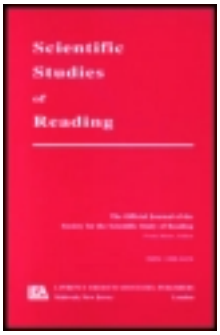


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# Relationships Among Cortical Thickness, Reading Skill, and Print Exposure in Adults

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This study investigated relationships among cortical thickness in the left-hemisphere reading network, and reading skill and experience in adult nonimpaired readers. Given the relationship between print exposure and reading, it is possible that print exposure is related to cortical structure. The pattern of correlations indicated that individuals with higher print exposure had better reading skills and thicker cortices. Furthermore, print exposure accounted for unique variance in cortical thickness in part of the left-hemisphere reading network after accounting for reading skill. This suggests that some of the variation in cortical thickness in adults might be attributable to reading experience, independently of reading skill.

Developmental scientists and reading theorists are interested in how brain development is related to the development of skilled behavior such as reading. Recent studies have shown that brain activation in dyslexic children can be influenced by reading instruction (e.g., B. A. Shaywitz et al., 2004). However, the impact of experience on brain structure is less well understood. Cortical development has been shown to be related to age (Sowell et al., 2004), and in theory, it should reflect experience-dependent learning as well as genetic/maturational processes. For example, changes in cortical thickness are associated with reading subskills such as phonological processing (Lu et al., 2007). Phonological processing, along with other aspects of reading, such as orthographic processing, is related to print exposure (Stanovich & Cunningham, 1992). In this study, we examine how reading skill and experience (print exposure) are associated with cortical thickness in several brain regions connected to reading.

## RELATIONSHIP BETWEEN READING EXPERIENCE AND READING SKILL

It is difficult to quantify reading experience, but there is an extensive literature on exposure to print. This environmental variable has been shown to be related to the cognitive processes underlying reading skill. Large differences in reading practice emerge as early as the first grade (Biemiller, 1977–1978), about the same time as differences in reading ability emerge. The

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relationship between reading ability and reading experience is likely bidirectional. Some children may experience lower exposure to printed materials because of lack of support and access to reading materials in their environment. However, children who experience greater difficulty with phonological awareness and decoding tend to be exposed to less text than their peers even when provided equal access (Share, 1995). Furthermore, poor readers often find themselves reading materials that are too difficult for them. Thus, the combination of lack of practice, deficient decoding skills, and overly difficult materials may place some children in unrewarding situations, resulting in fewer reading-related activities in childhood (Stanovich, 1986).

Subsequent studies have confirmed that print exposure is related to reading skill (e.g. Cunningham & Stanovich, 1997; Stanovich & Cunningham, 1992). Two questionnaires (the Author Recognition Task and Magazine Recognition Task), combined to form a composite print exposure variable, were correlated moderately with a variety of verbal and reading-related tasks (Stanovich & Cunningham, 1992). Supporting evidence is provided by studies showing that leisure-time reading contributes significantly to orthographic processing skill after partialling out phonological-processing skill (Braten, Lie, Andreassen, & Olaussen, 1999) and that print exposure accounts for independent variance in judgments about correctness of word spelling (i.e., orthographic structure) after controlling for variability in phonological decoding skill (McBride-Chang, Manis, Seidenberg, Custodio, & Doi, 1993).

## RELATIONSHIPS BETWEEN CORTICAL THICKNESS AND READING SKILL

Grey matter thickening is probably related to the formation of new connections between neurons, or to an increase in the physical extent (e.g., dendritic arbor) of existing neurons. Increased myelination of axons that lie within the grey matter could also result in apparent thickening. Grey matter thinning, on the other hand, may be related to synaptic pruning (the elimination of neuronal connections), or to an increase in myelination in the underlying white matter, resulting in compression of grey matter between the growing white matter and the skull. Grey matter thinning is likely caused by both of these processes (Lu et al., 2007; Sowell et al., 2004).

