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Socioeconomic Disparities in Language Input Are Associated With Children's Language-Related Brain Structure and Reading Skills

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The mechanisms underlying socioeconomic disparities in children's reading skills are not well understood. This study examined associations among socioeconomic background, home linguistic input, brain structure, and reading skills in 5-to-9-year-old children (N = 94). Naturalistic home audio recordings and high-resolution, T1-weighted MRI scans were acquired. Children who experienced more adult–child conversational turns or adult words had greater left perisylvian cortical surface area. Language input mediated the association between parental education and left perisylvian cortical surface area. Language input was indirectly associated with children's reading skills via left perisylvian surface area. Left perisylvian surface area mediated the association between parental education and children's reading skills. Language experience may thus partially explain socioeconomic disparities in language-supporting brain structure and in turn reading skills.

Socioeconomic disparities in children's language and literacy skills are well-documented, persistent, emerge early and widen over time (Pace, Luo, Hirsh-Pasek, & Golinkoff, 2017; Schwab & Lew-Williams, 2016). Socioeconomic factors, such as family income and parental education, are distal factors that likely exert their effects on development via proximal environmental factors, which in turn impact the brain in ways that explain observable cognitive performance. In line with this theoretical framework, recent work has linked socioeconomic background with differences in the structure and function of language-supporting cortical regions in children (Noble et al., 2015; Raizada, Richards, Meltzoff, & Kuhl, 2008). However, the underlying experiential and neural mechanisms through which socioeconomic background influences children's language and literacy outcomes have yet to be fully elucidated. An important next step to build on this emerging literature requires an examination of links among socioeconomic factors, language input and children's brain structure.

Linguistic input in the home represents a key mechanism through which socioeconomic factors may impact children's language-related brain structure, and in turn, reading outcomes. Higher socioeconomic status (SES) has been associated with higher quantity and quality of language input (Pace et al., 2017), which in turn predicts stronger language and reading skills in children (Bingham, 2007; Dickinson & Porche, 2011; Dieterich, Assel, Swank, Smith, & Landry, 2006; Hart & Risley, 1995; Hoff & Naigles, 2002; Hurtado, Marchman, & Fernald, 2008; Huttenlocher, Haight, Bryk, Seltzer, & Lyons, 1991; Rowe, 2012; Weisleder & Fernald, 2013). However, very little is known about the

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relations between children's language experiences and their brain structure. The goals of this study were to investigate associations between home linguistic input and children's brain structure, and to examine the role of these associations in explaining socioeconomic disparities in children's reading skills.

Theoretical Mechanisms Underlying Socioeconomic Disparities in Reading

Language and reading development are intimately linked, with language development in early through middle childhood among the strongest predictors of later reading skills (Dickinson, McCabe, Anastasopoulos, Peisner-Feinberg, & Poe, 2003; Muter, Hulme, Snowling, & Stevenson, 2004; NICHD Early Child Care Research Network, 2005; Storch & Whitehurst, 2002). In concert with genetic influences, language development and reading skills are theorized to result from a nested set of social contexts in which the child is embedded (Bronfenbrenner & Morris, 1998). At the most distal levels are socioeconomic factors, which are thought to exert their effects on language development through more proximal environmental factors. According to sociocultural and social-interactionist theoretical perspectives (Bruner, 1981; Vygotsky, 1978), children's language experiences are key proximal predictors of variability in language development (Hoff, 2006). These language experiences include the quantity and quality of adult speech to children, which are thought to shape children's brain development and in turn expressive and receptive language skills.

Early childhood is a sensitive period during which language experiences are thought to have especially pronounced effects on the development of language and its underlying neural circuitry. Yet, the plasticity of language-supporting neural networks continues into older ages, with research showing effects of language experience on language and reading development in middle childhood (Dickinson & Porche, 2011; Neuman, Kaefer, & Pinkham, 2018; Tenenbaum, Snow, Roach, & Kurland, 2005; Weizman & Snow, 2001). Parent–child interactions that are at the center of children's social worlds in early childhood continue to be an important source of children's language experiences in middle childhood, a period in which language and reading skills are rapidly developing (NICHD Early Child Care Research Network, 2005). Thus, collective theoretical and empirical work suggests that language input may link socioeconomic factors with the developing brain and, in turn, language and reading skills.

Socioeconomic Factors and the Developing Brain

In alignment with this theoretical framework, socioeconomic background has been consistently associated with the structure and function of language-supporting cortical regions in children (Farah, 2017; Hair, Hanson, Wolfe, & Pollak, 2015; Hanson et al., 2013; Raizada et al., 2008). Using structural magnetic resonance imaging (MRI), socioeconomic disadvantage has been associated with reduced gray matter in the left hemispheric cortical regions underlying language comprehension and production, as well as reading (Noble, Houston, Kan, & Sowell, 2012; Noble et al., 2015; Romeo et al., 2017), including perisylvian (i.e., superior temporal gyrus), inferior frontal, and occipitotemporal regions (Friederici, 2011; Jednoróg et al., 2012; Mackey et al., 2015). Although some neuroimaging studies have focused on cortical volume, more recent work has taken a surface-based approach by examining cortical thickness and surface area separately, based on evidence that these morphometric indices are developmentally and genetically distinct (Panizzon et al., 2009; Raznahan et al., 2011). Indeed, in the largest such study to date, higher family income and higher parental education were each robustly associated with greater cortical surface area, with particularly notable differences observed in left perisylvian cortical regions (Noble et al., 2015).

