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The relationship between brain structure and proficiency in reading and mathematics in children, adolescents, and emerging adults

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A R T I C L E I N F O

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A B S T R A C T

Behavioral and brain imaging studies speak to commonalities between reading and math. Here, we investigated relationships between individual differences in reading and math ability (single word reading and calculation) with brain anatomy (cortical thickness and surface area) in 342 participants between 6–22 years of age from the NIH Pediatric MRI Database. We found no brain-behavioral correlations in the full sample. When dividing the dataset into three age-specific subgroups, cortical thickness of the left supramarginal gyrus (SMG) and fusiform gyrus (FG) correlated with reading ability in the oldest subgroup (15–22 years) only. Next, we tested unique contributions of these educational measures to neuroanatomy. Single word reading ability, age, and their interaction all contributed unique variance to cortical thickness in the left SMG and intraparietal sulcus (IPS). Age, and the interaction between age and reading, predicted cortical thickness in the left FG. However, regression analyses for math ability showed no relationships with cortical thickness; nor for math or reading ability with surface area. Overall, our results demonstrate relationships between cortical thickness and reading ability in emerging adults, but not in younger age groups. Surprisingly, there were no such relationships with math, and hence no convergence between the reading and math results.

1. Introduction

Reading and math are culturally acquired skills that are critical for children in school, are used in daily life, and strongly predict later economic success and vocational outcomes (Ritchie and Bates, 2013; Lubinski et al., 2014). The acquisition of reading requires explicit training and builds on existing oral language and object recognition skills (Dehaene et al., 2010). Similarly, mathematical skills are learned by building upon basic numerical competencies such as numerical magnitude processing (Lyons et al., 2014; Schneider et al., 2017; Matejko & Ansari, 2018). Thus, the learning of reading and math occurs with explicit, education-based training over a protracted period of time. Even though reading and math are thought to be distinct academic skills, they are highly correlated with one another (Korhonen, Linnanmäki, & Aunio, 2012; Singer & Strasser, 2017), share some cognitive underpinnings (Alloway & Alloway, 2010; Child et al., 2018), and learning disabilities in reading and math frequently co-occur (Lewis, Hitch, & Walker, 1994; Moll et al., 2018; Wilcutt et al; 2013).

There are large individual differences for reading (Farley and Truog, 1970) and math skills (Dowker, 2005; Vanbinst and De Smedt, 2016), and brain imaging offers a window into how these are related to brain anatomy at different ages (Dehaene and Cohen, 2007). Numerous studies have investigated the association between brain structure and individual differences in reading or math separately, but studying reading and math simultaneously allows one to ask important questions about their overlapping neuroanatomical foundations. Specifically, the similar nature of their acquisition (through formal education) as well as evidence for shared cognitive constructs, suggests that reading and math may have mutual relationships with brain anatomy. Importantly, examining whether reading and math have a shared neuroanatomical basis may help explain the existence of relationships between these two skills. This will establish a foundation and also be important for future studies on reading and math disabilities, given that they co-occur at a higher rate than would be predicted by chance.

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Behavioral literature has shown that reading and math skills are moderately to strongly correlated (Hecht et al., 2001; Durand et al., 2005; Hart et al., 2009). Also, phonological awareness skills measured in kindergarten (e.g. sound segmentation and sound categorization) predict later reading (4th grade; approx. age 9–10 years) and also later arithmetic (5th grade; approx. age 10–11 years) outcomes (Hecht et al., 2001). Conversely, sensitivity to quantities and cardinal knowledge (i.e. understanding that each number refers to a particular quantity) predict math skills and also reading outcome (Chu et al., 2016). There is also evidence that domain-general cognitive processes, such as attention and working memory, are required for the successful acquisition of reading and math (Bull and Lee, 2014; Chu et al., 2016). These associations between reading and math may be indicative of reliance on the same neural substrates. Indeed, independent brain imaging studies of reading and arithmetic have found that there may be overlapping neural substrates (Houdé et al., 2010; Matejko and Ansari, 2015; Peters and De Smedt, 2018; Pollack and Ashby, 2018). More recently, this has been confirmed in studies examining these skills together (Evans et al., 2016), as described next.

Reading is largely supported by a left-hemisphere network which includes the inferior frontal gyrus (IFG in the frontal cortex, superior temporal, supramarginal (SMG) and angular gyri (AG) in the temporo-parietal cortex, and fusiform gyrus (FG) in the occipito-temporal cortex (Pugh et al., 2001; Maisog et al., 2008; Price, 2012; Martin et al., 2015). Arithmetic is supported by a bilateral frontal-parietal network that includes left and right inferior, middle, and superior frontal gyri (IFG, MFG, SFG), intraparietal sulci (IPS), superior parietal lobules (SPL), angular and supramarginal gyri, and occipito-temporal cortices (Dehaene et al., 2003; Ansari, 2008; Arsalidou and Taylor, 2011). Notably, the bilateral temporo-parietal and left inferior frontal cortices are active during both reading and arithmetic tasks (Prado et al., 2011; Evans et al., 2016).

While this work was conducted using functional neuroimaging (fMRI) in participants performing tasks, other studies have examined the relationship between brain anatomy and behavioral performance of reading or arithmetic (using standardized tests). Considering prior studies measuring gray matter volume in children, the left SMG and cerebellum have been shown to have a positive correlation with reading accuracy (Jednoróg et al., 2015) in a mix of French, Polish, and German readers ($n = 106$ controls). Yet, another study in a much larger sample of English-speaking children ($n = 404$) observed no such relationship in this or any other region between GMV and single real word reading performance (Torre and Eden, 2019). In adults, Pernet et al. (2009) reported a positive correlation between gray matter volume in the left STG and FG with pseudo-word reading in French readers ($n = 39$). Also in adults, He et al. (2013) reported positive correlations between gray matter volume in the left SMG and precuneus with phonological decoding in Chinese speakers with English as a second language performing English reading tests ($n = 416$). A relationship between reading ability and gray matter volume in left STS, SMG, and MTG, as well as diffuse bilateral frontal and parietal regions, have been reported by Johns et al. (2017) ($n = 35$), whereas a relationship with gray matter volume in left FG has been reported by Torre and Eden (2019), both studies conducted in adult readers of English. Taken together, it seems that relationships between gray matter volume and reading ability are more evident in adults than children. Less research has examined the relationship between gray matter volume and math skills, with two studies in children reporting positive correlations between gray matter volume in the left IPS with math performance (Li et al., 2013, $n = 59$; Price et al., 2016, $n = 50$) and one reporting a positive relationship between GMV in bilateral hippocampus and right IFG with elementary-level math test achievement Wilkey et al., 2018, $n = 49$). However, there are no studies in adults, leaving open the question of whether adults also show a relationship between brain anatomy and math ability.

The goal of the current study is to test for relationships between individual differences in reading and math proficiency with brain anatomy, thereby bringing together two independent lines of research on the brain-behavior relationships in reading and math. A second goal is to test these relationships in children as well as emerging adults as a way to gauge the role of age and/or experience on these relationships. Specifically, brain-behavior relationships in young children are more indicative of how individual brain anatomy supports the acquisition of reading and math, while in adults, relationships also reflect the outcome of learning-induced changes that come with experience. A third goal is to utilize measures that are more informative than gray matter volume, as discussed next.

While the studies described above tested gray matter volume, this measure does not distinguish between cortical thickness and cortical surface area, two measures which provide additional insights into specific aspects of brain anatomy (Pakkenberg and Gundersen, 1997; Im et al., 2008; Panizzon et al., 2009; Winkler et al., 2018). It has been proposed that cortical thickness reflects pruning (Shaw et al., 2006) or myelination (Natu et al., 2019) that can occur in response to the acquisition and refining of learned skills. Cortical surface area is thought to be determined by folding of the cortical sheet, which reflects genetically determined cortical folding patterns that may impact cognitive abilities in early development (Tramo et al., 1995; Kapellou et al., 2006; Pannizon et al., 2009), although it should be noted that it has also been speculated that surface area, like cortical thickness, may be influenced by experience-related pruning of synapses (Lyall et al., 2015; Schnack et al., 2015). Critically, cortical thickness and surface area are influenced by distinct genetic mechanisms and follow unique trajectories during typical development (Amlien et al., 2016; Lyall et al., 2015; Panizzon et al., 2009; Rakic, 1995; Wierenga et al., 2014; Winkler et al., 2010), with thickness gradually decreasing with age and surface area gradually increasing (Shaw et al., 2006). Taken together, much of the literature suggests that cortical thickness reflects neurodevelopmental processes that may be impacted by learning, experiences, or other plasticity-related mechanisms, making it an important measure when considering brain-behavioral relationships in the context of reading and arithmetic. Because reading and math are skills acquired during development, relationships between proficiency in these skills and brain anatomy could be a consequence of learning and, therefore, one would predict these to be reflected by measures of cortical thickness rather than surface area (especially at older ages). There may also be relationships with brain anatomy that exist or are formed during the early stages of learning (e.g. before being well-practiced in these skills), which are driven by factors unique to surface area rather than cortical thickness in younger individuals. In any case, the nature of the relationships between reading and/or math ability with cortical thickness and/or surface area in healthy participants at different ages is largely unknown, and the current study seeks to fill that gap.

