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The Relationship between Neuropsychological Tests of Visuospatial Function and Lobar Cortical Thickness

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Abstract

Introduction: Tests of visuospatial function are often administered in comprehensive neuropsychological evaluations. These tests are generally considered assays of parietal lobe function; however, the neural correlates of these tests, using modern imaging techniques, are not well understood. In the current study we investigated the relationship between three commonly used tests of visuospatial function and lobar cortical thickness in each hemisphere.

Method: Data from 374 patients who underwent a neuropsychological evaluation and MRI scans in an outpatient dementia clinic, were included in the analysis. We examined the relationships between cortical thickness, as assessed with Freesurfer, and performance on three tests: Judgment of Line Orientation (JoLO), Block Design (BD) from the Fourth edition of the Wechsler Adult Intelligence Scale, and Brief Visuospatial Memory Test-Revised Copy Trial (BVM-T-R-C) in patients who showed overall average performance on these tasks. Using a series of multiple regression models, we assessed which lobe's overall cortical thickness best predicted test performance.

Results: Among the individual lobes, JoLO performance was best predicted by cortical thickness in the right temporal lobe. BD performance was best predicted by cortical thickness in the right parietal lobe and BVM-T-R-C performance was best predicted by cortical thickness in the left parietal lobe.

Conclusions: Performance on constructional tests of visuospatial function appears to correspond best with underlying cortical thickness of the parietal lobes, while performance on

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visuospatial judgment tests appears to correspond best to temporal lobe thickness. Future research using voxel-wise and connectivity techniques, and including more diverse samples, will help further understanding of the regions and networks involved in visuospatial tests.

Keywords

visual spatial processing; parietal lobule; cortical thickness; neuropsychological tests; assessment

Visuospatial abilities are assessed as part of a comprehensive neuropsychological evaluation. There are many tasks developed to assess visuospatial functioning, including tests of visuospatial judgment and constructional tests, such as figure copy and reproduction of geometric designs (see Lezak, Howieson, & Loring, 2012; Strauss, Sherman, & Spreen, 2006). Some of the more commonly used visuospatial tests in clinical neuropsychology include Judgment of Line Orientation (JoLO; Benton, Sivan, Hamsher, Varney, & Spreen, 1994), Block Design (BD; Wechsler, 1955; PsychCorp, 2008), and different types of figure copy tasks (e.g. Rey Osterrieth Complex Figure Test: Copy Trial; Osterrieth, 1944, Bender-Gestalt II; Brannigan & Decker, 2003, Brief Visuospatial Memory Test-Revised: Copy Trial; Benedict, 1997). While many of these tests are administered in clinics routinely, their neural correlates are not yet clearly delineated.

Traditionally, visuospatial skills assessed by these tasks have been primarily attributed to the right hemisphere, which is more specialized to process nonverbal information, such as complex visual patterns, visuospatial transformations, spatial orientation, and nonverbal auditory signals (Lezak et al., 2012; Zillmer, Spiers, & Culbertson, 2008). Specifically, many lesion studies support the right parietal lobe, and particularly the angular gyrus and supramarginal gyrus, as playing a fundamental role in spatial cognition (Benton & Tranel, 1993; Berryhilla & Olson, 2008; Shinoura et al., 2009; Scott & Shoenberg, 2011).

Lesion studies, and more recently structural and functional imaging in those without lesions, have examined selective visuospatial task performance, with most research focusing on JoLO. Benton and colleagues' early work with JoLO indicated that patients with left hemisphere lesions performed better than those with right hemisphere damage (Benton, Varney, & Hamsher, 1978; Masure & Benton, 1983; Hamsher, Capruso, & Benton, 1992). A more recent study, using a lesion mapping technique, corroborated these results by showing that failure on JoLO was more strongly related to lesions in the right posterior parietal region (Tranel, Vianna, Manzel, Damasio, & Grabowski, 2009). In support, Biesbroek et al. (2014), who examined the anatomical correlates of the JoLO using assumption-free voxel-based lesion-symptom mapping in a sample of 111 patients with first time ischemic stroke, showed performance related to the supramarginal gyrus—as well as the right frontal lobe and superior temporal lobe. In terms of neural function, Deutsch, Bourbon, Papanicolaou, and Eisenberg (1988) found that increased activation of regional cerebral blood flow in the right hemisphere was associated with JoLO performance. Ng et al. (2000), using functional magnetic resonance imaging (fMRI) and a modified version of JoLO in 10 right handed male adults, found increased bilateral superior parietal task-related activation and a more prominent role of the right parietal lobe in starting the task. They corroborated these results with data from 17 patients with either right or left parietal lobe damage that also showed

significant impairments in JoLO performance, with right sided lesions showing relatively more impairment. Despite much support for parietal lobe involvement in JoLO performance, other authors have reported that the left hemisphere also plays an important role in visuospatial task performance (Martinez et al., 1997; Brown & Kosslyn 1993). Nevertheless, as reviewed by Tranel et al. (2009), most of the scientific literature related to the neuroanatomical correlates of JoLO performance suggests significant right hemisphere involvement, including parietal and parietal-occipital or parietal-temporal regions.