Similarly, at the level of brain function, research has demonstrated socioeconomic differences in the recruitment of language-supporting cortical regions during language and reading tasks (Conant, Liebenthal, Desai, & Binder, 2017; Farah, 2017; Noble, Wolmetz, Ochs, Farah, & McCandliss, 2006; Raizada et al., 2008). However, the proximal environmental factors through which socioeconomic background may influence language-related brain development are not well understood.

Socioeconomic Factors and Linguistic Input in the Home

Socioeconomic factors are strongly associated with the quantity and quality of linguistic input in the home (Pace et al., 2017; Schwab & Lew-Williams, 2016). Parents from more advantaged backgrounds tend to talk more with their children and use more complex, responsive language (e.g., more extensive vocabulary, longer sentences, more complex grammar) compared to parents from less advantaged backgrounds. In a seminal study, Hart and Risley (1995) observed large socioeconomic disparities in the number of words that children heard from their parents—more than three times as many in higher-income families as in lower-income families. Follow-up work revealed that 3-year-olds from lower-income families had less than half the vocabulary of their counterparts from higher-income families (Hart & Risley, 1995). In addition to the quantity of language input, the quality of language input is often an even stronger predictor of children's language skills (Hirsh-Pasek et al., 2015; Merz et al., 2015; Pace et al., 2017; Ramírez-Esparza, García-Sierra, & Kuhl, 2014; Rowe, 2012; Weisleder & Fernald, 2013). Both the amount and quality of adult speech that children hear have been found to mediate associations between family SES and children's language skills (Hoff, 2003; Huttenlocher, Waterfall, Vasilyeva, Vevea, & Hedges, 2010; Rowe, 2012; Schwab & Lew-Williams, 2016).

Linguistic stimulation is traditionally measured through naturalistic home observations which are then transcribed and coded—a labor-intensive process. More recently, a novel approach involving the Language Environment Analysis (LENA) system has been developed (Ganek & Eriks-Brophy, 2017). In this approach, the child wears a small digital recorder that can store up to 16 hr of recorded sound. LENA software then analyzes the recording and provides estimates of the number of adult words, adult–child conversational turns, and child vocalizations. Like studies using transcription, studies incorporating the LENA system have demonstrated significant associations between SES and linguistic stimulation in the home (Gilkerson et al., 2017; Romeo, Leonard, et al., 2018).

Linguistic Input in the Home and the Developing Brain

In research using functional neuroimaging and electrophysiological techniques, linguistic stimulation in the home has been linked with the function of children's language-supporting brain regions (Romeo, Leonard, et al., 2018; Sheridan, Sarsour, Jutte, D'Esposito, & Boyce, 2012). For example, one functional MRI (fMRI) study of 4- to 6-year-old children ($N = 36$) found that higher SES was associated with more adult–child conversational turns, which in turn were associated with greater left inferior frontal activation during a story listening task, independent of socioeconomic background (Romeo, Leonard, et al., 2018). In addition, in two event-related potential studies ($N = 27$–37), greater language input to the child was associated with brain responses indicative of greater learning of native-language speech (Garcia-Sierra, Ramírez-Esparza, & Kuhl, 2016; Garcia-Sierra et al., 2011).

At the structural level, a greater number of adult–child conversational turns was related to stronger, more coherent white matter connectivity in the left arcuate and superior longitudinal fasciculi, after accounting for SES and the overall amount of adult speech (Romeo, Segaran, et al., 2018). However, the extent to which linguistic input is linked with cortical gray matter structure is wholly unknown.

This Study

Here, we examined associations among family socioeconomic circumstance, linguistic input in the home, children's brain structure, and children's reading skills. A socioeconomically diverse sample of parents and children (5–9 years; $N = 94$) participated in this study. Linguistic input in the home was measured using the LENA system (Ganek & Eriks-Brophy, 2017; Gilkerson et al., 2017), and children completed high-resolution, T1-weighted MRI scans. Family income and parental education were examined separately as they represent distinct aspects of children's environments that contribute differentially to their development (Duncan & Magnuson, 2012).

As shown in Figure 1, we hypothesized that socioeconomic disparities would be found in home linguistic stimulation, replicating past work; and that higher-quality linguistic stimulation in the home would in turn be associated with greater surface area in left perisylvian cortical regions, even after controlling for SES indices. We also expected to find evidence of the following significant mediation effects: (a) home linguistic input would mediate the association between SES indices and children's left perisylvian cortical structure; (b) left perisylvian cortical structure would mediate the association between home linguistic input and children's reading skills; and (c) home linguistic input and left perisylvian cortical structure would jointly

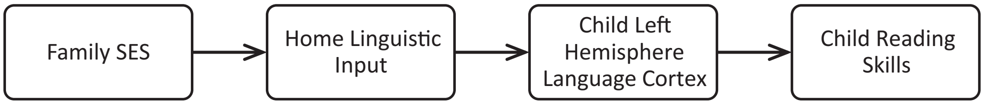

Figure 1. Hypothesized mechanistic model. SES = socioeconomic status.

mediate the association between SES indices and children's reading skills.

While descriptive and with a sample size typical of many neuroimaging studies, this study is an important addition to the emerging literature examining SES, brain structure and language and reading outcomes. We extend past work by testing an evidence-based mechanistic model of socioeconomic disparities in children's reading skills, and by focusing on structural (rather than functional) MRI. Such research is crucial to building an understanding of the mechanisms underlying socioeconomic disparities in reading skills.