Indeed, there are only a few studies on the relationships between cortical thickness with reading: one in children, and four in adults. The study in children, conducted recently by Perdue and colleagues (Perdue et al., 2020), found positive correlations between cortical thickness of the left superior temporal cortex with real word as well as with pseudoword reading ability in typical readers ($n = 76$); they found no correlations between surface area and either measure of reading ability. Turning to adult studies, two of the four adult studies reported no relationships between cortical thickness and reading in English speakers (Frye et al., 2010, $n = 16$ controls; Goldman and Manis, 2013, $n = 28$). In contrast, a third, also in English speakers ($n = 60$), found a positive relationship between cortical thickness of the left IPS, bilateral AG, and bilateral STG with performance on a task of irregular word reading, as well as a negative relationship between cortical thickness of the left central sulcus and FG, bilateral IFG and right lingual and supramarginal gyri with irregular word reading (Blackmon et al., 2010). The fourth study, also in English speakers ($n = 35$), found a positive relationship between cortical thickness of the right STG, precentral, lateral occipital cortices with single word reading (Johns et al., 2017). One of these studies measured surface area in addition to cortical thickness and reported a negative relationship between surface area and single real word reading in the left FG (Frye et al., 2010). Turning to mathematics, there has been one study in children (n = 48), which showed a negative relationship between cortical thickness in bilateral anterior and bilateral superior frontal gyri (SFG) with performance on math computations (Chaddock-Heyman et al., 2015). There has also been one study in adults (n = 89), which found no associations between measures of cortical thickness and arithmetic ability; this study did not measure surface area (Heidekum et al., 2020). There have been no studies of surface area and arithmetic ability. The current study seeks to specifically test within the same sample whether reading and math share relationships with brain structure, whether these relationships are observed across groups of different ages, and whether the findings vary based on the nature of the measure, cortical thickness vs. surface area.

Specifically, we tested the associations between cortical thickness and surface area with individual differences in performance on single real word reading and calculation tests in a large sample of typically-developing participants spanning early childhood, early adolescence, and emerging adulthood (i.e. late adolescence and young adults). Prior studies of brain anatomy, reviewed above, are too few and varied in their results to entirely inform our predictions, so in combination with results from functional brain imaging studies (Prado et al., 2011; Evans et al., 2016), we hypothesized that we would observe positive brain-behavior correlations for both reading and math in left frontal, temporo-parietal, and occipito-temporal regions (i.e., that brain regions will show greater cortical thickness, but perhaps not surface area, with better reading and math ability). Since gray matter volume studies looking at anatomical relationships with reading ability in adults (Pernet et al., 2009; Johns et al., 2017; Torre and Eden, 2019) have revealed more consistent brain-behavioral findings than those in children (Jednoróg et al., 2015; Torre and Eden, 2019), we further hypothesized to find correlations in adults, but not necessarily children. Prior fMRI studies on reading (Turkeltaub et al., 2003; Martin et al., 2015) and math (Ansari et al., 2005; Rivera et al., 2005; Ansari, 2008; Kaufmann et al., 2010; Houde et al., 2010; for review, see: Peters and DeSmedt, 2018) have reported age-related differences, reflecting increased age and experience. Our approach involved the same normative MRI data set used in our prior study on GMV (Torre and Eden, 2019), and the same division of different age subgroups, this time measuring cortical thickness and surface area, as well as examining math. Taken together, this study aims to expand our current knowledge on the relationships between brain anatomy and critical academic skills by examining different age groups, different anatomical measures, and importantly, both reading and math ability.

2. Material and methods

2.1. Participants

All data were acquired by the Brain Development Cooperative Group as part of a larger longitudinal study of typical pediatric development at six different sites in the U.S. (Evans and Brain Development Cooperative Group, 2006). Parental consent and assent was obtained from minors participating in the study. Our prior study used this same database to draw on a group of participants to examine relationships between GMV and reading (Torre and Eden, 2019). From this database, we identified a cross-sectional sample of participants aged 6–22 years (n = 404) who were healthy, native English speakers with no diagnosed background of reading, math, or language impairment (while the database also contains longitudinal data, there were not enough high-quality scans at each timepoint for all subjects). Following the Freesurfer pipeline (described below), all scans were visually inspected for quality assurance and segmented data were manually edited using the guidelines laid out by the Freesurfer developers (http://surfer.nmr.mgh.harvard.edu/fswiki/edits). Following manual inspection of each scan, we excluded individuals with clear (i.e. identifiable) errors in segmentation. A total of 62 images were discarded from analyses based on poor quality parcellation of the cortical surface, leaving a final sample size of 342 participants for analyses. All analyses controlled for scanner site and sex.

To address our hypothesis that there are associations between CT and SA with reading and math skills and that such associations may occur within specific age groups, we first conducted our statistical analyses in all 342 participants and then divided this sample for additional analyses within three different age groups: (1) ages 6–9 (n = 103), (2) ages 10–14 (n = 147), and (3) ages 15–22 (n = 92). The study of these age groups allowed us to draw parallels to prior studies focused on children and adults (described in the introduction). These groups roughly correspond to individuals (1) learning to read and perform math, (2) individuals practicing reading and math, and (3) individuals experienced in both reading and math, respectively. The groups also roughly map onto to elementary, middle, and high-school/college ages. The specific division by age is based on previous research involving the same anatomical measures of interest (Shaw et al., 2006) as well as a recent study of this same sample (Torre and Eden, 2019).

2.2. Behavioral measures

Participants in the NIH Pediatric MRI Data Repository completed a large battery of tests. From this battery, the present study used reading, math, IQ, and socioeconomic status (SES) measures for analyses. Reading ability was measured using the Letter-Word Identification (LW-ID) subtest of the Woodcock-Johnson III Tests of Achievement (Woodcock and Bonner Johnson, 2011), which is an untimed test of single real word reading based on word items that range in difficulty. Mathematical ability was measured using the Calculation subtest of the Woodcock-Johnson III, which is an untimed paper-and-pencil test with items that increase in problem difficulty. Items range from number writing, single- and double-digit calculation, to geometry and trigonometry problems. IQ was measured using the Wechsler Abbreviated Scale of Intelligence (WASI) (Wechsler, 2003), which provided a full-scale measure of IQ. SES was approximated using two separate measures: 1) average parental education in 2) adjusted family income years (Noble et al., 2015). As described below, our analyses accounted for effects of IQ, based on its moderate to strong correlation with behavioral measures of reading and math skills (White, 1982; Sirin, 2005; Ramsden et al., 2013), as well as its relationship with CT and SA (Shaw et al., 2006; Narr et al., 2007; Karama et al., 2011). Our analyses also accounted for effects of SES, based on its correlations with measures of reading and math (see Farah, 2018 for review) as well as CT and SA (Jednoróg et al., 2012; Brito et al., 2014; Noble et al., 2015; Piccolo et al., 2016; Brito et al., 2017).

Relevant to our study, the NIH Pediatric MRI Data Repository excluded children of parents with limited English proficiency, children with current or past treatment for psychiatric or language disorders, and children with behavioral reading, math, or IQ performance <70. No further selection criteria were applied to our study. Imaging data were inspected and rated for quality (scale of 1–5) by two blind scorers from our lab; the best quality scan (of three scans) for each subject was selected for use in our study. This resulted in 342 scans of individuals aged 6–22 years of age.