Patients with right hemisphere injuries also tend to have difficulties with the BD task (Lezak et al., 2012). Wilde, Boake, & Sherer (2000) showed that patients with moderate and severe traumatic brain injuries (TBI) who had right hemisphere craniotomies made a greater percentage of BD broken configuration errors compared to patients with diffuse injuries and left hemisphere craniotomies. Large sample historical lesion studies have also shown that patients with right parietal lesions show selective impairments on BD (Warrington, James, & Maciejewski, 1986). Separate studies have shown that left hemisphere lesions are less associated with significantly lowered BD scores, unless the left parietal region is involved (Benton, 1967; Kertesz & Drobrowski, 1981). In terms of parietal lobe function, WAIS performance IQ (including BD scores), has been associated with increased glucose metabolism in the right posterior parietal region (Chase et al., 1984).

Right hemisphere lesions have also been associated with increased difficulties in figure copy tasks, although these studies have not focused on the Brief Visuospatial Memory Test–Revised Copy Trial (BVM-T-R-C). Initial lesion investigations have shown less accurate performance on the Rey Osterrieth Complex Figure (ROCF) copy trial in patients with right sided versus left sided damage (Binder, 1982) and increased difficulties with spatial organization of the figure in patients with parietal-occipital damage (Pillon, 1981). Similarly, right-sided frontal lobe damage has been associated with significantly more difficulties copying the designs of the Benton Visual Retention Test Copy Administration, when compared to left-sided frontal damage (Benton, 1968, 1969). In the Biesbroek et al. (2014) study previously mentioned, examiners found shared anatomical correlates of the ROCF copy trial and JoLO in the right frontal lobe, superior temporal lobe, and supramarginal gyrus; poor performance on the ROCF was also uniquely related to lesions in the right superior parietal lobe, angular gyrus, and middle occipital gyrus. Functional imaging has also been supportive of a role for the parietal lobes in drawing tasks. Makuuchi, Kaminaga, & Sugishita (2003) used fMRI with 17 right handed healthy participants while they performed a drawing task and found bilateral parietal activation in all of them. Notably, they also found activation in the ventral premotor area and posterior part of the inferior temporal sulcus.

To our knowledge, the reports of lobar cortical thickness measurements and their relationship with visuospatial tasks currently in the literature are scarce. Sowell et al. (2008) explored the relationship between ROCF copy performance and cortical thickness in participants (ages 8 to 25) with fetal alcohol spectrum disorders (FASD) and controls. Results indicated that in the controls thinner cortex in large areas of the parietal, temporal, and frontal lobes was related to better performance in ROCF. The counterintuitive association between thinner cortex and better performance was explained as a likely result of

neural pruning and increase myelination in this age group. In contrast, in the FASD group, thinner cortex in small regions confined to the left frontal lobe were related to worse ROCF copy performance (Sowell et al. 2008). Cortical thickness measurements have shown fruitful results in other neurocognitive domains, including executive control (Schmidt, Burge, Visscher, & Ross, 2016) and complex nonverbal problem solving (Burzynska et al., 2012), and have also been used to study clinical samples, including patients with MS (Pellicano et al., 2010), and different types of dementia (AD, frontotemporal dementia, Huntington's disease) or cognitive decline (e.g. Lehman et al., 2010; Hartikainen et al., 2012; Noh et al., 2014; Labuschagne et al., 2016).

In the current study, we take three standard tests of visuospatial function (JoLO, BD, and BVM-T-R-C) and assess their relationship with lobar cortical thickness in each hemisphere. Participants in the study were older adult patients in an outpatient dementia and movement disorders clinic. It was hypothesized that greater cortical thickness in the parietal lobes will significantly predict better scores on the visuospatial tasks.