Method

Participants

Recruitment

Participants were recruited from community events and posting flyers in local neighborhoods in New York, New York. A socioeconomically diverse sample was recruited by ensuring that families in the study represented a wide range of parental educational attainment. Interested families were contacted by phone and screened for eligibility. Inclusionary criteria were as follows: (a) between 5 and 9 years of age, (b) born at or after 37 weeks of gestation, (c) born from a singleton pregnancy, (d) no history of medical or psychiatric problems, (e) the primary caregiver and child were proficient in English, and English was the language spoken most often in the home. Children with contraindications for MRI scanning were excluded.

Sample Characteristics

Children ranged from 5.06 to 9.87 years of age (61% female), family income ranged from $2,880 to $350,000 (income-to-needs ratio range: 0.17–15.21), and parental education ranged from 6.50 to 20.00 years. Children were 50% Hispanic/Latino, 31% African American, non-Hispanic/Latino, and 14% White, non-Hispanic/Latino (see Table 1).

Sample Sizes

There were 94 total families who completed questionnaires and the child testing battery. Of those, 80 provided LENA data. LENA data were missing for families who declined to schedule the LENA recording days (n = 3), did not return the LENA recorder (n = 8), or returned the recorder without recorded data (n = 3).

Table 1
Descriptive Statistics for Sample Characteristics (N = 94)

	M	*SD*
Child age (years)	7.03	1.29
Parental education (years)	14.14	2.64
Family income-to-needs ratio	2.68	2.79
Letter-Word Identification subtest standard score	110.72	13.90
Word Attack subtest standard score	109.05	11.77
Passage Comprehension subtest standard score	103.40	11.75
	%	*n*
Child sex (female)	60.64	57
Child race/ethnicity		
African American, non-Hispanic/Latino	30.85	29
Hispanic/Latino	50.00	47
White, non-Hispanic/Latino	13.83	13
Other	5.32	5
Family income below U.S. poverty threshold[a]	29.79	28
Parent proficient in a second language[b]	55.29	47
Child exposed to a second language but not proficient[c]	26.09	24
Child proficient in a second language[c]	15.22	14

[a]Defined as an income-to-needs ratio < 1.00. [b]Data for eight families were missing. [c]Data for two families were missing.

Of the 94 total families, 85 were enrolled in the MRI portion of the study and participated in a mock scan. Of that group, MRI data were acquired for 66 children. MRI data were missing because the family or child chose not to participate in the MRI scanning session following the mock scan (n = 12) or because the child was fidgety, afraid, or uninterested during the mock scan and the MRI scan was therefore not scheduled (n = 7).

There were no significant differences between participants who had both MRI and LENA data and those who did not in terms of child sex, $\chi^2(1) = 0.02$, $p = .90$, child race/ethnicity, $\chi^2(2) = 3.73$, $p = .16$, family income-to-needs ratio, $t(92) = -.39$, $p = .70$, or parental education, $t(92) = -1.37$, $p = .17$. However, the subsample with both MRI and LENA data was older on average (7.38 vs. 6.67 years) than those without these data, $t(92) = -2.79$, $p = .01$, due to older children being more likely to complete the mock scan and MRI scan.

Procedure

Families participated in two campus visits within a month. During the first visit, informed consent/assent was obtained from parents and children. Children then completed a neurocognitive task battery, while parents completed questionnaires and were given a LENA recorder with instructions. Finally, a mock MRI session was performed to familiarize children with scanning. During the second visit, children completed the MRI scan. All procedures were approved by the Institutional Review Boards at the New York State Psychiatric Institute and Teachers College, Columbia University.

Image Acquisition and Processing

MRI data were acquired on a 3-Tesla General Electric MR750 scanner with a 32-channel head coil at the New York State Psychiatric Institute. During scanning, children watched a movie of their choice. Children completed a high-resolution, T1-weighted fast spoiled gradient echo scan with the following parameters: sagittal acquisition; TR = 7.1 ms; TE = min full; inversion time (TI) = 500 ms; flip angle = 11 degrees; 176 slices; 1.0 mm slice thickness; field of view (FOV) = 25 cm; inplane resolution = 1×1 mm.

All images were visually inspected for motion artifacts and ghosting, leading to exclusion of 15, and a final sample of 51 usable scans. There was no manual editing of data that were deemed eligible for inclusion. Images were processed using standard automated procedures in the FreeSurfer software suite (http://surfer.nmr.mgh.harvard.edu/; version 6.0). These included removal of non-brain tissue, image intensity normalization, and construction of white/gray matter and gray matter/cerebrospinal fluid boundaries (Dale, Fischl, & Sereno, 1999; Fischl & Dale, 2000). Following cortical surface reconstruction, automated procedures parcellate the cerebral cortex into regions based on gyral and sulcal structure (Desikan et al., 2006; Fischl et al., 2004), using the Desikan-Killiany atlas (Desikan et al., 2006).

Measures

SES Indices

Parents reported their annual household income and the number of adults and children in the household. The income-to-needs ratio was calculated by dividing household income by the poverty threshold for the size of the family. Family income-to-needs ratio was log-transformed to correct for positive skew. In addition, parents reported on their years of educational attainment, which were averaged across the number of parents in the household.

Language Input

Parents were given a 2-ounce LENA Pro digital language processor (DLP), which fits in a child's shirt pocket and stores up to 16 hr of digitally recorded audio (Xu, Yapanel, & Gray, 2009). They were also given two child-sized t-shirts with specially designed pockets to hold the DLP securely. Parents were instructed to record eight continuous hours each day for 2 days (weekend days or days when children were primarily at home), amounting to 16 recorded hours. The average number of days between LENA recording and the MRI scan was 5.80 (SD = 15.10), with a maximum of 65 days.