Group averages and standard deviations for behavioral performance on reading, math, and IQ are reported for the whole group in Table 1 and for each of the three age-specific subgroups in Table 2. A one-way ANOVA was conducted to evaluate any statistically significant differences in reading and math standard scores between the three age groups. There were differences for reading ($F(2,208) = 7.12$, $p < .001$; one-way ANOVA), and a post-hoc *t*-test revealed that both the youngest and middle age groups were significantly better at reading compared to the oldest age group ($t(193) = 3.66$, $p < .001$ and $t(237) = 2.33$, $p = .021$, respectively). Of note, matching all groups on standard reading scores by removing subjects with lower reading scores from the oldest age

Table 1
Demographics and Behavioral Measures for Full Sample. Mean, standard deviation, and range of single real word reading, math calculation, and IQ for full group of 342 participants. Reading, math, and IQ standard scores have a mean of 100, and one standard deviation of 15 points.

	Mean	Standard Deviation	Range
N	342		
Age	12.01	3.76	6–22
Single Real Word Reading (Standard)	108.40	11.02	71 – 151
Single Real Word Reading (Raw)	57.72	12.61	17 – 76
Math Calculation (Standard)	110.32	11.91	77 – 152
Math Calculation (Raw)	22.50	8.77	3 – 44
IQ	111.59	12.13	79 – 160

group did not alter the findings of any of our reported analyses, so this point is not discussed further (see Supplemental Findings for results of these tests).

2.3. Imaging measures

2.3.1. MRI data acquisition

Images taken from the NIH Pediatric MRI Data Repository were acquired using General Electric or Siemens 1.5 T scanners located at six different pediatric study centers as part of the original study. Images were collected using a 3D T1-weighted spoiled gradient recalled (SPGR) echo sequence (TR (ms) = 22–25, TE (ms) = 10–11, FOV (mm) = 256, 1 mm slice thickness, voxel size =1 mm isotropic). For more detail, see Evans et al., 2015 or www.pediatricmri.nih.gov.

2.3.2. MRI data preprocessing

Each individual's structural MRI scan was pre-processed separately using a surface-based automated processing stream that requires no manual user intervention. The Freesurfer image analysis suite version 6.0 (http://surfer.nmr.mgh.harvard.edu/) was used to perform automated cortical reconstruction, segmentation, and parcellation. Processing was performed using the Recon-All function. In brief, the Freesurfer pipeline involves skull stripping (Ségonne et al., 2004), registration to Talairach space, intensity normalization (Sled et al., 1998), white matter segmentation, tessellation of the gray and white matter boundary, and automated topology correction (Fischl et al., 2001; Segonne et al., 2007). After the cortical surface is inflated (Fischl et al., 1999), the cortex is parcellated with respect to the structure of the gyri and sulci (Fischl et al., 2004; Desikan et al., 2006). Cortical thickness is calculated as the closest distance from the gray/white boundary to the gray/CSF boundary at each vertex on the tessellated white matter surface, and surface area is calculated as the total area of the triangles connected to a vertex (Fischl & Dale, 2000). Average cortical thickness and surface area were calculated for each parcellated region and for each hemisphere. Next, we used the Destrieux atlas (Destrieux et al., 2010) to extract measures of vertex-wise cortical thickness and surface area for our *a-priori* regions of interest (ROIs).

2.3.3. Regions of interest (ROIs)

We focused our analyses on brain regions shown in the published literature to be engaged in reading, math, or both, in children and adults. The seven ROIs identified from the literature on studies of reading were: the left inferior frontal gyrus (IFG), left and right superior temporal gyrus (STG), left angular gyrus (AG), left and right supramarginal gyrus (SMG), and left fusiform gyrus (FG) (Price, 2012; Martin et al., 2015). The eleven ROIs identified from the literature on studies of math were: the left IFG, left and right superior frontal gyrus (SFG), left and right middle frontal gyrus (MFG), left AG, left SMG, left and right intraparietal sulcus (IPS), and left and right FG (Dehaene et al., 2003; Ansari, 2008; Arsalidou and Taylor, 2011; Grotheer et al., 2016; Yeo et al., 2017; Peters and De Smedt, 2018). Both reading and math ROIs included the left IFG, AG, SMG, and FG, indicating four brain regions common to both skills and resulting in 14 ROIs total. Given the main hypothesis of commonality between reading and arithmetic, we would expect this kind of overlap amongst the ROIs. While we describe these ROIs as either "reading- or math-specific" from here onwards, it is important to note that this does not imply that they are exclusive to one or the other, but rather, describe which category of studies (reading or math) they were derived from. These ROIs were identified based on their anatomical label, with their corresponding regions parcellated using the Destrieux atlas utility in Freesurfer (Fischl et al., 2004; Destrieux et al., 2010). All task specific-ROIs were submitted to the analyses focused on reading as well as the analyses focused on math analyses. The ROIs are listed in Table 3.

2.4. Statistical analyses

The analyses included 342 participants since these had complete data for reading, math, and IQ measures, and their anatomical scans passed quality control checks. For all of these participants, anatomical measures of cortical thickness and surface area were extracted to test for relationships between brain anatomy and reading and math across different ages. All analyses were conducted in SPSS V24.0 (IBM Corp).

Table 3
Regions of Interest (ROIs) Used in Analyses. Description of areas of ROIs selected from functional studies of task-based activation in response to reading or math tasks in typical individuals. ROIs were selected on the basis of consistent citation as the reading and math networks.

	Regions of Interest	Hemisphere
Reading	Inferior frontal gyrus	L
	Superior temporal gyrus	L, R
	Angular gyrus	L
	Supramarginal gyrus	L, R
	Fusiform gyrus	L
Math	Inferior frontal gyrus	L
	Superior frontal gyrus	L, R
	Middle frontal gyrus	L, R
	Angular gyrus	L
	Supramarginal gyrus	L
	Intraparietal sulcus	L, R
	Fusiform gyrus	L, R

Table 2
Demographics and Behavioral Measures for Age Groups. Mean, standard deviation, and range of reading ability, IQ, and SES for three subgroups of participants based on age. Reading, math, and IQ standard scores have a mean of 100, and one standard deviation of 15 points. Last column shows result from one-way ANOVA.

	Ages 6–9 Mean (SD)	Range	Ages 10–14 Mean (SD)	Range	Ages 15–22 Mean (SD)	Range	p-value
N	103		147		92		
Age	7.86 (0.96)	6–9	11.78 (1.48)	10–14	17.0 (1.82)	15–22	<.001
Single Real Word Reading (Standard)	111.1 (12.2)	90 – 148	108.5 (10.6)	71 – 151	105.3 (9.47)	85 – 134	<.001
Single Real Word Reading (Raw)	44.09 (11.6)	17 – 66	60.49 (7.4)	28 – 75	68.71 (3.77)	56 – 76	<.001
Math Calculation (Standard)	110.0 (11.4)	77 – 147	111 (11.4)	81 – 145	110.0 (13.3)	82 – 152	.662
Math Calculation (Raw)	12.5 (4.77)	3 – 24	24 (5.2)	9 – 38	31.3 (5.04)	19 – 44	<.001
Full Scale IQ	112.37 (13.5)	79 – 156	111.75 (11.9)	79 – 160	110.46 (10.8)	85 – 133	.635

2.4.1. Testing correlations between cortical thickness or surface area with reading or math

First, to test our main research question about relationships between brain anatomy and performance on reading and arithmetic, we conducted four sets of correlation analyses for each of the ROIs (cortical thickness with reading, cortical thickness with calculation, surface area with reading, surface area with calculation) to address whether individual differences in measures of cortical thickness or surface area are linearly related to standardized scores of reading or math ability. This approach allowed for comparisons to prior studies where the focus of investigation has been only on either reading or math, and mostly on either cortical thickness or surface area. For similar reasons, our analyses were conducted in distinct age groups, as prior studies had focused on children or adults and never both. Specifically, we first examined relationships between cortical thickness or surface area with reading or math ability in the entire sample ($n = 342$) and then conducted the same correlation analyses separately for each of the three age-specific subgroups. For all of these analyses, correlations tested the relationship between cortical thickness or surface area in each of the 14 ROIs with standard scores of single real word reading or calculation. All analyses used partial correlations to account for IQ, SES, scanner site, and sex. When examining the entire sample (but not when examining each age group), age was also accounted for in the analysis. All correlations were evaluated for significance using a threshold of $p < 0.05$, and a Holm-Bonferroni correction was applied to correct for multiple comparisons using the Holm-Bonferroni automated step-down Excel calculator (Gaetano, 2013) correcting for 56 tests (14 ROIs for 4 dependent variables) (Holm, 1979; Abdi, 2010; Gaetano, 2013).