Methods

Procedure

This study was reviewed and approved by the Cleveland Clinic Institutional Review Board. Data for the current study were retrieved from archival medical records in an outpatient neurology center specializing in dementia and movement disorders of individuals seen for a neuropsychological evaluation as part of routine diagnostic work up between 2012 and 2016. After initial evaluation by neurology, patients were referred for further evaluation by neuropsychology, as well as, structural brain MRI for differential diagnosis and treatment planning purposes. As these data are the focus of the present study, specific diagnostic information for the analyzed sample were not available; however, typical diagnostic considerations include: mild cognitive impairment, Alzheimer's disease, dementia with Lewy-bodies, Parkinson's disease and Parkinson's plus syndromes (e.g., progressive supranuclear palsy), vascular dementia, frontotemporal dementias, and subjective memory complaints. Neuropsychological assessments were completed in a single three-hour visit consisting of a clinical interview and comprehensive neuropsychological testing. Cases were selected for inclusion only from participants with MRI and who had successfully completed all five trials of the BVM-T-R, the JoLO, and BD.

MRI Acquisition

MRI scans were obtained on a 3T Verio scanner, with a 32-channel head coil. Acquisition parameters were a TR/TE/TI of 1900/2.32/900, 1mm axial slice, and 9 degree flip angle. Images were visually inspected and discarded due to incomplete brain coverage, as well as motion and acquisition artifacts. The remaining images were processed entirely in Freesurfer version 6.0 (Dale Fischl, & Sereno, 1999), using all steps of the cortical reconstruction process.

Quality assurance of the freesurfer data followed a multistep process. Scans were inspected for accurate identification of the pial surface and grey-white boundary for each hemisphere

via visual inspection of snapshots from the inferior, superior, lateral, and medial perspectives. A total of 16 snapshots were visually inspected for each of the scans. Only those scans that passed inspection were included.

Cortical thickness measurements were extracted from the Freesurfer automatic cortical parcellation output and merged into an SPSS database with demographic and neuropsychological test scores. We then further calculated total cortical thickness values for each lobe and hemisphere. The regions included in each lobe were as follows: Frontal: superior frontal, rostral and caudal middle frontal, pars opercularis, pars triangularis, pars orbitalis, lateral and medial orbitofrontal, precentral, paracentral, frontal pole, rostral and caudal anterior cingulate; parietal: superior parietal, inferior parietal, supramarginal, postcentral, precuneus, posterior cingulate, isthmus; temporal: superior, middle and inferior temporal, banks of the superior temporal sulcus, fusiform, transverse temporal, entorhinal, temporal pole, parahippocampal; occipital: lateral occipital, lingual, cuneus, pericalcarine.

Neuropsychological Measures

Block Design—BD is a subtest of the Wechsler Adult Intelligence Scale, 4th Edition (WAIS-IV; Wechsler, 2008). It consists of the physical reproduction of 2-dimensional model designs of increasing difficulty, using a set of bicolored blocks arranged in a 2×2 or 3×3 array. Each trial is timed, and bonus points are awarded for fast completion times. Scores on this measure range from 0 – 66, with higher scores reflecting better task performance. For a 70 year old, a score of 13 or lower would be in the mildly impaired range.

Judgment of Line Orientation—The JoLO (Benton et al., 1994) is a test of visuospatial judgment that consists of matching two lines, angled in different orientations, to eleven numbered target lines presented in an equally spaced spatial array spanning 180 degrees. The patient chooses the numbers of the two target lines that correspond to the angles of the two stimulus lines. Two points are possible per trial, with a maximum of up to 30 points; higher scores reflect better performance. For a 70 year old, a score of 11 or lower would be in the mildly impaired range.

Brief Visuospatial Memory Test, Revised—The BVMT-R (Benedict, 1997) is a test of visuospatial memory that consists of three separate learning trials, during which patients are asked to draw from memory a set of 6 geometrical figures that are presented in a grid for 10 seconds. After 25 minutes patients are asked to draw the figures again from memory (delayed recall), followed by a forced-choice recognition trial, during which they have to identify the original figures among a set of distractors. The Copy trial (BVMT-R-C) is an optional condition and consists of copying the original six figures as accurately as possible and in their correct location on a sheet of paper while the stimuli remains in view. Points are awarded for both accuracy and placement, with a maximum score of 12 points. In the current study the BVMT-R-C was administered immediately after the recognition trial. For a 70 year old, a score of 10 or less would be considered below normal limits.