Upon return of the DLPs, data were uploaded and analyzed using LENA software. LENA software provided estimates of the total number of adult words spoken in the recording, the total number of child vocalizations, and the total number of adult–child conversational turns, defined as an adult utterance followed by a child utterance within 5-s or vice versa. These totals were then divided by the amount of recording time in hours to generate hourly adult words, conversational turns, and child vocalizations.

Audio recording time. The majority of families (66%) had 16 hr of recording time. Three families with < 5 hr of recording time and one family that used the recorder incorrectly were excluded from analyses, for a final total of 76 families with usable LENA data. Recording time ranged from 5.18 to 16.00 hours (M = 14.22, SD = 3.24, skew = −1.73, kurtosis = 1.64). Of the total sample of 76 recordings, there were 11 recordings that were < 10 hr. Of the sample of 42 children with both LENA and MRI data, there were eight recordings that were < 10 hr. Audio recording time was not associated with hourly adult word count ($r = -.07$, $p = .55$), but was significantly associated with hourly conversational turns ($r = -.32$, $p = .005$) and child vocalizations ($r = -.29$, $p = .01$). Audio recording time was included in analyses as a covariate, and we conducted supplemental analyses excluding recordings < 10 hr.

Reliability check. LENA speech identification algorithms have demonstrated strong reliability, with approximately 82% accuracy for adult speech and 76% accuracy for the speech of children up to 3 years of age (Gilkerson et al., 2017). The LENA system has been formally validated up to 4 years of age, and recent work has successfully used LENA algorithms with older children (Romeo, Leonard, et al., 2018; Vohr, Topol, Watson, St Pierre, & Tucker, 2014; Wang, Pan, Miller, & Cortina, 2014).

As an additional check, we examined the reliability of child vocalization counts in our sample following previously used procedures (Weisleder & Fernald, 2013). Twelve 5-min chunks were transcribed from 10 randomly chosen home audio recordings, generating 60 min of transcribed speech for each of these 10 participants. To include chunks that were representative of the entire recording, four 5-min chunks were selected randomly from the top-, middle-, and bottom-third of the distribution of child vocalization counts for each participant, totaling 20 min of transcribed speech in each bin for each participant. Analysis of these transcriptions revealed a strong correlation between automated estimates of child vocalizations and transcriber-based child vocalization counts ($r = .74$, $p < .001$), confirming that the LENA system's estimates of child vocalizations in recordings of 5- to 9-year-old children are as reliable as those used in younger children.

Reading Skills

Children's reading skills were measured using the Woodcock–Johnson Tests of Achievement III (Woodcock, McGrew, & Mather, 2001) Letter-Word Identification, Word Attack, and Passage Comprehension subtests. Raw scores on these subtests were strongly correlated ($r = .89$–$.95$, $p < .0001$) and thus were standardized and averaged to create a reading composite.

Statistical Analyses

Analyses were conducted in SAS (version 9.4 SAS Institute Inc., Cary, NC, USA) and FreeSurfer software (https://surfer.nmr.mgh.harvard.edu/). Multiple linear regression analyses (general linear model procedure in SAS) were employed to examine associations of SES indices (family income-to-needs ratio, parental education) with hourly adult word count, conversational turns, and child vocalizations, with effect sizes (partial eta squared [η_p^2]) reported. Associations of home linguistic input with child brain morphometry were examined using whole-brain-corrected, vertex-wise analyses. Cortical thickness and surface area analyses were conducted with the Query, Design, Estimate, Contrast (QDEC) surface-based analysis tool, using a 10 mm smoothing kernel and cluster-wise correction for multiple comparisons. Monte Carlo null-Z simulations were conducted with the cluster-wise p-value threshold set to .05 and the vertex-wise threshold set to .01. Cortical thickness/surface area data for significant cluster(s) identified in the vertex-wise analyses were extracted for each participant and imported into SAS for further analyses.

Child age, sex, ethnicity, and audio recording time were included as covariates in all regression and mediation analyses. Race was not significant in any of the analyses and was thus dropped as a covariate. Parental education and family income-to-needs ratio were included as covariates in analyses, as appropriate. Given the ethnic diversity of our sample and evidence of links between bilingualism and children's brain structure and function (Garcia-Sierra et al., 2016; Kuhl et al., 2016), the potential effects of children's exposure to a second language were carefully considered. Being Hispanic/Latino was strongly associated with both parental proficiency in a second language, $\chi^2(1, N = 86) = 26.53$, $p < .0001$, and child exposure to a second language, $\chi^2(2, N = 92) = 28.83$, $p < .0001$. Results were the same whether child ethnicity or exposure to a second language were included as covariates in analyses.

Table 2
Descriptive Statistics and Zero-Order Correlations for SES Factors, Home Linguistic Input, and Children's Reading Skills

	M	*SD*	1	2	3	4	5	6
1. Family income-to-needs ratio	2.68	2.79	—					
2. Parental education	14.14	2.64	.68***	—				
3. Hourly adult words	1,183.67	550.82	.27*	.42***	—			
4. Hourly conversational turns	47.99	26.49	.20+	.25*	.78***	—		
5. Hourly child vocalizations	187.13	96.61	.12	.12	.56***	.85***	—	
6. Reading composite[a]	0.00	1.00	.08	.19+	−.02	−.02	−.08	—

Note. Sample size for the socioeconomic status (SES) measures and reading composite was 94; sample size for the Language Environment Analysis variables (hourly adult words, conversational turns, and child vocalizations) was 76.
[a]Created by standardizing and averaging scores on the Letter-Word Identification ($M = 34.70$, $SD = 15.09$), Word Attack ($M = 11.82$, $SD = 8.02$), and Passage Comprehension ($M = 17.52$, $SD = 8.40$) subtests.
+$p < .10$. *$p < .05$. ***$p < .001$.