Because we employed a cross-sectional design, it is not possible to fully evaluate the role of age and experience on these brain behavioral relationships (a longitudinal study would better serve this purpose). However, we conducted exploratory analyses to examine whether there are differences in the strengths of the correlations between anatomy and reading or math amongst the age-specific subgroups. Specifically, we used a Fisher's Z Test to determine whether the correlation coefficients (between significant relationships observed cortical thickness or surface area with single real word reading or calculation) significantly differed across the three age groups in cases where a significant relationship was found (Cohen & Cohen, 1983; Lenhard & Lenhard, 2014). Results of this test were evaluated at a significance level of $p < .05$.

2.4.2. Testing for unique contributions of reading and math ability to cortical thickness and surface area

Next, we conducted multiple regression analyses for the entire sample to evaluate whether reading and math contribute unique variance to cortical thickness or surface area in any of the 14 regions of interest. One regression was carried out for each ROI: 14 multiple regressions for cortical thickness and 14 multiple regressions for surface area. For each analysis, cortical thickness or surface area was entered as the dependent variable in a linear regression that modeled the unique contributions of the following independent variables: single real word reading, calculation, age, IQ SES, scanner site, and sex. Again, we explored the potential role of age by adding the interaction terms "single word reading x age" and "calculation x age" as independent variables to these models to test for any indication of age-dependent moderations of any relationships between brain anatomy and reading or math ability. Models were considered significant at a threshold of $p < .05$ (Holm-Bonferroni correction applied) and statistical contributions to variance were considered significant at $p < .05$. We focus the reporting of the results on findings where the model was significant for the reading or math variables (reading, reading x age, calculation, or calculation x age (see Fig. 2).

3. Results

3.1. Testing for correlations between cortical thickness or surface area with reading ability

For the full sample, there were no associations between cortical thickness or surface area with single word reading ability in any of the 14 ROIs. Looking specifically at the age-specific subgroups, in the youngest age group (ages 6–9), correlation analyses revealed no relationships between cortical thickness with single word reading ability in the reading-specific ROIs. Correlation analyses also revealed no relationships between surface area with single word reading ability in the reading-specific ROIs. When conducting the same analyses in the middle age group (ages 10–14), there again were no significant relationships between cortical thickness or surface area with single word reading. However, in the oldest age group (ages 15–22) the same analysis approach yielded two significant correlations: cortical thickness in the left SMG (Pearson's $r(85) = .305$, $p = .004$) and in the left FG (Pearson's $r(85) = .257$, $p = .016$) were significantly correlated with single word reading ability. Finally, there were no significant relationships between surface area and single real word reading within this oldest age group. See Fig. 1.

When testing whether these correlations significantly differ between age groups, we observed that the correlation between cortical thickness in the left SMG and single word reading was significantly higher in the oldest group compared to the middle (left SMG: $Z(85,140) = -3.07$, $p = .001$) and youngest age groups (left SMG: $Z(8596) = -2.58$, $p = .005$). We also observed that the correlation between cortical thickness in the left FG with single word reading was significantly higher in the oldest group compared to the middle group (left FG: $Z(85,140) = -2.20$, $p = .014$) and marginally significantly higher in the oldest group compared to the youngest group (left FG: $Z(8596) = -1.68$, $p = .046$). See Fig. 2.

3.2. Testing for correlations between cortical thickness or surface area with math ability

For the full sample, there were no associations between cortical thickness or surface area with calculation ability in any of the 14 ROIs. Turning to the three age groups, there were no significant correlations between cortical thickness or surface area with calculation in the youngest age group (ages 6–9), the middle age group (ages 10–14), nor the oldest age group (ages 15–22) in any of the 14 ROIs.

3.3. Testing for unique contributions of reading and math ability to cortical thickness

The multiple regressions, conducted in the entire sample for 14 ROIs with cortical thickness revealed that single word reading ability, the interaction between single word reading ability and age, and age each contributed unique variance to cortical thickness in the left SMG (model $F(10,341) = 5.26$, $p < .001$); reading: $\beta = -0.458$, $p = .018$; reading x age: $\beta = 1.50$, $p = .012$; age: $\beta = -1.26$, $p = .018$). Second, we observed a similar relationship in the left IPS, where single word reading ability, the interaction between single word reading ability and age, and age each contributed unique variance to cortical thickness (model $F(10,341) = 19.7$, $p < .001$); reading: $\beta = -.426$, $p = .010$; reading x age: $\beta = 1.08$, $p = .033$; age: $\beta = -1.19$, $p = .009$). Third, we observed that an interaction between reading ability and age (but not reading ability alone) and age contributed unique variance to cortical thickness in the left FG (model $F(10,341) = 20.9$, $p < .001$; reading x age: $\beta = 1.05$, $p = .035$; age: $\beta = -1.33$, $p = .003$) (See Fig. 3). For these models (left SMG, left IPS, and left FG), no other variables contributed significant variance (see Supplemental Materials). Further, calculation ability and the interaction between age and calculation ability did not contribute significant unique variance to cortical thickness in any of these or any

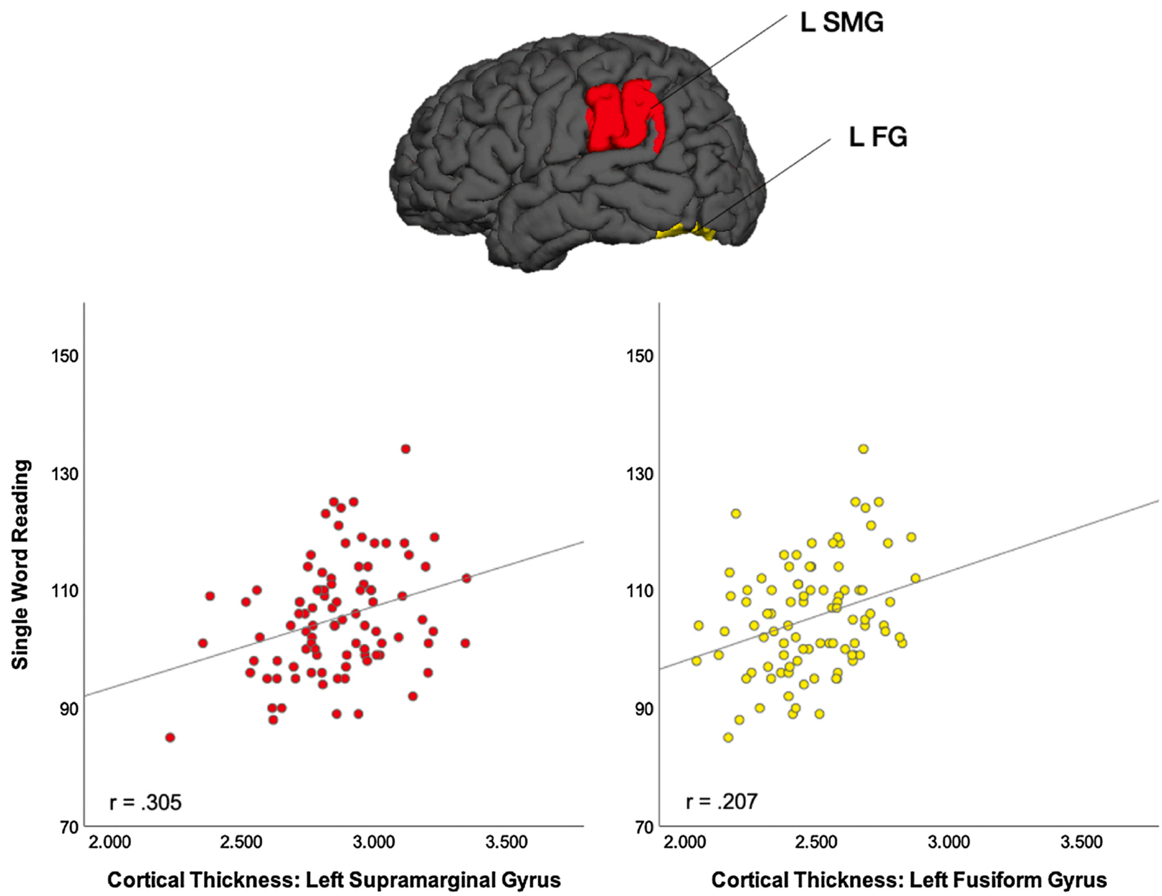

Fig. 1. Correlations between cortical thickness and single real word reading: Region of Interest Analysis. Top: Visualization of left SMG and left FG ROIs. Bottom: Significant correlation between cortical thickness in the left SMG and single word reading in ages 15 – 22 (Pearson's r(85) = .305, p = .004) and between cortical thickness in the left FG and single word reading in ages 15 – 22 (Pearson's r(85) = .257, p = .016). Correlations partialled out IQ, SES, scanner site, and sex.

other regions. In addition to these models, age contributed unique variance to cortical thickness (not included in Fig. 2) in left MFG (model F (10,341) = 8.12, p < .001; age: β = -1.26, p = .015), right AG (model F (10,341) = 6.93, p < .001; age: β = -1.81, p = .001), right SMG (model F (10,341) = 6.08, p < .001; age: β = -1.12, p = .034), and right IPS (model F (10,341) = 14.2, p < .001; age: β = -1.26, p = .009).