One of the few longitudinal studies (Sowell et al., 2004) of cortical thickness in normal development showed a general pattern of grey matter thinning, with two notable exceptions. Grey matter thickening was seen in the left inferior frontal gyrus (IFG; Brodmann Area [BA] 44/45) and in bilateral superior temporal gyrus (STG; BA 22), in children between ages 5 and 11. Lu et al. (2007), in turn, found that cortical thickness in the IFG was positively correlated with improvements in phonological processing ability in a sample of nonimpaired children. This relationship was not due to general maturation, because the thickness change in the region did not correlate with another behavioral measure that also improved with age—manual motor skills. In fact, the increase in motor skills correlated with grey matter thinning in a separate cortical region in the motor strip, providing a double dissociation. It was proposed that the segment of the developmental trajectory captured by this study showed grey matter thinning as a result of motor skill consolidation and grey matter thickening in phonological regions as a result of reading skill acquisition.

Lu et al.'s (2007) findings suggest that variation in cortical thickness need not strictly be the result of chronological maturation but could be driven by experience-dependent learning. When

compared with other skills such as motor coordination, reading skills begin to be acquired significantly later in life. It is therefore not surprising to find increased cortical thickness in regions primarily associated with reading subskills, whereas much of the rest of the cortex is thinning. The association of cortical thickness variation with environmental or experiential change is consistent with developmental data on brain maturation (e.g., Giedd et al., 1999).

## NEURAL BASIS FOR READING SKILL

Other than the Lu et al. (2007) study, there is scant research investigating associations between brain structure and reading in normally developing individuals. However, research on dyslexia provides possibly relevant findings. Some studies have indicated that dyslexia represents the lowest end of a continuum of reading skill (e.g., S. E. Shaywitz, Escobar, Shaywitz, Fletcher, & Makuch, 1992). If this is indeed the case, then the brain regions that have been identified as functionally or structurally abnormal in dyslexia should also be important for skilled reading.

A number of studies have found different cortical structure in dyslexic readers than normally progressing readers, primarily in the posterior section of the reading network. Smaller grey matter volume in dyslexic readers has been found in the left angular gyrus (AG), supramarginal gyrus (SMG), precentral and insular cortices (Hoeft et al., 2007), in the inferior (Vinckenbosch, Robichon, & Eliez, 2005) and middle temporal gyri (Silani et al., 2005; Vinckenbosch et al., 2005), in bilateral IFG (W. E. Brown et al., 2001), and bilateral occipito-temporal cortex (OT; Kronbichler et al., 2008). Two studies found smaller STG volume for dyslexic (W. E. Brown et al., 2001; Hoeft et al., 2007), though another found greater volume in the same region (Vinckenbosch et al., 2005). Kronbichler et al. (2008) found greater grey matter volume in dyslexic adolescents in the left superior temporal sulcus as well. The dyslexia studies provide clues as to brain areas where structural relationships might be found with print exposure or aspects of reading skill.

## THE CURRENT STUDY

The first aim of this study was to investigate links between individual differences in reading skill and cortical thickness in several regions within the reading network in an adult sample of nonimpaired readers. The second aim was to replicate prior research demonstrating that print exposure was positively correlated with verbal and reading skills and to extend those relationships to the neurobiological measurement of cortical thickness.

Using previous research as a guide, our regions of interest included the following, which together comprise the left-hemisphere reading network: (a) OT/BA 37 (e.g., Cohen et al., 2000; Cohen et al., 2002), which includes the functionally defined "visual word form" area on the fusiform gyrus and surrounding tissue; (b) IFG/BA 44-45 (e.g., B. A. Shaywitz, Lyon, & Shaywitz, 2006); (c) STG/BA 22 (e.g., Joseph, Noble, & Eden, 2001); (d) AG/BA 39 (e.g., Pugh et al., 2000); and (e) SMG/BA 40 (e.g., Kronbichler et al., 2006).

Because the adults in our sample are older and more experienced in reading than the children of the Lu et al. (2007) study, it is difficult to make predictions. One possibility is that there would

be a negative correlation between reading skill and cortical thickness in cortical regions of interest related to reading. This might occur because by adulthood, cortical thickness measurements would show evidence for reading skill consolidation, much like the pattern obtained for manual motor skills in childhood. An alternative hypothesis, consistent with the thickening observed by Lu et al. (2007) in peri-Sylvian areas, is that reading skills are so complex that the neural structures involved in reading do not enter a thinning phase by early adulthood, as other neural structures (e.g., motor cortex) do, but instead increase in thickness as the individual gains skill and experience in reading.