To test the significance of indirect (or mediated) effects (*ab* path), bias-corrected bootstrapping via the PROCESS macro was conducted, with a 95% confidence interval (Hayes, 2013). The effect is significant when the confidence interval does not include zero. One participant's data were excluded due to exceeding cutoffs on both leverage (Mahalanobis distance, robust minimum covariance determinant distance) and outlier (standardized robust residual) statistics.

Results

Descriptive Statistics and Zero-Order Correlations

Hourly adult words ranged from 166.43 to 2,622.31 (skew = .55; kurtosis = −.006); hourly conversational turns from 4.93 to 132.18 (skew = .89; kurtosis = .85); and hourly child vocalizations from 29.11 to 452.63 (skew = .75; kurtosis = .009; see Table 2). Family income-to-needs ratio and parental education were significantly positively associated with hourly adult words, and parental education was significantly positively associated with hourly conversational turns (see Table 2).

Socioeconomic Factors Are Associated With Language Input

Higher parental education and family income-to-needs ratio were each significantly associated with both higher hourly adult word count and higher hourly conversational turns, after adjusting for child age, sex, ethnicity, and audio recording time, $\beta = .33–.44$, $p = .01$ to $< .001$, $\eta^2_p = .10–.19$ (see Figure 2). Neither SES factor was significantly associated with hourly child vocalizations, $\beta = .21–.24$, $p = .05–.07$ (see Table S1).

Language Input is Associated With Left Perisylvian Cortical Surface Area

Higher hourly conversational turns were significantly associated with greater cortical surface area in one left hemisphere cluster which survived whole-brain correction for multiple comparisons ($p = .0001$, corrected). The peak coordinate fell within the superior temporal gyrus with the cluster also including all of the transverse temporal gyrus and parts of the insula, middle temporal gyrus, supramarginal gyrus, and postcentral gyrus.

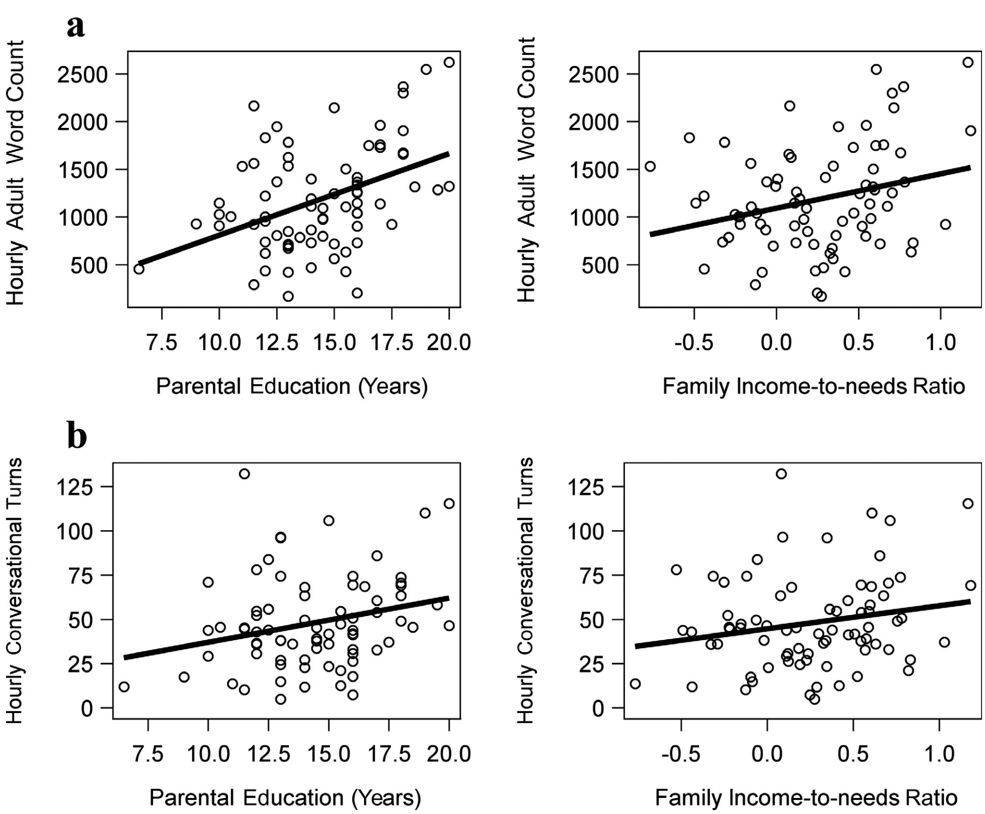

Figure 2. Scatterplots of (a) hourly adult word count and (b) hourly conversational turns as functions of parental education and family income-to-needs ratio (N = 76). Regression analyses controlled for child age, sex, ethnicity, and audio recording time.

Table 3
Significant Clusters for Left Hemisphere Surface Area, Corrected for Multiple Comparisons (N = 42)

Cluster #	Anatomical region of peak coordinate[a]	Area (mm^2)	Peak Talairach coordinates x	y	z	Vertices in cluster (n)	$p_{cluster}$
Hourly conversational turns							
1	Superior temporal	3,197.99	−42.5	−14.4	−10.3	7,112	.0001
Hourly adult word count							
1	Superior temporal	1,218.78	−45.6	−12.5	−9.7	2,917	.0013

[a]Label from the Desikan-Killiany gyral-based atlas.