Additional Measures—In order to better characterize our sample, we also included available scores from the Wide Range Achievement Test, 4th Edition Reading Subtest

(WRAT-4) and Activities of Daily Living Questionnaire (ADLQ). The WRAT-4 (Wilkinson & Robertson, 2006) reading subtest has been validated for use as a measure of overall premorbid intelligence in this population (see Lezak et al., 2012; Berg Swan, Banks, & Miller, 2016). It consists of reading a list of 55 increasingly difficult, phonetically irregular words. The total number of correctly read words is then converted to an age-adjusted scaled score, which serves as the proxy for overall premorbid intelligence.

The ADLQ (Johnson, Barion, Rademaker, Rehkemper, & Weintraub, 2004) is a self-report measure completed by relatives or significant others of the patient. It assesses everyday functioning in the following areas: communication, self-care, household care, employment and recreation, shopping and money, and travel. In our sample, 110 of the patients presented to the interview and evaluation alone, therefore this measure was not administered. Scores of the visuospatial tests and additional measures are presented in table 1.

Data Analysis

The cognitive test scores were not normally distributed; therefore, they were converted to z-scores using the dataset's mean and standard deviation. Several multiple regression models were then fitted to evaluate the relationship between cortical thickness and cognitive test performance. For each cognitive task, the total raw score was used as the primary outcome in order to maximize available variance and to avoid potential confounds associated with comparisons of different normative data among various age groups and between tests. Initial models were first fitted using the average thickness of the right and left hemisphere individually to assess the overall relationship between functioning and general hemispheric cortical thickness. To evaluate the lobar specificity of task performance, separate models were then fitted using the left or right cortical thickness for each primary lobe as a predictor, again using cognitive test performance as the outcome. A total of 30 models were produced. Demographic variables including age, years of education, and sex were also entered as predictors in each model to account for these influences on test performance. Overall model fit was evaluated via change in R-squared values. Bayesian information criteria (BIC) values were also calculated for each model based on the resulting likelihood ratio to assist in identifying the best fitting model within each lobe for each cognitive test. Standardized regression coefficients and the associated 95% confidence intervals were also evaluated to determine the influence of cortical thickness on cognitive test performance relative to the entered demographic variables.

Results

After processing 434 scans in Freesurfer, 20 scans failed the visual inspection, and were subsequently inspected slice-by-slice to determine the cause of the poor Freesurfer segmentation. The failed segmentations were due to motion (n=14), missing or corrupted slices (n=7), low contrast (n=3), and a lesion. A further 40 left handed patients were removed. All subsequent analysis was performed on the remaining 374 patients.

Data from 374 patients were included in the analysis, a summary of their demographics is included in Table 1. Mean thicknesses of each lobe and hemisphere is presented in Table 2.

Results of the regression models are presented in Tables 3 and 4. Greater cortical thickness was associated with better task performance in the included tests.

Average left hemisphere thickness was significantly positively associated with BD performance and the overall model including demographic variables accounted for 44% of the variance in task performance ($F(4, 369) = 21.48; p < .001$). Mean right hemisphere thickness was also significantly positively associated with BD performance, which in addition to demographic variables, also accounted for 44% of the total variance ($F(4, 369) = 21.19; p < .001$) and was the best fitting model with a *BIC* value of -47.61 . Among the individual lobes, the right parietal lobe accounted for the largest proportion of variance (43%) in BD score ($F(4, 369) = 20.86, p < 0.001$) and was positively associated with performance.

For JoLO, average left hemisphere thickness was significantly positively associated with test performance and the overall model accounted for the 20.1% of the variance in test performance ($F(4, 369) = 23.28, p < 0.001$). Average right hemisphere thickness was also significantly positively associated with JoLO performance and in addition to demographic variables, accounted for 20.1% of the variance in performance ($F(4, 369) = 23.15, p < .001$). Among the individual lobes, the right temporal lobe ($F(4, 369) = 22.16, p < 0.001$) accounted for the largest proportion of variance in JoLO score (19%) and was positively associated with performance; it was also the best fitting model, with a *BIC* value of -56.18 .

For BVMT-R-C, average left hemispheric thickness was significantly positively associated with test performance, though the overall model accounted for only 8% of the total variance ($F(4, 369) = 9.26, p < 0.001$). Right hemisphere thickness was also significantly positively associated with BVMT-R-C scores and accounted for a similar proportion (7%) of test performance as the left hemisphere ($F(4, 369) = 7.94, p < 0.001$). Among the individual lobes, the left parietal lobe accounted for the greatest proportion of variance in test performance (9%; $F(4, 369) = 10.47, p < 0.001$), and was positively associated with performance; this was also the best fitting model with a *BIC* value of -10.62 .