3.4. *Testing for unique contributions of reading and math ability to surface area*

The multiple regressions for surface area (conducted like the analysis of cortical thickness above on the entire sample of 342 participants for 14 ROIs) revealed no significant contributions of single word reading, calculation, or the interaction with age for these two skills. Age was not significant in any of the ROIs.

4. Discussion

The present study sought to test for relationships between brain anatomy (cortical thickness and surface area) and individual differences in key academic skills (reading and math) to test their potentially shared neuroanatomical bases, as suggested by a corpus of behavioral and functional neuroimaging studies. We examined two anatomical variables thought to be associated with different aspects of development (cortical thickness and surface area), as well as different age groups (children, adolescents, and emerging adults). This approach allowed us to gain more information in a single study than previous disparate studies that mostly focused on only one of these two academic skills, one anatomical measure, and one age group. We hypothesized that individual differences in single word reading and calculation ability would be positively associated with cortical thickness (rather than surface area) in some of the same cortical regions. We also hypothesized that such relationships would be observed in adults, but not necessarily children.

First, we tested for linear correlations between cortical thickness or surface area with reading or math ability using approaches consistent with prior studies focusing on a single age group and on one of these two skills. Using 14 *a-priori* regions of interest (seven areas associated with reading, eleven with calculation, with four of these associated with both), we found that cortical thickness of the left SMG and FG were positively correlated with single word reading ability in the oldest age group (ages 15–22), but not in the groups of children or younger adolescents. There were no correlations between brain anatomy and calculation ability in any of the three age groups, and thus no anatomical overlap for correlations with reading and calculation. There were no correlations between surface area with reading or math ability. Second, of the regression models conducted for cortical thickness, we found that in two ROIs, single word reading ability, age, and the interaction between reading ability and age contributed unique variance to cortical thickness: the left SMG and the left IPS. We also found that age, and the interaction between reading ability and age (but not reading ability alone), contributed unique variance to cortical thickness in the left FG. However, we found no contribution of calculation ability, nor an interaction of age and calculation ability, to cortical thickness in any of the ROIs. Neither reading nor calculation ability, nor their interactions with age, contributed unique variance to surface area in any of the ROIs. Our findings provide evidence for a few relationships between brain anatomy and reading ability in typically developing emerging adults,

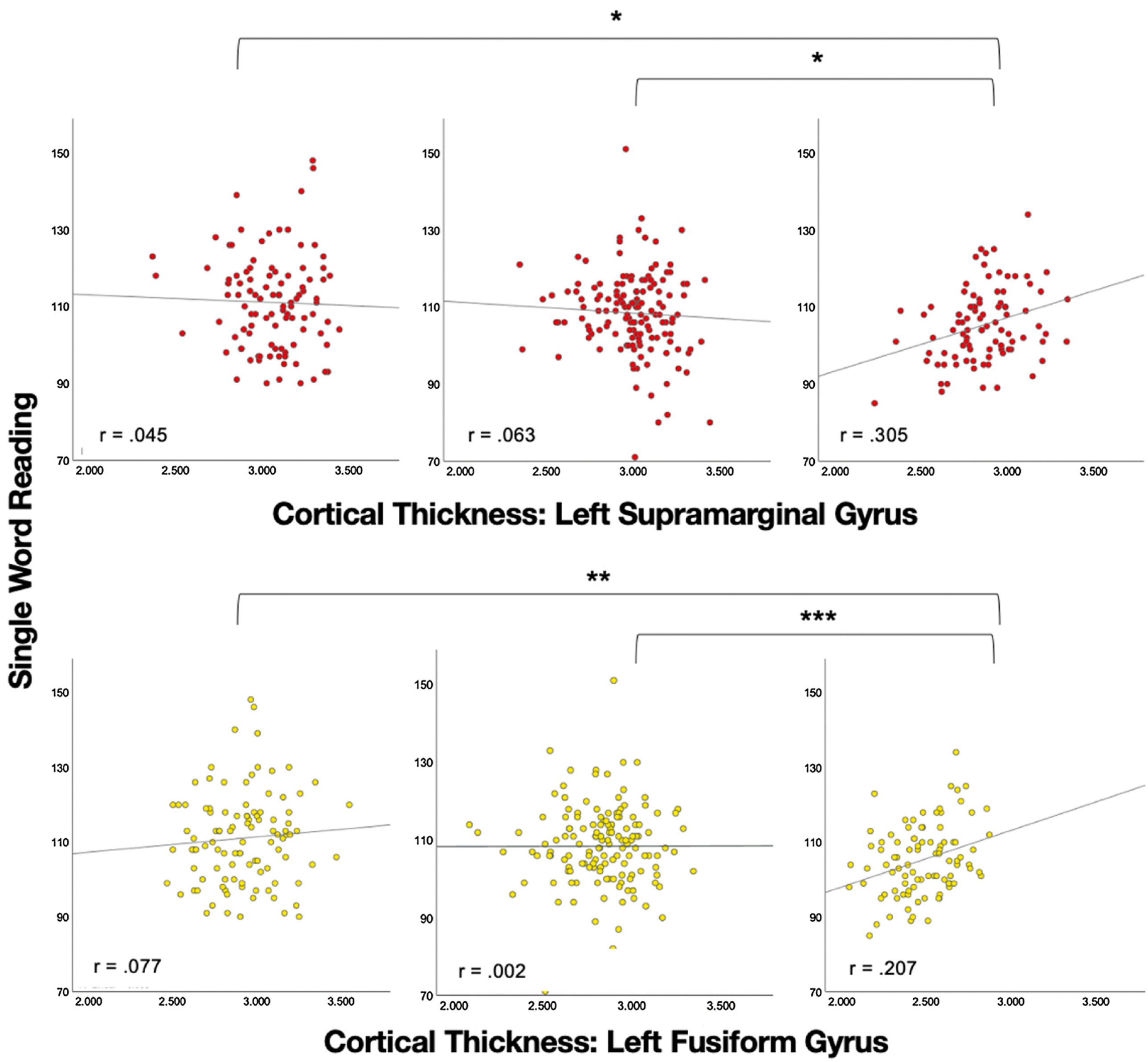

Fig. 2. Differences in the Correlations between Cortical Thickness in the left SMG and left FG with Single Word Reading Across Age Groups. Top: Correlation coefficients (Pearson's r) of the relationship between cortical thickness in the left SMG and single word reading significantly differ between the youngest and oldest age groups, as well as the middle and oldest age groups (youngest to oldest: left to right). Bottom: Correlation coefficients between cortical thickness in the left FG and single word reading significantly differs between the youngest and oldest age groups, as well as the middle and oldest age groups. * = $p < 0.05$, ** = $p < .01$, *** = $p < .001$.

but none for calculation ability and therefore none shared by the same brain regions for reading and calculation ability. The relationships between cortical thickness and single real word reading ability were observed in older adolescents/emerging adults, most notably in the left SMG, but not in children or younger adolescents.

4.1. Relationships between cortical thickness and reading ability, but not calculation ability

The possibility that reading and math share neural correlates has been suggested by results from independent studies of reading and math which report activity in the same brain regions (Houde et al., 2010; Peters and De Smedt, 2018; Pollack and Ashby, 2018). Additionally, two studies have directly shown an overlap in the functional networks that support both of these skills (Prado et al., 2011; Evans et al., 2016), specifically in the bilateral temporo-parietal and left inferior frontal cortices (i.e. the regions of interest to our study). This converges with behavioral studies showing that reading and math may share some cognitive constructs (Bull and Lee, 2014; Chu et al., 2016). While we observed some brain-behavioral relationships for reading, we did not observe any relationships between either cortical thickness or surface area with calculation ability for any age group, either when using correlation or multiple regression approaches. Of note, one of the three regions in which relationships between cortical thickness and reading ability was observed, the left FG, is a region that was designated both a reading- and math-specific ROI. Another was the left IPS, which was designated as a "math-specific" ROI, meaning that it emerged from the literature on math. As such, the failure to identify areas of overlap is due to an absence of any relationships with math, and not because of a lack of convergence between anatomical correlations with reading and math abilities.