Covariates in this analysis included child age, sex, ethnicity, parental education, and audio recording time (see Table 3 and Figure 3).

Similarly, higher hourly adult words were significantly associated with greater cortical surface area in one left hemisphere cluster which survived whole-brain correction for multiple comparisons (p = .0013, corrected). The peak coordinate fell within the superior temporal gyrus with the cluster also including parts of the transverse temporal gyrus and insula (see Table 3 and Figure 3). There were no significant clusters in the right hemisphere for either hourly conversational turns or adult words.

The adult word count cluster was mostly encompassed within the larger conversational turns cluster, and the effect size for conversational turns

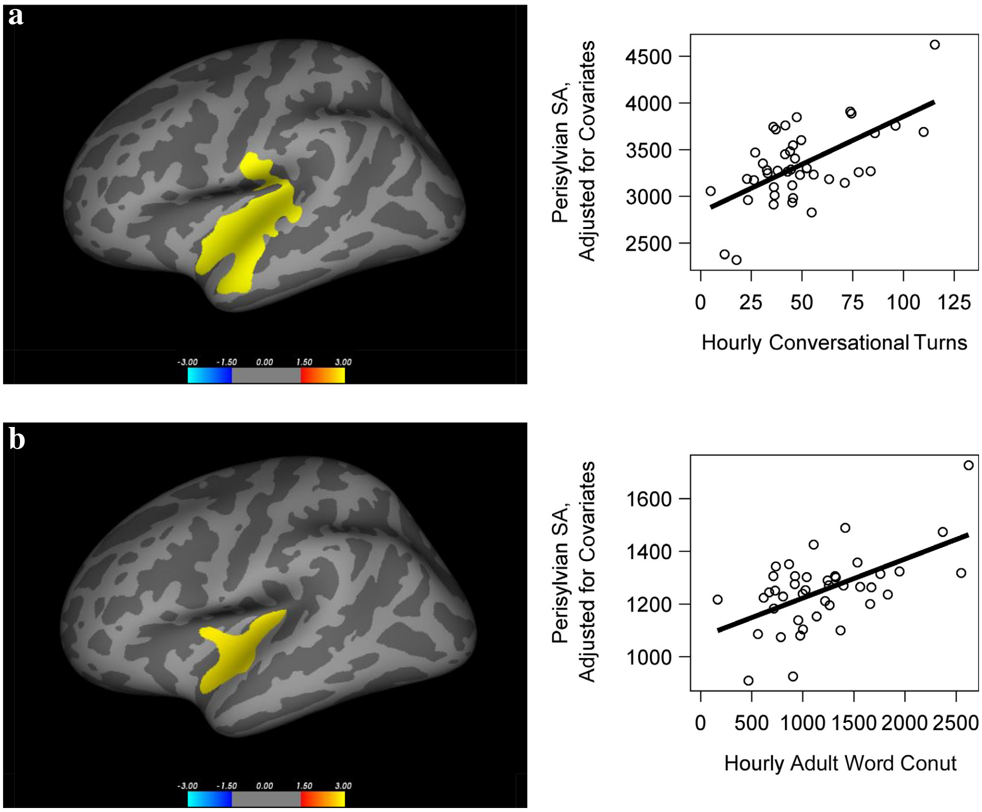

Figure 3. (a) Children who experienced more conversational turns per hour had greater surface area (SA) in the left perisylvian cortex cluster shown here (p = .0001), with a peak coordinate in the superior temporal gyrus (N = 42). (b) Children who experienced more adult words per hour had greater surface area in the left perisylvian cortex cluster shown here (p = .0013), again with a peak coordinate in the superior temporal gyrus. This cluster fell nearly completely within the larger cluster for conversational turns. Colors denote the −log10 (p-value). Child age, sex, ethnicity, parental education, and audio recording time were included as covariates in these models. [Color figure can be viewed at wileyonlinelibrary.com]

(η_p^2 = .47) was 15% greater than the effect size for adult word count (η_p^2 = .40; see Table S2). However, neither hourly conversational turns nor adult words remained significant after additionally controlling for the other, likely due at least in part to their strong inter-correlation (r = .78, p < .0001). Thus, hourly conversational turns and adult words were associated with a similar and largely overlapping left perisylvian cortical region, with a larger effect size for conversational turns compared to adult word count. Surface area data for the area of overlap (hereafter termed "left perisylvian cortex") were extracted and imported into SAS for further analyses. There were no significant surface area clusters associated with hourly child vocalizations or cortical thickness clusters. Because the extracted brain region represented overlapping variance between hourly adult words and hourly conversational turns, principal component analysis with hourly adult words and conversational turns was used to extract a single "language input" component with an eigenvalue > 1.0 (explaining 89% of the total variance), which was used in the mediation analyses.

Socioeconomic Factors, Language Input, and Left Perisylvian Cortical Surface Area

Higher parental education was significantly associated with greater surface area in the left perisylvian cortex, β = .39, p = .01, η_p^2 = .17, but family income-to-needs ratio was not, β = .27, p = .10, η_p^2 = .07 (see Table S3). Language input significantly mediated the association between parental education and left perisylvian cortical surface area, controlling for child age, sex, ethnicity, and audio recording time, indirect effect = .26, 95% CI [.0187, .5665]. Specifically, higher parental education was significantly associated with greater language input, which was in turn significantly associated with greater left perisylvian cortical surface area (see Figure 4). There was no indirect effect of family income-to-needs on left perisylvian cortical surface area via language input.