Discussion

In the present study we examined the relationship between three commonly used tests of visuospatial function and lobar cortical thickness in each hemisphere. Consistent with our hypotheses, results indicated that among the individual lobes BD performance was best predicted by cortical thickness in the right parietal lobe and BVMT-R-C performance was best predicted by cortical thickness in the left parietal lobe. However, JoLO performance was best predicted by cortical thickness in the right temporal lobe. In each case, thicker cortex was related to better scores. Our results suggest that constructional tests of visuospatial function are more strongly associated with underlying cortical thickness of the parietal lobes, while visuospatial judgment tests are more strongly associated to temporal lobe thickness.

The current findings were partially consistent with previous research. In contrast with our hypothesis, JoLO scores were mainly associated with cortical thickness in the right temporal

lobe. This is consistent with previous findings based on lesion studies that suggested a primary involvement of the right hemisphere (Hamsher et al., 1992), although less consistent with other findings reflecting mostly parietal lobe involvement (e.g. Tranel et al., 2009). Activation studies show more variation in terms of the brain regions involved. For example, using fMRI and a modified version of JoLO, Ng. et al. (2000) reported increased bilateral superior parietal lobe activation during this task. There are also reports of left hemisphere involvement in this task (e.g. Martinez et al., 1997). Similarly, Hannay et al. (1987) found increased bilateral cerebral blood flow in temporo-occipital areas utilizing a short version of JoLO. Biesbroek et al. (2014) reported that right superior parietal lobule and angular and middle occipital gyri lesions were associated with poor ROCF performance, but not with JoLO performance. Both ROCF and JoLO shared right hemispheric correlates including, the superior temporal lobe. The authors suggested that the shared regions underlie the visuo-perceptive component included in both tasks, whereas the parietal-occipital regions associated with ROCF underlie the visuo-constructive component particular to this test (Biesbroek et al., 2014). Our results could be explained by a similar dichotomy considering that both BD and BVMT-R-C involve a visuo-constructive component, while JoLO does not.

As hypothesized, our finding that among the individual lobes BD is mainly associated with cortical thickness in the parietal lobe in the right hemisphere was consistent with previous reports based on patients with right parietal lesions (e.g. Benton, 1967; Warrington et al., 1986) and increased glucose metabolism in the right parietal region determined by positron emission tomography (Chase et al., 1984). Our finding that overall right hemisphere thickness was the most predictive of BD performance suggests that this is a complicated task that involves a complex network of regions. Specifically, any type of brain impairment tends to negatively affect BD scores (Lezak et al., 2012), and patients with left hemisphere lesions (Akshoomoff, Delis, & Kiefner, 1989) or frontal lobe damage (Johanson, Gustafson, & Risberg, 1986) show different types of deficits on this task. This is likely related to BD requiring complex planning and organization on top of basic visuospatial skills.

Also, as hypothesized, BVMT-R-C scores were mainly associated with parietal lobe cortical thickness in the left hemisphere. This was somewhat consistent with previous studies (e.g. Makuuchi et al., 2003). Similarly, Tranel, Rudrauf, Vianna and Damasio (2008) reported that damage to the left inferior frontal-parietal opercular cortices in addition to right parietal cortices, specifically the supramarginal gyrus, were associated with impairments in the clock drawing task. Moreover, studies with left hemisphere damaged patients have shown that they tend to divide the design into small units and distort or miss details, while right hemisphere damaged patients tend to completely miss elements or distort the gestalt of the design (Binder, 1982; Scott & Shoenberg, 2011), suggesting bilateral cortical involvement in drawing. Other reports have also suggested left and right hemispheric involvement in figure copy tasks (Chechlac, Mantini, Gillebert, & Humphreys, 2015), while earlier studies suggested the right hemisphere played a more important role in design copy (Benton, 1969). Nevertheless, it is important to note that these studies used different types of copy tasks (other than BVMT-R-C) and there were remarkable methodological differences among them. For example, Makuuchi et al. (2003) used a combination of finger drawing and naming in their study, while Chechlac et al. (2015) used the Complex Figure Copy task from the Birmingham Cognitive Screen (BCoS) battery. Consistent with Makuuchi et al.

(2003), our results support the prediction that drawing requires both parietal lobes and that damage to any side may cause impairments in performance.