## METHODS

### Participants

Participants included 28 adult college students (19 female, 9 male) of varying reading skill, with average to above-average verbal and nonverbal IQ scores as assessed by the Woodcock−Johnson III Tests of Cognitive Abilities (WJ−III; Woodcock, McGrew, & Mather, 2001). All participants were classified as nonimpaired readers, by scoring at or above the 40th percentile on either Word Identification or Word Attack subtests of the WJ−III Tests of Achievement (see Table 1 for

TABLE 1
Descriptive Statistics

| | M | SD | *Range* |
|---|---|---|---|
| STG (BA22) | 2.95 | .42 | 1.69−3.65 |
| OT (BA37) | 2.46 | .48 | 1.42−3.24 |
| AG (BA39) | 3.05 | .50 | 1.60−3.67 |
| SMG (BA40) | 2.87 | .55 | 1.50−3.75 |
| IFG oper. (BA44) | 3.13 | .45 | 1.88−3.93 |
| IFG triang. (BA45) | 3.18 | .48 | 1.92−4.04 |
| Word ID | 107.64 | 8.59 | 95.00−124.00 |
| Word Attack | 100.25 | 10.30 | 78.00−117.00 |
| Comprehension | 234.86 | 16.07 | 185.00−251.00 |
| TOWRE-SWE | 104.27 | 10.34 | 76.00−114.00 |
| TOWRE-PDE | 97.21 | 9.12 | 78.00−110.50 |
| Verbal IQ | 106.25 | 8.04 | 93.00−121.00 |
| Spatial Relations | 113.75 | 9.25 | 100.00−133.00 |
| Title Recognition | .11 | .93 | −1.76−1.96 |
| Author Recognition | .10 | .93 | −1.58−1.62 |
| Magazine Recognition | −.01 | .79 | −2.74−1.22 |

*Note.* All cortical thickness measurements are in millimeters, rounded to the nearest hundredth. Word ID, Word Attack, Nelson-Denny Comprehension, Test of Word Reading Efficiency–Sight Word Efficiency subtest (TOWRE-SWE), TOWRE–Phonological Decoding Efficiency subtest (TOWRE-PDE), Verbal IQ, and Spatial Relations are all standardized scores. Title Recognition, Author Recognition, and Magazine Recognition Tests are all $z$ scores. STG = superior temporal gyrus; BA = Brodmann Area; OT = occipito-temporal cortex; AG = angular gyrus; SMG = supramarginal gyrus; IFG = inferior frontal gyrus; oper. = opercularis; triang. = triangularis.

standard scores). Average age was 20 years and ranged from 18.58 to 24.58 years. All participants were strongly right handed, as assessed by the Edinburgh Handedness Questionnaire (Oldfield, 1971); had normal or corrected-to-normal vision; were native monolingual English speakers; and, according to self-report, had no history of neurobiological abnormalities. In addition, all participants filled out a brief demographic background questionnaire. All participants also passed MRI safety screening and gave written consent.

## Behavioral Measures

The Verbal Comprehension and Spatial Relations subtests of the WJ−III Tests of Cognitive Ability and the Word Identification, Word Attack, and Spelling subtests of the WJ−III Tests of Achievement were administered. The Nelson-Denny Reading Test (J. Brown, Fishco, & Hanna, 1993) provided an assessment of ability in reading comprehension and reading rate. The Test of Word Reading Efficiency (TOWRE; Torgesen, Wagner, & Rashotte, 1999) was administered. The TOWRE comprises two subtests. The Sight Word Efficiency subtest (TOWRE-SWE) assesses the number of real printed words that can be accurately read aloud within 45 s. The Phonological Decoding Efficiency subtest (TOWRE-PDE) similarly assesses the number of pronounceable printed pseudowords that can be accurately decoded in 45 s. The emphasis for both tasks is on accurate reading with speed. Two lists of each type were given.

## Print Exposure Measures

Three print exposure tests were developed and modeled after the tests designed by Stanovich and Cunningham (1992). Each recognition test was scored by subtracting the proportion of foil items incorrectly checked from the proportion of genuine items correctly checked.