Language Input, Left Perisylvian Cortical Surface Area, and Children's Reading Skills

Language input was not significantly associated with children's reading skills after controlling for child age, sex, ethnicity, parental education, and audio recording time, β = −.11, p = .15 (see Table S4). Nonetheless, language input was significantly indirectly associated with children's reading skills via left perisylvian cortical surface area, indirect effect = .23, 95% CI [.0468, .4730]. Specifically, greater language input was significantly associated with greater left perisylvian surface area, which in turn was significantly associated with higher reading skills (see Figure 5).

Parental Education, Left Perisylvian Cortical Surface Area, and Children's Reading Skills

Higher parental education, β = .18, p = .005, η_p^2 = .09, but not family income-to-needs ratio, β = .12, p = .07, η_p^2 = .04, was significantly associated with higher reading skills, independent of child age, sex, and ethnicity (see Table S5). Left perisylvian cortical surface area significantly mediated the association between parental education and reading skills (indirect effect = .11, 95% CI [.0012, .3333]), but home linguistic input did not (see Figure 6). There were no significant indirect

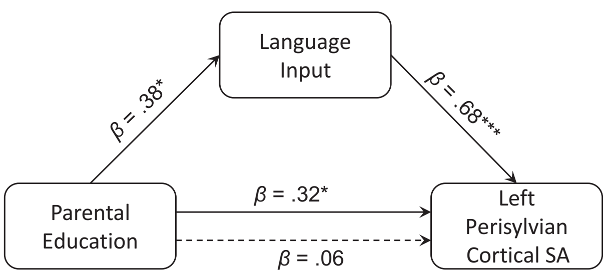

Figure 4. Home language input significantly mediated the association between parental education and left perisylvian cortical surface area (SA; N = 42). The solid line from parental education to left perisylvian cortical SA represents the total association (c path). The dotted line represents the direct association (c' path). Covariates were child age, sex, ethnicity, and audio recording time.
* p < .05. *** p < .001.

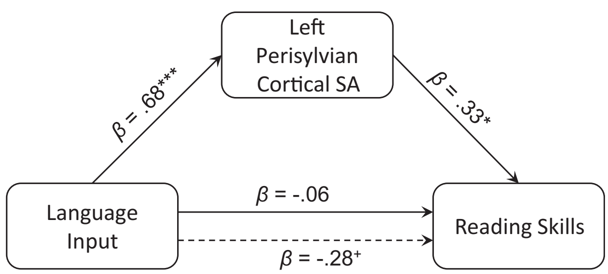

Figure 5. Home language input was significantly indirectly associated with children's reading skills via left perisylvian cortical surface area (SA; N = 42). The solid line from language input to reading skills represents the total association (c path). The dotted line represents the direct association (c' path). Covariates were child age, sex, ethnicity, audio recording time, and parental education.
^+p < .10. * p < .05. *** p < .001.

effects of family income-to-needs ratio on reading skills via language input or left perisylvian surface area.

Supplemental Analyses

Due to the potential for nonindependence affecting the language input and cortical surface area associations in the mediation models in Figures 4 and 5 (Vul, Harris, Winkielman, & Pashler, 2009), we re-ran these models using anatomically defined left superior temporal gyrus surface area, based on the Desikan-Killiany atlas. Results were the same for the first mediation model, indirect effect = .20, 95% CI [.0199, .5205] (see Figure S1), but did not hold for the second mediation model, indirect effect = .11, 95% CI [−.0283, .3025] (see Figure S1).

To further account for variability in audio recording time, we re-ran our main analyses excluding participants (n = 8) with < 10 hr of audio recording time (range of remaining participants: 11.97-16.00 hours). For hourly conversational turns, surface area in one left hemisphere cluster survived multiple comparison correction at the .05 threshold, after controlling for child age, sex, ethnicity, parental education, and audio recording time (see Table S6 and Figure S2). The peak coordinate fell within the transverse temporal gyrus, with the cluster also including parts of the superior temporal gyrus, middle temporal gyrus, insula, and supramarginal gyrus. Similarly, for hourly adult words, surface area in one left hemisphere cluster survived multiple comparison correction at the .05 threshold (see Table S6 and Figure S2). The peak coordinate fell within the superior temporal gyrus, with the cluster also including parts of the transverse temporal gyrus, middle temporal gyrus, and insula. There were no significant surface area clusters for hourly child vocalizations.

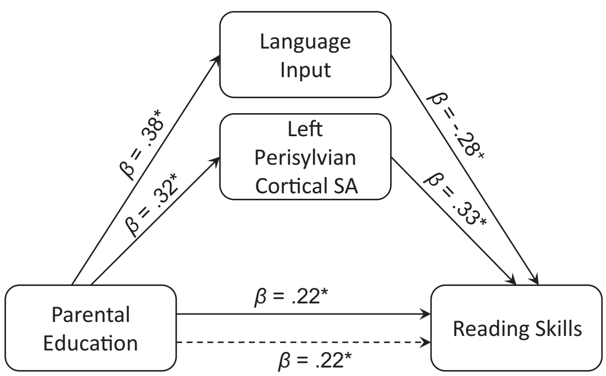

Figure 6. Left perisylvian cortical surface area (SA) significantly mediated the association between parental education and children's reading skills (N = 42). The solid line between parental education and reading skills represents the total association (c path). The dotted line represents the direct association (c' path). Covariates were child age, sex, ethnicity, and audio recording time.
$^{+}p < .10$. $^{*}p < .05$.