Several limitations of the current study need to be acknowledged. The sample consisted mostly of older adult outpatients in a dementia and movement disorders clinic, which limits the generalizability of our findings. Moreover, we were not able to include a healthy control group that underwent the same battery of tests and imaging. Further, this was a true clinical sample rather than a well-defined and cleanly diagnosed research cohort. Neuropsychology is part of the diagnostic work up in the clinic and there are no definitive diagnostic data. While this could be seen as a weakness, it might also be a strength in that our cohort was likely diagnostically diverse, and had a range of atrophy to different lobes, whereas a clean Alzheimer's sample, for example, would show less differentiation between lobes. Similarly, our results likely reflect those of clinics offering geriatric neuropsychology, and hence have translational value. Additionally, the current results are limited by the lobar perspective of the analyses that precludes potentially important findings related to cortical thickness of lobar subregions. However, we thought this was an important first step considering that the results can be compared with most of the literature that has focused on hemispheric or lobar lesion studies. Further, it opens the door for further analysis of performance in these tests and cortical thickness in parietal and temporal sub regions.

The present study suggests interesting differences in the neural underpinnings of constructional and judgment-based visuospatial neuropsychological tasks, in patients without lesions. Greater regional cortical thickness in a dementia clinic population likely reflects the importance of neural integrity and its association with better outcomes in the context of risk for onset of neural loss or cognitive impairment. Functional measures, such as FDG pet or fMRI may be more sensitive to revealing networks important for task performance, and may help to identify patterns related to compensation. Additional studies combining lesion detection and functional imaging are needed to further specify the neural networks involved in visuospatial tests. For example, Chechlacz et al. (2015) used combined methods (automated delineation of stroke lesions in conjunction with tract-wise lesion deficit analysis based on diffusion tensor imaging) to investigate the neural correlates of a complex figure task in a large sample of sub-acute stroke patients. Findings indicated that global feature processing in figure copy was related to a right hemisphere network, while processing of local features was associated with a neural network confined to the left hemisphere. Any of these studies might target more specific regions as the most important neuroanatomical correlates of these tests, whereas in the current study we took a lobar approach. This is consistent with the way we, as neuropsychologists, are taught about measures. We of course also underscore the importance of finding cortical correlates of test performance for more specific lobar regions and the clinical implications of such findings. Subsequent studies should address this question.

Future research using functional imaging, voxel-wise techniques, as well as connectivity techniques, including more diverse samples, and including a well-characterized control group may help clarify the regions and networks involved in visuospatial tests. Further understanding of the relationships between clinical tests and the underlying neuroanatomy is warranted.

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Table 1

Description of sample in terms of demographic characteristics, visuospatial tests, predicted overall IQ, and level of functional impairment

Characteristic/Test	Frequency				
Sex	48.1% Women				
Handedness	100% Right				
Race	82.1% Caucasian	5.4% African American	1.6% Hispanic	2.4% Asian	8.5% Unspecified/Other
	<i>N</i>	<i>M</i>	<i>SD</i>		
Age (Years)	374	69.65	10.56		
Education (Years)	374	15.15	2.75		
JoLO (Raw)	374	22.48	4.84		
BVMT-R-C (Raw)	374	10.95	1.14		
BD (Raw)	374	29.76	9.63		
WRAT (ss)	374	101.43	12.63		
ADLQ (%)	264	22.65	16.69		

Note. JoLO = Judgment of line Orientation; BVMT-R-C = Brief Visuospatial Memory Test copy; BD = Block Design; WRAT = Wide Range Achievement Test Reading (IQ estimate); ADLQ = Activities of Daily Living Questionnaire (<33% is considered minimal impairment). Raw = raw score; ss = standard score, % = percentage.

Table 2

Mean cortical thickness of the left and right hemispheres and lobes

Lobe	Hemisphere	
	<u>Left</u>	<u>Right</u>
Parietal	2.27 (0.11)	2.26 (0.11)
Frontal	2.46 (0.11)	2.47 (0.12)
Temporal	2.70 (0.18)	2.73 (0.19)
Occipital	1.93 (0.09)	1.97 (0.10)
Overall	2.38 (1.02)	2.39 (1.07)