The Author Recognition Test (ART) was a checklist in which subjects indicate that they are familiar with the name of a particular popular author or writer by putting a check mark next to his or her name. The version used in this study included 40 authors mixed with 15 foils—names that are not known to be authors or writers. The 55 items were listed in alphabetical order, and there was no time limit to the test. Although the measure was based on the one used by Stanovich and Cunningham (1992), it had all new authors chosen from national best-seller lists and from books nominated as favorites by adults ages 18 to 35 in an Internet survey conducted for the present study.

The design and structure of the Title Recognition Test (TRT) was parallel to the ART, but it utilized book titles instead of authors. The checklist comprised 40 targets mixed with 15 foils, listed alphabetically. Similar to the ART, these titles were selected from the national best-seller lists and the Internet survey responses.

The Magazine Recognition Test (MRT) had a structure similar to the ART and TRT but was designed to tap into a different type of extracurricular reading. Because the ART and TRT were biased toward books, the MRT allowed for those who prefer magazine reading. This checklist comprised 60 target items and 50 foils, listed alphabetically. The list was dominated by popular magazines, rather than scholarly or academic publications. All items were chosen from lists of magazines nominated as favorites by adults ages 18 to 35 in an Internet survey.

## MRI Acquisition

Images were acquired with a Siemens MAGNETOM Trio 3-Tesla MRI unit (Siemens Medical Solutions, Malvern, PA) using a CP head coil. Earplugs and sound-dampening headphones were employed to shield the participants from acoustic noise, and foam padding was used to minimize head movement. High-resolution structural images were acquired via a T1-weighted MPRAGE sequence (TR = 2530 ms, TE = 3.09 ms, TI = 800 ms, FoV = 256 mm × 256 mm, Matrix = 256 × 256, 208 sagittal slices, slice thickness = 1 mm). This design allowed for the capture of a whole brain image (including cerebellum) with no gaps, and 1-$mm^3$ isotropic voxels. Images were subjected to online 3D PACE motion correction during acquisition.

## MRI Processing

Brainvoyager QX 1.10.3 (Brain Innovation, Maastricht, the Netherlands) was used to process the data. Each data set was corrected for inhomogeneity and then normalized into standard stereotaxic space (Talairach & Tournoux, 1988). Following preprocessing, each image underwent a user-guided advanced segmentation procedure, which labels each voxel as white matter, grey matter, or nonbrain tissue. It should be noted that the segmentation procedures, and therefore the MRI measurements of cortical thickness, are based on differences in signal intensity between grey and white matter. Therefore, anything that could change the relative signal intensities could cause apparent increases or decreases in cortical thickness measurements.

The process by which each image is normalized into Talairach space is somewhat crude, as the dimensions of the image are distorted to fit standardized measurements. Therefore, any single Talairach coordinate may represent two different anatomical structures on two different images. To improve the spatial correspondence mapping between participants' brains, a cortex-based intersubject alignment procedure was executed, in which reconstructed cortices are aligned using curvature information reflecting the gyral and sulcal folding patterns. It has been shown that a cortical matching approach improves statistical analyses across subjects by reducing anatomical variability (Fischl, Sereno, Tootell, & Dale, 1999).

The alignment proceeds iteratively following a coarse-to-fine matching strategy, which starts with highly smoothed curvature maps and progresses to only slightly smoothed maps. Starting with the coarse alignment provided by Talairach normalization, this method ensures that the smoothed curvature maps of the individual participants will have enough overlap for the procedure to converge without user intervention (Goebel, Hasson, Lefi, & Malach, 2004; Goebel, Staedtler, Munk, & Muckli, 2002). Visual inspections as well as a measure of the average mean squared curvature difference have revealed that this procedure reliably achieved alignment of major gyri and sulci (BVQX Documentation, Brain Innovation, Maastricht, the Netherlands).