As described in the introduction, there has been only one study examining the relationship between cortical thickness and math ability in children (Chaddock-Heyman et al., 2015), which was focused on the

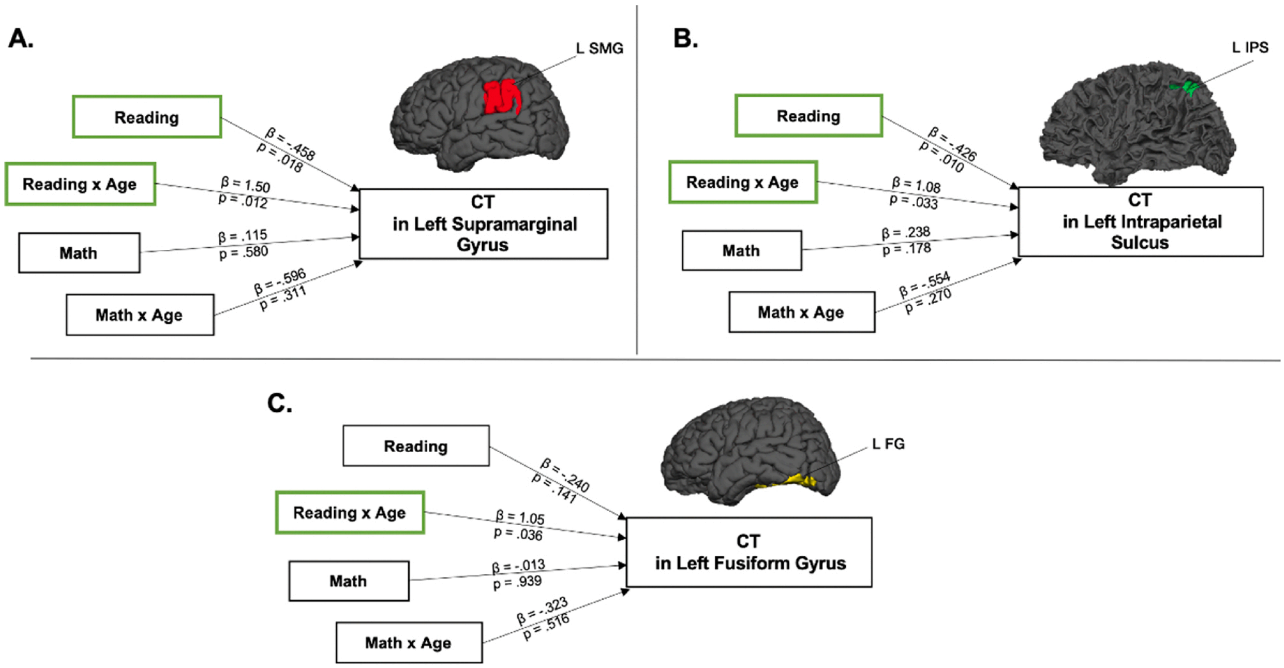

Fig. 3. Unique contributions of single word reading, math calculation, age, and IQ to cortical thickness in the left SMG, FG, and IPS. We present only those models where the contribution to CT was significant for at least one of the variables of interest (reading, reading x age, calculation, or calculation x age). There were three multiple regression models that emerged, all of which indicated that an interaction between single word reading and age contributes unique variance to CT. A) Left SMG: model $F = 5.26$, $p < .001$; B) Left IPS: model $F = 19.7$, $p < .001$; and C) Left FG: model $F = 20.9$, $p < .001$.

role of aerobic fitness in cortical thickness and mathematics achievement, and one study examining relationships between cortical thickness and math in adults (Heidekum et al., 2020). In children, cortical thickness in the bilateral anterior and bilateral superior frontal gyrus was found to be negatively associated with math ability, whereas the study in adults (who were slightly older than our emerging adult sample) found no correlations between cortical thickness and math. While our results in adults are the same as those of Heidekum et al., 2020, who also tested a large sample size, the discrepancy between the finding in children by Chaddock-Heyman and colleagues and our study could be due to various experimental differences. For instance, Chaddock-Heyman and colleagues had a smaller sample size ($n = 48$), used a different set of ROIs (nine in total), and did not control for multiple comparisons. In terms of sample size, the present study is larger than all prior studies correlating cortical thickness with academic skills, with 103, 147, and 92 participants in our respective age groups. The locations of our math-based ROIs were based on functional activation studies of basic number and arithmetic processing (Ansari et al., 2006; Cantlon et al., 2006; Mussolin et al., 2010; Arsalidou and Taylor, 2011; Bugden et al., 2012; Peters & DeSmedt, 2018). One concern may be that these ROIs did not capture all areas involved in calculation, and we addressed this in a *post-hoc* whole-brain correlation analyses: here, too, we found no significant correlations. When not correcting for multiple comparisons in the ROI analyses, as was done in Chaddock-Heyman et al., we still did not find cortical thickness to be correlated with math. Lastly, Chaddock-Heyman measured arithmetic using the Wide-Range Achievement Test (WRAT), while we used the calculation subtest from the Woodcock-Johnson. Similar to the Woodcock-Johnson, the WRAT is a commonly used achievement test to assess individual differences in academic skills (Wilkson and Robertson, 2006). The WRAT's arithmetic subtest is an untimed paper-and-pencil test and taps into a variety of mathematical concepts (i.e. number symbol knowledge, single and double-digit calculation, algebra, and geometry) depending on age and level of experience of the participant, as does the Woodcock-Johnson calculation subtest. As such, our study, in a substantially larger sample, does not replicate the relationships between cortical thickness in the bilateral anterior and superior frontal gyrus and math ability by Chaddock-Heyman and colleagues. It is possible that a measure focused on one homogenous aspect of numerical or mathematical abilities (e.g., only early numeracy skills, single and double-digit arithmetic, or symbolic magnitude processing) may uncover brain-behavior relationships that we did not. Our conclusions are therefore limited to this measure (which was the only math measure in the NIH Pediatric MRI Data Repository), and future research will need to investigate whether cortical thickness or surface area relate to other measures of mathematical ability.

Finally, a possible explanation for our results (and those by Heidekum et al., 2020) of no anatomical relationship with calculation ability is that math is not practiced as frequently during childhood as reading (Stacy et al., 2017). Reading is needed to succeed across many subjects and is therefore practiced in many contexts. In contrast, math training is often more isolated. The amount of training needed to alter cortical thickness may be substantial. It is possible that the math training individuals typically receive does not meet the threshold to make changes to cortical thickness, resulting in no observable brain-behavior correlations. Given that there were no relationships for calculation ability, the remainder of the discussion will focus on the brain regions which had a relationship with reading ability.

4.2. Left fusiform gyrus cortical thickness and reading ability

We found that cortical thickness in the left FG was positively correlated with reading ability in the oldest age group (ages 15–22), but not in the two younger age groups. Previous GMV studies had reported a positive correlation between GMV of the left FG with reading ability in adults (Pernet et al., 2009; Torre and Eden, 2019), but prior cortical thickness studies in adults did not report findings in the left FG (Frye et al., 2010; Goldman and Manis, 2013; Johns et al., 2017), except for one, which reported a negative correlation with irregular word reading (Blackmon et al., 2010). Further, our regression model showed that the interaction between reading ability and age (but not reading ability itself), as well as age, contributed unique variance to cortical thickness in the left FG. Because the relationship between cortical thickness and age alone is negative and the correlation between cortical thickness and reading ability is positive, we assume that despite the cortical thinning that occurs with normal development in the left FG, stronger reading ability is associated with greater cortical thickness in this region by adulthood.