Table 3

Multiple Linear Regression Models, Left Hemisphere

Test	Predictor	R^2	B	$Beta$	Confidence Interval	BIC
BD	LH mean thickness *	0.18	2.20	0.23	1.24 to 3.17	-44.41
	Age *		-0.03	-0.25	-0.04 to -0.02	
	Education *		0.07	0.18	0.03 to 0.10	
	Gender *		0.21	0.11	0.02 to 0.40	
	Occipital *	0.16	1.46	0.13	0.42 to 2.50	-36.48
	Age *		-0.03	0.30	-0.04 to -0.02	
	Education *		0.06	0.10	0.03 to 0.10	
	Gender *		0.20	0.95	0.00 to 0.39	
	Parietal *	0.18	1.88	0.20	0.94 to 2.81	-44.14
	Age *		-0.03	-0.25	-0.04 to -0.02	
	Education *		0.07	0.18	0.03 to 0.10	
	Gender *		0.21	0.11	0.02 to 0.40	
	Frontal *	0.18	1.76	0.20	0.90 to 2.62	-45.06
	Age *		-0.03	-0.27	-0.04 to -0.02	
	Education *		0.07	0.18	0.03 to 0.10	
	Gender *		0.23	0.11	0.03 to 0.42	
	Temporal *	0.17	1.04	0.19	0.481 to 1.60	-41.87
	Age *		-0.03	-0.25	-0.04 to -0.02	
	Education *		0.06	0.18	0.03 to 0.10	
	Gender *		0.23	0.11	0.02 to 0.41	
JoLO	LH mean thickness *	0.20	1.85	0.19	0.90 to 2.81	-54.09
	Age *		-0.01	-0.10	-0.02 to 0.00	
	Education *		0.02	0.21	0.04 to 0.11	
	Gender *		0.59	0.30	0.40 to 0.78	
	Occipital	0.18	1.14	0.11	0.11 to 2.17	-45.06
	Age *		-0.01	-0.15	-0.02 to -0.01	
	Education *		0.08	0.21	0.04 to 0.11	
	Gender *		0.58	0.29	0.39 to 0.77	
	Parietal *	0.20	1.71	0.18	0.78 to 2.63	-53.37
	Age		-0.01	-0.10	-0.02 to 0.00	
	Education *		0.08	0.22	0.04 to 0.11	
	Gender *		0.59	0.30	0.40 to 0.78	
	Frontal *	0.20	1.69	0.19	0.85 to 2.54	-55.71

Test	Predictor	R^2	B	$Beta$	Confidence Interval	BIC
	Age *		-0.01	-0.11	-0.02 to -0.00	
	Education *		0.08	0.21	0.04 to 0.11	
	Gender *		0.61	0.31	0.42 to 0.80	
	Temporal *	0.20	0.97	0.18	0.42 to 1.53	-51.97
	Age		-0.01	-0.10	-0.02 to 0.00	
	Education *		0.08	0.21	0.04 to 0.11	
	Gender *		0.60	0.30	0.41 to 0.79	
	BVMT-R-C LH mean thickness *	0.08	1.85	0.19	0.83 to 2.88	-5.57
	Age		-0.01	-0.09	-0.02 to 0.01	
	Education *		0.06	0.16	0.02 to 0.10	
	Gender *		-0.25	-0.12	-0.45 to -0.05	
	Occipital *	0.09	1.81	0.17	0.72 to 2.89	-4.01
	Age *		-0.01	-0.13	-0.02 to -0.00	
	Education *		0.06	0.16	0.02 to 0.09	
	Gender *		-0.26	-0.13	-0.46 to -0.06	
	Parietal *	0.10	2.07	0.22	1.09 to 3.04	-10.62
	Age		-0.01	-0.08	-0.02 to 0.00	
	Education *		0.06	0.17	0.03 to 0.10	
	Gender *		-0.24	-0.12	-0.44 to -0.04	
	Frontal	0.07	0.98	0.11	0.07 to 1.89	2.08
	Age *		-0.01	-0.13	-0.02 to -0.00	
	Education *		0.06	0.16	0.02 to 0.10	
	Gender *		-0.25	-0.12	-0.45 to -0.04	
	Temporal *	0.07	0.69	0.12	0.09 to 1.28	1.27
	Age		-0.01	-0.11	-0.02 to 0.00	
	Education *		0.06	0.16	0.02 to 0.10	
	Gender *		-0.25	-0.12	-0.45 to -0.05	

Note.

* = $p < .05$;

JoLO = Judgment of line Orientation; BVMT-R-C = Brief Visuospatial Memory Test Revised Copy Trial; BD = Block Design; LH mean thickness = left hemisphere average cortical thickness.

