explained based on sex differences in the basal ganglia function, particularly the striatal dopamine system, females having greater dopamine release in the right globus pallidus, and males in the ventral striatum, putamen, and caudate nucleus, possibly due to differential effects of sex hormones on the dopaminergic system (Rijpkema et al., 2012). In a study comparing children (ages seven to 11) with adults, the caudate, putamen and amygdala in the male children, and the palladium in the female children were found to have greater volumes than the sex-matched adult groups. Also, while the overall volume of subcortical gray matter structures for female children were comparable to adult females, male children showed larger volumes compared to male adults.

Sexual dimorphisms were found in developmental changes in brain structure in the first two decades of life. In a longitudinal study involving 387 subjects, ages three to 27 years, widespread sex differences in developmental trajectories were found across the brain, with peak GMVs occurring earlier with females, and total cerebral volume peaking at 10.5 years in females and 14.5 years in males. A meta-analysis on sexual dimorphisms in brain structure and involving 126 studies with adults showed higher GMV for males, among other areas, in putamen and parts of the cerebellum. In the same study higher GMV was reported for females, again among other areas, in the inferior and middle frontal gyrus, and bilateral precuneus (Ruigrok et al., 2014). These findings show overlapping areas in terms of the sexual dimorphisms found in the current study. One interpretation is that some of the areas that show larger GMV in adulthood are more central for the finger gnosis task and in general for sensorimotor processing. This hypothesis appears to be in contrast with the findings in this study, where lower GMV in different regions was associated with higher finger gnosis. However, previous research has shown that the association of structural features, such as GMV and overall cortical thickness, with cognitive performance does not follow a linear pattern. For example Shaw et al. (2006) investigated the trajectory of change in cortical thickness from early childhood to adulthood and reported predominantly negative

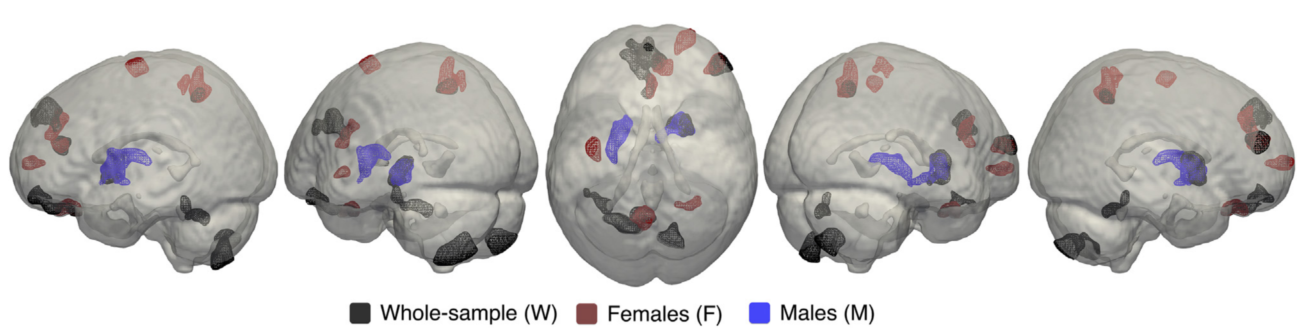

Fig. 3. Areas showing significant negative correlations between finger gnosis and GMV overlapped for the whole-sample, females, and males. The left & right putamen clusters for males and the middle and superior frontal clusters for females mostly overlapped with the clusters for the whole-sample.

correlations between intelligence and cortical thickness in early development and a positive correlation in later development and beyond. In parallel to this, Wilke et al. (2003) reported negative correlations between intelligence and GMV in posterior areas, in particular the parietal cortex, in addition to a positive correlation in the anterior cingulate area, with a group of five- to 18- year-old children. The correlations were stronger in older children. Studies exploring the relation between GMV and intelligence in adults have shown either no negative correlations (e.g., Haier et al., 2004) or negative correlations in a few of clusters (only with males; indicating sexual dimorphisms in this trend), while positive correlations in extensive, distributed frontal, temporal, and parietal clusters (Narr et al., 2007).

Maturational changes at the cellular level that take place between early childhood and adolescence, such as myelination and synaptic pruning, leads to overall cortical thinning (Sowell, 2004). This process follows different trajectories for systems supporting varying functions; earlier for sensory and motor functions, later for cognitive and executive functions. Given the sensorimotor nature of the finger gnosis task studied here and the age group studied, the negative correlations observed can be interpreted as earlier maturation of specific systems associated with performance in the task. Overall the results reported here show the significance of the maturation of a frontoparietal network for finger gnosis, and gender differences in the developmental trajectories followed for the finger sensorimotor network for females and males.

To conclude, evidence from both neuropsychological cases and studies with healthy adults and children point to a relation between finger gnosis and cognitive abilities. More recently the relation between finger gnosis and mathematical abilities of children has been under intense scrutiny, with some studies showing that finger gnosis abilities predict or correlate with numerical abilities. Nevertheless, the mechanisms with which finger gnosis relates to numerical abilities, and in general to cognition is not well understood. Part of the problem is the scarcity of findings on the neural correlates of and structural features related to the development of finger gnosis in children. In this study we present the first findings on the structural features, in particular GMV that correlates with finger gnosis in seven- to 10- year-old children. Overall, the results reported here show the significance of the GMV of a frontoparietal and cerebellar network for finger gnosis, and sex differences in regions where GMV correlates with finger gnosis. While finger gnosis scores correlated with a wider distribution of frontal and parietal regions in females, the correlations were limited to two striatal areas for males.

DECLARATION OF INTEREST

None.

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