The left FG is home to the putative visual word form area (VWFA), a portion of visual cortex thought to be responsive to visual words, but only once reading skills have been acquired (Mccandliss et al., 2003; Dehaene and Cohen, 2011). It has been argued that this region did not evolve to process words, but rather, is co-opted from object recognition for the purpose of reading (Dehaene et al., 2005) and that its functional development is tied to advancements in reading skill (i.e. it is not due to brain maturation alone) (McCandliss et al., 2003). In support of this, brain imaging studies have shown increases in activation in response to written words with age/skill level, likely representing increased reliance on sight-word reading in mature/skilled readers (Maurer et al., 2005; Brem et al., 2010; Dehaene et al., 2010; Ben-Shachar et al., 2011; Martin et al., 2015; Dehaene-Lambertz et al., 2018). Notably, using a meta-analysis approach, Martin et al. showed that adults have more extensive activation in the left occipito-temporal cortex compared to children during reading tasks (Martin et al., 2015). Our findings of correlations between cortical thickness and reading ability in our oldest (and most experienced) age group, as well as our finding of an interaction between reading ability and age contributing unique variance in cortical thickness in this region, converges with previous evidence that the VWFA shows experience-dependent increases in brain activity for reading (Dehaene et al., 2010; Martin et al., 2015). Unlike the left SMG and IPS, we did not find reading ability by itself to contribute to cortical thickness in left FG (only in the context of age).

It is possible that more reading experience is coupled with anatomical as well as physiological changes, resulting in our observed positive association between cortical thickness and reading ability in our emerging adult group. Interestingly, our observation of more cortical thickness in better readers in the FG in this age group is similar to our earlier study measuring GMV in largely the same sample (Torre and Eden, 2019). In this prior study, we observed that GMV of the left FG was positively related to reading ability in emerging adults, but not in the younger age groups. In contrast, three of the four prior studies examining associations between cortical thickness with reading ability did not observe a relationship for the left FG, and the fourth found a negative relationship reading (Blackmon et al., 2010), whereas our relationship was positive. The study by Blackmon and colleagues measured irregular word reading (exception words) on the Wechsler Test of Adult Reading and focused on adults aged 19–66 years. Notably, this assessment of reading ability is much more reliant on an individual's prior experience with irregular grapheme-to-phoneme relationships than the measure used in our study, which taps into an individual's familiarity with typical phonetic rules as well as sight word skills (Blackmon et al., 2010). Also of note, one prior report found that surface area, not cortical thickness, of the left FG was negatively correlated with reading ability (Frye et al., 2010). Studies of dyslexia can also inform the interpretation of cortical thickness and surface area studies of reading. For instance, groups with dyslexia have been shown to have less cortical thickness in the left FG when compared to controls (Altarelli et al., 2013), which is line with other structural (as well as functional) imaging studies showing less GMV (and fMRI activity) in the left FG in dyslexia (Linkersdörfer et al., 2012) and the present result that lower reading ability is associated with less cortical thickness.

4.3. Left supramarginal gyrus cortical thickness and reading ability

We found that cortical thickness of the left SMG was positively correlated with reading ability in the oldest age group (ages 15–22), but not in the two younger age groups. This is consistent with prior findings of correlations between gray matter volume of the left SMG and reading ability in adults (He et al., 2013), although it should be noted that a prior study of children also identified such a relationship (Jednoróg et al., 2015). None of the four prior studies examining relationships between cortical thickness and reading ability reported the left SMG, though one of the studies did observe such a relationship in the nearby angular gyrus (Blackmon et al., 2010). The multiple regressions further revealed that single word reading ability, age, and the interaction between single word reading ability and age each contributed unique variance to cortical thickness in the left SMG.

The left SMG is a hub of the dorsal reading pathway (Cohen et al., 2008) and is thought to support the processes involving letter-sound correspondences that underlie word decoding (Démonet et al., 1992; Pugh et al., 2001). Unlike the ventral pathway, which is thought to undergo neuronal recycling from object to visual word form recognition in left FG, the dorsal temporo-parietal regions are thought to subserve aspects of oral language in reading (Perfetti and Bolger, 2004). Our finding that stronger reading ability is associated with greater cortical thickness in this region fits with the large body of functional brain imaging studies that have identified activity in the left SMG during reading (Price et al., 1996; Moore & Price, 1999; Pugh et al., 2001; Jobard et al., 2003; Richlan et al., 2009; Price 2012), though two meta-analyses of fMRI studies of reading did not find the left SMG specifically (Turkeltaub et al., 2002; Martin et al., 2015). Like the left FG, associations between the left SMG cortical thickness in the present study and reading were positive despite the negative correlation between CT and age for this region. It is tempting to suggest that with age, a relationship between cortical thickness of the left SMG with single word reading ability is crystallized, and the significant differences between the correlations for the oldest versus the two younger age groups reflect as much; yet, longitudinal studies are needed to specifically test this. Interestingly, reading ability alone contributed to cortical thickness of the left SMG, perhaps reflecting the relationship between oral language and reading skills. This could be further investigated by testing whether the association between cortical thickness and reading proficiency is explained by phonological processing abilities. A similar idea has been set forth by He et al. (2013), whose work found positive associations between gray matter volume and phonological decoding in adults (He et al., 2013). Further, Goldman and Manis (2013) found that cortical thickness of the left SMG was positively associated with exposure to printed materials, a measure that is correlated with reading ability, in college-aged students (even though they found no relationships here for single word reading, per se). Additional information on the left SMG's role in reading comes from research on dyslexia, which suggests that the structure and function of the SMG are altered in groups with this reading disability (Richlan et al., 2009; Linkersdörfer et al., 2012).

Our findings of a relationship between left SMG and reading ability differ from previous studies in adults showing no such relationships with left SMG cortical thickness, surface area, or gray matter volume (Blackmon et al., 2010; Frye et al., 2010; Goldman and Manis, 2013; Johns et al., 2017; Torre and Eden, 2019). However, these differences are likely due to variations in the methods in the prior literature and highlight the importance of our study's investigation of cortical thickness and surface area in children, adolescents, and emerging adults, with prior studies focusing on only one of these measures and one of these age groups.

4.4. Left intraparietal sulcus cortical thickness and reading ability

While the IPS did not emerge as significant in any of our correlation analyses, the regression model found that single word reading ability, the interaction between single word reading and age, and age itself contributed unique variance to cortical thickness the left IPS (similar to the left SMG findings discussed above). One of the four studies looking at this anatomical measure reported a positive relationship between cortical thickness in the left IPS with irregular word reading ability (Blackmon et al., 2010), also in adults, while two studies have observed a relationship between GMV of this region with math abilities (Li et al., 2013; Price et al., 2016). The left IPS was an ROI chosen from the math literature (Ansari, 2008; Arsalidou and Taylor, 2011; Menon, 2015; Peters & DeSmedt, 2018), making it surprising that cortical thickness of this region was associated with single word reading ability, and not calculation ability. Interestingly, a meta-analysis of fMRI studies of reading has shown the left IPS is recruited for reading, but only in adults and not children (Martin et al., 2015). However, the left IPS is not typically considered a primary reading foci of the brain, particularly for children (Price, 2012; Martin et al., 2015). Thus, this region's role in reading may be indirect in nature or due to other skills that influence single word reading. For instance, the left IPS has been associated with verbal working memory (Becker et al., 1999; Jonides et al., 1998; Turkeltaub et al., 2003), the ability to store, rehearse, and manipulate phonological codes in mind (Jonides et al., 1998). Few studies have explicitly examined whether brain regions involved in working memory (or attention) overlap with those involved in reading and math in the same individuals. However, meta-analyses of attention and working memory (Constantinidis and Klingberg, 2016; Vossel et al., 2014) indicate that networks for executive function may converge with some of the ROIs included in this study, such as the left IPS and other inferior parietal and superior temporal regions. It has also been suggested that the left IPS plays a role in the reading network by modulating the activity of the left FG (Richlan, 2012; Wandell and Le, 2017). Similar to our findings for the left FG and SMG, cortical thickness of the left IPS was also positively associated with the interaction between single word reading and age. This relationship suggests that the correlation between cortical thickness in the left IPS and reading strengthens with age, perhaps as reading skill increases, but again, longitudinal studies are needed to test this assertion. Notably, we observed no association between the left IPS and single word reading in our correlation tests. Future work should aim to determine the role of the IPS in reading, particularly in the context of reading ability. Indeed, while the left IPS has not been considered a canonical reading region of the brain, some studies have suggested that this region is under-activated in dyslexia (Richlan et al., 2011), though no studies have shown anatomical differences in the IPS in dyslexia.