This analysis used the explicit target approach in performing the intersubject cortex-based alignment. One representative image, on which all regions of interest were predefined, was selected as a target to which all other images were subsequently aligned. This procedure is done separately for right and left hemispheres. Following intersubject alignment procedures, cortical thickness measurements were extracted for each region of interest. Cortical thickness varies substantially across space and a simple orthogonal measurement technique may lead to erroneous thickness estimates. To avoid these problems, the cortical thickness measurements in

Brainvoyager are based on the Laplace method (Jones, Buchbinder, & Aharon, 2000, for additional implementations of this method, see, e.g., Davis et al., 2008; Geuze et al., 2008). High levels of correspondence have been shown between cortical thickness maps derived from structural MRI and those of postmortem studies conducted more than 80 years ago (Sowell et al., 2004; Von Economo, 1929), which lends confidence in the validity of MRI measurements of cortical thickness.

Statistical analysis was conducted using SPSS 17.0. First, all three print exposure measurements were converted to $z$ scores. Pearson correlations indicated that the ART and TRT were significantly positively correlated (.518, $p = .005$). The MRT did not significantly correlate with the ART (.260, $p = .182$) or TRT (.181, $p = .358$). However, a factor analysis revealed that all three measurements loaded on the same factor, which allowed us to combine them into a single print exposure composite variable. Pearson correlations were obtained for all variable pairs, and then regression analyses were conducted for each set of variables (comprising one cortical thickness measurement and one reading skill measure) that correlated with each other as well as with the composite print exposure variable.

## RESULTS

Cortical thickness measurements were extracted from six regions of interest within the left-hemisphere reading network: STG (BA22); OT (BA37); AG (BA39); SMG (BA40); IFG, pars opercularis (BA44); and IFG, pars triangularis (BA45; see Figure 1). Table 1 presents the descriptive statistics for reading skill and print exposure variables and cortical thickness measurements. As can be seen in Table 1, the measurements of cortical thickness in this study are consistent with previous data on cortical thickness (e.g., Sowell et al., 2004).

Pearson correlation coefficients (Table 2) were obtained to analyze the associations between the reading skill variables, print exposure composite score, and cortical thickness measurements. Measures of general cognitive ability were given primarily for sample description and were

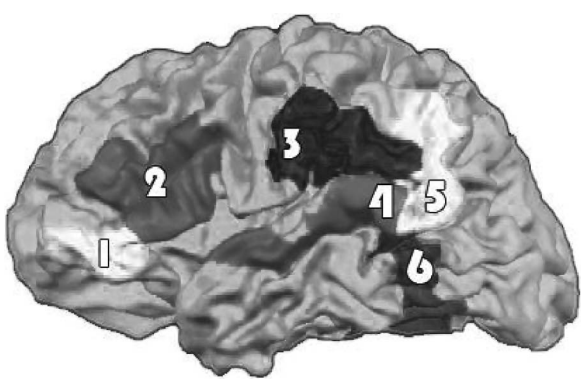


FIGURE 1 Regions of interest, displayed on an individual subject's reconstructed left hemisphere (1, BA45. 2, BA44. 3, BA39. 4, BA22. 5, BA40. 6, BA37).

TABLE 2
Correlation Matrix—Regions of Interest, Control Regions, Measures of Reading Skill, and Print Exposure

| | | *Regions of Interest* | | | | | | *Control Regions* | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Print Exp. Composite* | *STG (BA22)* | *OT (BA37)* | *AG (BA39)* | *SMG (BA40)* | *IFG oper. (BA44)* | *IFG triang. (BA45)* | *Inter-mediate Post-central (BA1)* | *Caudal Post-central (BA2)* | *Rostral Post-central (BA3)* | *Inferior Temporal (BA20)* | *Middle Temporal (BA21)* | *Orbito-Frontal (BA47)* |
| Word ID | .592** | .263 | .250 | .284 | .272 | .174 | −.040 | −.001 | .117 | .219 | .244 | .238 | −.058 |
| Word Attack | .467* | .032 | .254 | .186 | .113 | .014 | −.141 | −.177 | −.024 | .017 | .115 | .022 | −.137 |
| Comprehension | .547** | .222 | .250 | .397* | .230 | .333 | .412* | .171 | .002 | .358 | .226 | .149 | .203 |
| TOWRE-SWE | .415* | .325 | .230 | .367 | .207 | .149 | .206 | .239 | .342 | .221 | .265 | .140 | .129 |
| TOWRE-PDE | .322 | .109 | .181 | .177 | .090 | −.124 | −.093 | .024 | .190 | .230 | .120 | −.086 | −.112 |
| Pleasure Reading | .552** | .262 | .253 | .417* | .452* | .293 | .276 | −.050 | −.005 | .392* | −.016 | .222 | .163 |
| Print Exp. Composite | — | .318 | .419* | .509** | .448* | .485** | .400* | .072 | .029 | .272 | .263 | .332 | .249 |
| STG (BA22) | .318 | — | .557** | .794** | .801** | .455* | .494** | .374* | .283 | .273 | .672** | .753** | .501** |
| OT (BA37) | .419* | .557** | — | .661** | .678** | .521** | .581** | .302 | .134 | .340 | .761** | .592** | .668** |
| AG (BA39) | .509** | .794** | .661** | — | .882** | .634** | .712** | .477* | .220 | .393* | .695** | .695** | .706** |
| SMG (BA40) | .448* | .801** | .678** | .882** | — | .621** | .648** | .406* | .304 | .483** | .725** | .709** | .731** |
| IFG oper. (BA44) | .485** | .455* | .521** | .634** | .621** | — | .789** | .519** | .141 | .537** | .613** | .630** | .746** |
| IFG triang. (BA45) | .400* | .494** | .581** | .712** | .648** | .789** | — | .551** | .092 | .482** | .592** | .527** | .851** |