Table 4

Multiple Linear Regression Models, Right Hemisphere

Test	Predictors	R^2	B	$Beta$	Confidence Interval	BIC
BD	RH mean thickness *	0.19	2.06	0.22	1.10 to 3.00	-47.61
	Age *		-0.03	-0.25	-0.04 to -0.02	
	Education *		0.07	0.19	0.03 to 0.10	
	Gender *		0.20	0.10	0.01 to 0.39	
	Occipital *	0.17	1.51	0.15	0.52 to 2.51	-37.82
	Age *		-0.03	-0.30	-0.04 to -0.02	
	Education *		0.07	0.18	0.03 to 0.10	
	Gender		0.19	0.09	-0.00 to 0.38	
	Parietal *	0.18	1.92	0.22	1.03 to 2.80	-46.43
	Age *		-0.03	-0.25	-0.04 to -0.02	
	Education *		0.07	0.19	0.04 to 0.10	
	Gender *		0.20	0.10	0.01 to 0.39	
	Frontal	0.16	1.17	0.14	0.38 to 1.96	-37.37
	Age *		-0.03	-0.29	-0.04 to -0.02	
	Education *		0.06	0.18	0.03 to 0.10	
	Gender *		0.22	0.11	0.03 to 0.42	
	Temporal *	0.18	1.06	0.20	0.51 to 1.60	-43.23
	Age *		-0.02	-0.24	-0.04 to -0.01	
	Education *		0.06	0.17	0.03 to 0.10	
	Gender *		0.22	0.11	0.03 to 0.41	
JoLO	RH mean thickness *	0.20	1.74	0.19	0.83 to 2.66	-54.09
	Age *		-0.01	-0.10	-0.02 to 0.00	
	Education *		0.08	0.22	0.04 to 0.11	
	Gender *		0.59	0.29	0.40 to 0.77	
	Occipital *	0.19	1.34	0.13	0.36 to 2.33	-47.35
	Age *		-0.01	-0.14	-0.02 to -0.01	
	Education *		0.08	0.21	0.04 to 0.11	
	Gender *		0.58	0.29	0.38 to 0.77	
	Parietal *	0.20	1.70	0.19	0.83 to 2.58	-54.77
	Age		-0.01	-0.10	-0.02 to 0.00	
	Education *		0.08	0.22	0.05 to 0.12	
	Gender *		0.58	0.29	0.40 to 0.77	
	Frontal *	0.19	1.29	0.16	0.52 to 2.07	-51.04
	Age *		-0.01	-0.13	-0.02 to -0.00	

Test	Predictors	R^2	B	$Beta$	Confidence Interval	BIC
BVMC-R-C	Education *		0.08	0.21	0.04 to 0.11	
	Gender *		0.61	0.31	0.42 to 0.80	
	Temporal *	0.21	1.10	0.21	0.57 to 1.64	-56.18
	Age		-0.01	-0.08	-0.02 to 0.00	
	Education *		0.07	0.20	0.04 to 0.11	
	Gender *		0.61	0.30	0.42 to 0.80	
	RH mean thickness *	.069	1.39	.148	.41 to 2.374	-1.09
	Age		-0.01	-0.11	-0.02 to 0.00	
	Education *		0.06	0.17	0.02 to 0.10	
	Gender *		-0.26	-0.13	-0.46 to -0.05	
BVMC-R-C	Occipital *	0.08	1.32	0.13	0.27 to 2.37	0.46
	Age *		-0.01	-0.14	-0.02 to -0.00	
	Education *		0.06	0.17	0.02 to 0.10	
	Gender *		-0.27	-0.13	-0.47 to -0.06	
	Parietal *	0.08	1.32	0.15	0.37 to 2.26	-1.16
	Age		-0.01	-0.11	-0.02 to 0.00	
	Education *		0.06	0.17	0.03 to 0.10	
	Gender *		-0.26	-0.13	-0.46 to -0.06	
	Frontal	0.06	0.54	0.07	-0.30 to 1.38	4.88
	Age *		-0.01	-0.14	-0.03 to -0.00	
BVMC-R-C	Education *		0.06	0.16	0.02 to 0.10	
	Gender *		-0.25	-0.13	-0.46 to -0.04	
	Temporal *	0.07	0.65	0.12	0.07 to 1.24	1.67
	Age		-0.01	-0.11	-0.02 to 0.00	
	Education *		0.06	0.16	0.02 to 0.09	
	Gender *		-0.25	-0.12	-0.45 to -0.04	

Note.

* = $p < .05$;

JoLO = Judgment of line Orientation; BVMC-R-C = Brief Visuospatial Memory Test Revised Copy Trial; BD = Block Design; RH mean thickness = right hemisphere average cortical thickness.