4.5. The role of experience on behavioral relationships with brain structure

Numerous studies have reported individual differences in brain anatomy are related to skills that require explicit training (e.g. Maguire et al., 2000; Draganski et al., 2004). Few, however, have examined these associations (particularly for cortical thickness and surface area measures) for skills taught through formal education. Reading and math skills are acquired over a protracted time period, so although our study was not longitudinal in design, exploratory analyses of interactions between age and reading/math proficiency would provide a glimpse into whether age/experience contributes unique variance to cortical thickness or surface area. We found that the strength of the associations between reading and cortical thickness in the left FG, SMG, and IPS were moderated by age and thus potentially reading experience. While age is not always equivalent to experience, much evidence suggests that our findings reflect a relationship between brain anatomy and single word reading skills that are concomitant with experience. First, raw reading scores increase with age for our sample, as would be expected, reflecting growing expertise. Second, anatomical studies of children with dyslexia have shown that after successful reading intervention focusing on imagery and visualization, there are gray matter volume increases in the left FG (Krafnick et al., 2014). At the same time, measures of cortical thickness and surface area (Winkler et al., 2010), as well as single word reading skills (DeFries et al., 1987; Davis et al., 2001), are in part genetically influenced. However, our data cannot disentangle complex interactions between genetics, environment, and experience and future work will need to examine these factors. Our cross-sectional design also limits the extent to which we can determine the role of age and/or experience in the relationship between cortical thickness and reading ability, and these can be addressed in future studies using longitudinal approaches.

For the only prior study conducted in children, Perdue and colleagues (Perdue et al., 2020) found positive correlations between cortical thickness of the left superior temporal cortex with real words (and pseudowords), a finding that we did not replicate in our larger sample and despite having a left STG ROI. Of the four prior studies on cortical thickness in adults, two reported other relationships not observed in our sample: Blackmon and colleagues observed positive correlations between cortical thickness and exception word reading in the bilateral angular gyrus and STG, as well as negative correlations for cortical thickness in the bilateral IFG, left central sulcus, and right lingual and supramarginal gyri, as well as the FG, as noted above (Blackmon et al., 2010). Another study observed a positive correlation between cortical thickness of the right STG with reading ability, as well as relationships in areas not among our regions of interest, such as the right precentral and lateral occipital gyri (Johns et al., 2017). However, when conducting a *post-hoc* whole brain correlation in our full sample (as well as within the age-specific subgroups) to capture any relationships in areas outside our ROIs, no new regions were revealed to have relationships with reading ability when corrected (Supplemental Fig. S2−3). Additionally, when correcting for age given that even our oldest age group spanned seven years and included developing individuals (Jerningan et al., 2011), our main findings did not change. These inconsistencies from prior adult studies might be due to differences in sample size and measurement methods. For instance, the sample sizes of these four adult studies were 60, 39, 28, and 32 participants, while the sample size of our oldest age group alone had 92 participants. Also, these previous studies used whole-brain approaches, whereas we focused on *a-priori* ROIs in our primary analyses. Our findings underscore the importance of future research focused on understanding how the experience with word form processing and phonological decoding contributes to the anatomical relationships between cortical thickness and reading outcome in adults, preferentially using longitudinal designs.

4.6. Cortical thickness, but not surface area, is associated with reading ability

While we observed relationships between cortical thickness and reading, it must be noted that these were constrained to just a few of the candidate ROIs, and prior studies on cortical thickness have also reported only a few findings. Two studies reported no correlations (Frye et al., 2010; Goldman and Manis, 2013), while two others observed relationships between cortical thickness and reading ability in the left IPS, bilateral AG, and bilateral STG (Blackmon et al., 2010), as well as the right STG, precentral, and lateral occipital cortices (Johns et al., 2017). Turning to children and adolescents, we had no findings of a relationship between cortical thickness and reading, while Purdue and colleagues, the only prior study in children, found a relationship between cortical thickness with reading in the left superior temporal cortex (Perdue et al., 2020). Cortical thickness is a measure theorized to reflect multiple neuronal mechanisms that may be affected by experience throughout development (Shaw et al., 2008; Zatorre et al., 2012; Natu et al., 2019). Thus, one can only speculate that neurogenesis, synaptogenesis, or other changes in neuronal morphology are the mechanisms that underlie our observations and those previously reported, especially in emerging adults. Our findings, together with prior reports in children and adults illustrate an emerging picture (which needs to be facilitated by longitudinal studies) of how cortical thickness in some left hemisphere regions is associated with better reading ability in adults.

We observed no relationships between academic skills (reading and math) with surface area. Surface area is thought to be influenced by genetic mechanisms that occur early in neurodevelopment (Tramo et al., 1995; Panizzon et al., 2009; Wierenga et al., 2014), and since some of this occurs even before birth (Kapellou et al., 2006), the absence of any relationship between surface area and learned academic skills is reasonable. Learning-induced relationships between brain anatomy and reading (or math) skills may be more likely observed for other anatomical measures, as illustrated by our findings for cortical thickness.

4.7. Roles of sex and SES on brain-behavior relationships with academic skills

While not the main question(s) of our study, understanding the associations between brain anatomy and academic skills in developmental samples requires consideration of sex and SES. First, while our present study did not find sex to contribute to relationships between measures of surface-based anatomy with reading, we have previously shown that correlations between gray matter volume and reading ability (namely in left superior temporal gyrus and fusiform gyrus) are sex-specific (Torre and Eden, 2019). While some studies have reported sex differences in brain activation during reading tasks (e.g. Burman et al., 2008) as well as a role of sex in gray matter volume differences in dyslexia, a reading disability (Evans et al., 2013), the extent to which sex plays a role in reading acquisition or brain-behavioral relationships with reading is unclear (see Etchell et al., 2018 for review). We also did not find sex to contribute to relationships between cortical thickness or surface area with calculation, which aligns with prior research that has found little or no evidence for sex differences in basic numerical or mathematical processing (Kersey et al., 2018; Spelke, 2005). Further, boys and girls have been shown to have equivalent math-related neural responses, suggesting that no biological sex differences exist in mathematical processing (Kersey et al., 2018). Second, SES is a significant predictor of not only neuroanatomy (see Brito and Noble, 2014 for review) but also reading (Peterson & Pennington, 2015; Reardon, 2011) and math abilities (Elliott and Bachman, 2018), and the SES gap in reading and math achievement persists across development. Our present work did not identify SES as a significant factor in the observed relationships between cortical thickness and reading ability, nor did our prior study on gray matter volume (Torre and Eden, 2019). However, recent work has shown that SES contributes to cortical thickening in response to reading intervention in children with reading disability (Romeo et al., 2017), and numerous studies have demonstrated a role of SES in brain activity during language tasks, some of which are related to reading skills (see Farah, 2017 for review). Similarly, the neural correlates of arithmetic differ depending on parental SES (Demir-Lira et al., 2016; Demir et al., 2015). Our lack of any brain-behavioral relationships for math provided little opportunity to probe the role of SES, but ultimately, this measure had no observable impact on any of our findings, even those related to reading.

5. Conclusions

Our study found that there are positive linear correlations between cortical thickness of the left SMG and FG with reading ability in older adolescents and emerging adults but not children or younger adolescents. We also found that reading ability and the interaction between reading ability with age contributed unique variance to cortical thickness in the left SMG and IPS. However, there were no associations between cortical thickness and math skills, and therefore, no anatomical overlap for associations with both reading and math, as we had predicted. No relationships with reading or math were observed for surface area. These findings provide a comprehensive picture of the few regions where brain-behavior relationships exist with reading in emerging adults and, critically, the absence of any such relationship between math and brain anatomy.

Declaration of Competing Interest

The content of this study is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Mental Health or National Institutes of Health. Data employed in the preparation of this article were obtained from the Pediatric MRI Data Repository created by the NIH MRI Study of Normal Brain Development, Release #5. These data derive from a multi-site, longitudinal study of typically developing children, from ages newborn through young adulthood conducted by the Brain Development Cooperative Group and supported by the National Institute of Child Health and Human Development, the National Institute on Drug Abuse, the National Institute of Mental Health, and the National Institute of Neurological Disorders and Stroke (Contract #s: N01-HD02-3343, N01-MH0-0002, and N01-NS-9-2314, -2315, -2316, -2317, -2319, and -2320). A listing of the participating sites and a complete listen of the study investigators can be found at http://www.bic.mni.mcgill.ca/nihpd/info/participating_centers.html. GE, AAM, and GAT are supported by the Eunice Kennedy Shriver National Institute of Child Health and Human Development (R01 HD081078). We thank Natalie Smith, Lu Collina, Margaret McDermott, Lailah Fritz, Nichole Schlosberg, Cambria Revsine, and Lucy Core for their help in preparing the data. Declarations of interest: none.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.dcn.2020.100856.

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