*Note.* STG = superior temporal gyrus; BA = Brodmann Area; OT = occipito-temporal cortex; AG = angular gyrus; SMG = supramarginal gyrus; IFG = inferior frontal gyrus; oper. = opercularis; triang. = triangularis; TOWRE–SWE = Test of Word Reading Efficiency–Sight Word Efficiency subtest; PDE = Phonological Decoding Efficiency subtest; exp. = exposure.

*Correlation is significant at the .05 level (two-tailed). **Correlation is significant at the .01 level (two-tailed).

omitted from these analyses to avoid increasing the experiment-wise Type I error rate for correlations. Reading comprehension correlated with cortical thickness in AG and in IFG triangularis. The correlation between phonological skill (as measured here by Word Attack and TOWRE-PDE) and IFG and STG thickness that was reported for children by Lu et al. (2007) did not hold for the adults in this study.

The print exposure composite variable was moderately correlated with reading skill. Both measures of word reading—Word Identification and TOWRE-SWE—correlated with print exposure, as did Word Attack and comprehension. Given the prior evidence that print exposure is associated with verbal skills, comprehension, and orthographic processing (e.g., Cunningham & Stanovich, 1997; McBride-Chang et al., 1993; Stanovich & Cunningham, 1992), these results are not surprising.

Print exposure was the most consistent correlate of cortical thickness throughout the left-hemisphere reading network, having significant correlations with five of the six regions of interest: OT, AG, SMG, IFG opercularis, and IFG triangularis. The pattern of correlations indicates that individuals with more print exposure had thicker cortices within the left-hemisphere reading network. Converging evidence for the relationship between reading experience and cortical thickness comes from the "pleasure reading" item on the background questionnaire. The question was, "How often in the last four weeks did you read for pleasure at least 30 minutes?" There are six possible responses ranging from *very rarely* to *once a day or more*. Responses on this question correlated with cortical thickness in AG and SMG, as well as with the composite print exposure variable.

To ensure that there was not a global effect of print exposure on cortical thickness, we investigated six additional left-hemisphere regions that neighbor our primary regions of interest but have not been implicated in studies of reading skill and dyslexia: BA1, BA2, BA3 (which combine to form the postcentral gyrus), BA20 (inferior temporal gyrus), BA21 (middle temporal gyrus), and BA47 (orbital frontal region). Cortical thickness in these six regions did not have significant correlations with the print exposure variable or with any of the reading skill measurements (see Table 2).

The next issue we addressed was whether print exposure and reading skill are completely overlapping or account for somewhat distinct aspects of variability in cortical thickness. There were only two regions of interest, AG and IFG triangularis, that had significant correlations with print exposure and one reading variable, reading comprehension (see Figure 2 for scatterplots). When comprehension and print exposure were entered into a simultaneous regression predicting cortical thickness in IFG triangularis, both variables were reduced to nonsignificance (see Table 3). For a regression predicting AG thickness, print exposure remained a significant predictor of cortical thickness ($p = .050$). Based on this, it is reasonable to infer that the Nelson-Denny reading comprehension test and our measurements of print exposure share common variance in their relationship with cortical thickness. The finding in one case (AG) of unique variance accounted for by print exposure indicates that print exposure is not simply a proxy for reading comprehension skill.

## DISCUSSION

The overall correlation pattern showed that adult readers with more print exposure were better readers and had thicker cortices within the left-hemisphere reading network. Print exposure was

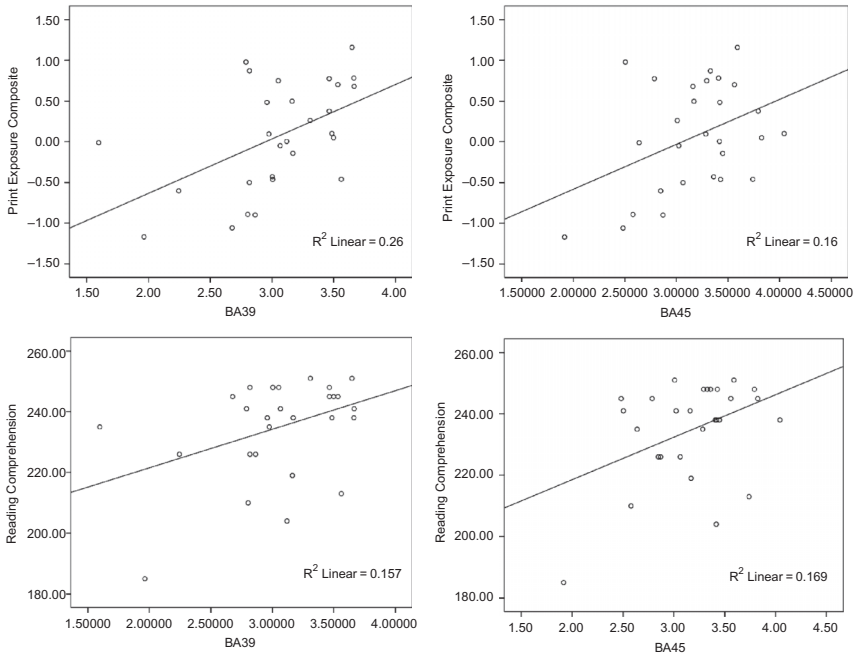


FIGURE 2 Scatterplots for print exposure, reading comprehension, angular gyrus, and inferior frontal gyrus triangularis.

TABLE 3
Predictors of Cortical Thickness in Angular Gyrus (AG) and Inferior Frontal Gyrus (IFG) Triangularis

| | *AG (BA39)* | | *IFG Triangularis (BA45)* | |
|---|---|---|---|---|
| *Variable* | B | *95% CI* | B | *95% CI* |
| Constant | 1.791 | [–1.27, 4.85] | 1.245 | [–1.80, 4.29] |
| Print exposure | .318* | [0.00, 0.64] | .181 | [–0.01, 0.02] |
| Reading comprehension | .005 | [–0.10, 0.02] | .008 | [–0.14, 0.50] |
| $R^2$ | .279 | | .462 | |
| $F$ | 4.847* | | 3.390 | |

*Note.* BA = Brodmann Area; CI = confidence interval.
$^*p \leq .05$.

the most consistent correlate of cortical thickness throughout the left-hemisphere reading network. In addition, print exposure accounted for unique variance in cortical thickness beyond the variation predicted by reading skill. To our knowledge this is the first study to investigate the relationship between reading experience and cortical structure.

The correlation between phonological processing and IFG thickness that has previously been reported in child samples (Lu et al., 2007) was not found for the adults in this study. The measures

of phonological processing used in this study, Word Attack and TOWRE-PDE, mainly measure decoding skill. It is possible that the measures of phonological processing used by Lu et al. (2007) tap into some other phonological subskill. It is more likely, however, that this relationship does not persist into adulthood; older skilled readers may rely less on phonological decoding when they are reading than do younger readers. Findings consistent with this explanation are provided by a 5-year longitudinal study showing that as children developed into skilled readers, the proportion of the variance of overall reading skill accounted for by phonological variables declined (Wagner et al., 1997).

We proposed two alternative hypotheses for the relationships between reading skill, reading experience, and cortical thickness in adulthood. First, there might be a negative correlation between reading skill and cortical thickness and between reading experience and cortical thickness, as by adulthood the cortical regions involved in reading would have become thinner in a skill consolidation phase. Alternatively, there could be a positive correlation between reading skill and cortical thickness (and a positive correlation between reading experience and cortical thickness). The data indicate that more reading experience and higher reading skill is associated with increased cortical thickness. This is potentially the most interesting finding in the study.

It may be that reading is so complex that it never enters the skill consolidation phase. Instead of at first building up neural connections and subsequently pruning out the unnecessary ones, perhaps the new connections being formed continue to outnumber the older ones that are removed throughout development and into adulthood. This would suggest that reading skill, reading experience, and cortical thickness would be positively correlated from childhood through adulthood. The finding may also mean that the trajectory of reading-related cortical development beyond childhood that was tentatively proposed by Lu et al. (2007) might not hold, but longitudinal data are needed to test this possibility more directly.

Other evidence indicates that dyslexic readers may have lower cortical density and volume in various regions of the reading network (e.g., W. E. Brown et al., 2001; Hoeft et al., 2007; Kronbichler et al., 2007; Silani et al., 2005; Vinckenbosch et al., 2005). This finding appears to be consistent with our finding that reading skill and cortical thickness are positively correlated. However, without longitudinal data obtained over the entire period of reading acquisition, it is difficult to know which of several possible growth patterns occur. For example, future skilled and less skilled readers might have the same cortical thickness at age 5, but through increased opportunities to read, or other developmental factors, skilled readers end up with a thicker cortex at age 20. In contrast, better readers might have a thicker cortex at age 5, and both groups might show the Lu et al. (2007) pattern of reductions in cortical thickness between age 5 and 20. However, at age 20, there might still be an advantage in cortical thickness for better readers. A third possibility is that better readers have a thicker cortex at age 5 and the gap increases between age 5 and 20.

Recently, longitudinal data have hinted at the dynamic nature of the relationship between cortical thickness and stable, heritable traits such as intelligence (Shaw et al., 2006). In particular, the data indicate that it is the developmental trajectory of cortical thickness, rather than cortical thickness itself, that is correlated with intelligence. A related study found that in late adolescents, there are significant genetic contributions to cortical thickness in several regions, including superior parietal and inferior occipital cortices (Lenroot et al., 2009). It is particularly interesting that these regions coincide with several of the regions of interest from this study, in which we found a significant association with print exposure, an environmental variable. More research is

necessary to tease apart the relative genetic and environmental contributions to cortical thickness in the reading network, as reading is a skill that by definition requires experience to develop.

This was the first study to examine the relationship between print exposure, an environmental variable, and cortical thickness, a neurobiological variable. That there are massive differences in print exposure seems clear. As early as elementary school, children begin to diverge in reading experience with a continually expanding gap between skilled and poor readers (Stanovich, 1986). In a typical late-elementary school classroom, children in an average reading group may be exposed to reading materials containing as many as 10 times more words during the academic year than children in a low reading group. Children in a high reading group may read an additional 10 times more words than even those in an average reading group, making the discrepancy between words encountered in a single year by the poorest readers and the most skilled readers as much as 100 times, or two orders of magnitude (Nagy & Anderson, 1984). Further, students in the highest groups are more likely to engage in extracurricular reading, making the gap bigger still (Allen, Cipielewski, & Stanovich, 1992).

The study of Colombian guerrillas (Carreiras et al., 2009) reflects the critical importance of reading experience for reading skill and brain development. Compared with illiterates, these late-literate adults showed increases in grey matter as a result of reading instruction, throughout much of the left-hemisphere reading network, including the supramarginal (BA40) and superior temporal (BA22) gyri, as well as the angular (BA39) gyri bilaterally.

In conclusion, the study indicates that variation in cortical thickness is related to both reading skill and print exposure in adult skilled readers and that some part of the variation in cortical thickness in adults might be attributable to reading experience, independently of reading skill. Next steps in the research are to compare people with and without serious reading difficulties and to obtain cross-sectional and longitudinal data on children to tease apart the relative contributions of experience and reading ability to brain development.

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