Discussion

The goal of this study was to examine associations among family socioeconomic background, home linguistic input, children's brain structure, and children's reading skills. Results supported our primary hypotheses. We replicated the frequently documented socioeconomic disparities in the home language environment: Higher parental education and higher family income-to-needs ratio were each associated with higher hourly adult–child conversational turns and hourly adult words. In addition, children who experienced more conversational turns or more adult words had significantly greater surface area in the left perisylvian cortex, with a larger effect size for conversational turns. These associations survived whole-brain correction for multiple comparisons, remained significant after controlling for SES indices, and were specific to language input (conversational turns, adult words) rather than child vocalizations. Furthermore, a language input composite (composed of hourly conversational turns and adult words) significantly mediated the association between parental education and children's left perisylvian cortical surface area. Results also indicated a role for these associations in explaining socioeconomic disparities in children's reading skills. Home language input was indirectly associated with children's reading skills via left perisylvian cortical surface area, and left perisylvian cortical surface area significantly mediated the association between parental education and children's reading skills.

To our knowledge, this is the first study showing associations between naturalistic observations of adult speech in the home and children's gray matter morphometry. Hourly adult–child conversational turns and hourly adult words were both significantly associated with surface area in a left perisylvian cortical region that included the superior temporal gyrus. Left perisylvian cortical regions, including the superior temporal gyrus, are centrally involved in language production and comprehension (Schlaggar & McCandliss, 2007; Turkeltaub, Gareau, Flowers, Zeffiro, & Eden, 2003). Our findings at the structural level complement previous fMRI research linking conversational turns with activation of another language-supporting region, the left inferior frontal gyrus, during a language processing task (Romeo, Leonard, et al., 2018). These results are also well-aligned with research showing links between adult–child conversational turns and white matter connectivity in the left arcuate and superior longitudinal fasciculi (Romeo, Segaran, et al., 2018).

Interestingly, the number of child vocalizations was unrelated to differences in brain structure. While bidirectional effects cannot be ruled out, this suggests that our findings do not merely reflect an artifact whereby more talkative children have greater surface area and also engender more parental conversation. Our findings are thus consistent with the notion that frequent adult–child conversational turns and adult speech may directly impact language-related brain structure, over and above the plasticity induced by the child's own language production.

Consistent with previous work (Noble et al., 2015), higher parental education was significantly associated with greater left perisylvian cortical surface area. Home language input fully mediated this association (see Figure 4). These results are the first to show associations fulfilling the classic pattern of mediation wherein significant socioeconomic differences in children's language-supporting brain structure were attributable to more frequent language input in the home. Together, these associations substantiate, at the neural level, hypotheses about the critical role of children's language experiences in explaining how socioeconomic disadvantage may alter language-supporting brain structure, potentially leading to difficulties with reading.

Longitudinal studies in humans have indicated that cortical surface area increases through middle childhood and then decreases during adolescence (Mills & Tamnes, 2014; Raznahan et al., 2011). This study may suggest steeper childhood increases in cortical surface area as a result of heightened linguistic stimulation in more advantaged families, but longitudinal studies would be needed to test this possibility.

There was also a significant indirect association between home language input and children's reading skills via surface area in the left perisylvian cortex, partially paralleling previous fMRI results (Romeo, Leonard, et al., 2018). This indirect association emerged despite the lack of a significant "total" association between language input and children's reading skills. One possible explanation for this result may be the relatively older age of the children, and the potential for the home language environment measured earlier in childhood to be a better predictor of future reading success. Indeed, most work with the LENA system has involved children younger than those studied here. Although we validated the use of LENA in our 5- to 9-year-old participants, it would be valuable to examine the same associations earlier in childhood.

We additionally found that left perisylvian cortical surface area significantly mediated the association between parental education and children's reading skills. This finding points to left perisylvian cortical structure, which may in part be a product of linguistic exposure, as a mechanism through which socioeconomic circumstances may affect children's reading skills.

These mediation models were significant for parental education but not family income-to-needs ratio. This is consistent with previous work suggesting that parental education may be the component of SES most relevant to children's language development (Hoff, 2006, 2013; Huttenlocher et al., 2010). Family income and parental education have been identified as independent predictors of children's development, representing unique aspects of children's environments. Whereas family income has been more related to the material resources of the home environment, parental education may be more reflective of the quality of parent–child interactions (Duncan & Magnuson, 2012).

Hourly conversational turns and adult words were highly correlated, such that neither was uniquely associated with children's language-supporting brain structure after accounting for the other. Thus, we cannot definitively attribute correlations with children's brain structure to either one specifically. However, the adult word count cluster was nearly completely encompassed within the conversational turn count cluster. While both showed large effect sizes, the effect size of the link between conversational turns and brain structure was 15% larger than the corresponding effect size for adult word count. In past studies, the quality of language input has been found to be more predictive of language development compared to the quantity of speech the child hears from adults (Pace et al., 2017; Ramírez-Esparza, García-Sierra, & Kuhl, 2017; Ramírez-Esparza et al., 2014; Weisleder & Fernald, 2013). Indeed, adult–child conversational turns may reflect reciprocal, back-and-forth social interactions, which are thought to be a cornerstone of children's language development (Pace et al., 2017).

The findings presented here may have implications for programs and policies seeking to improve language and literacy in children from disadvantaged families. These results suggest that improving children's language exposure via prevention and intervention programs may benefit their structural brain development. This work also speaks to the potential value of integrating measures of brain structure and function into studies testing policy-relevant research questions. Policymakers should consider evidence from neuroscience and the implications of this work for investments in children and families.

There are some limitations to take into account when interpreting these findings. First, this study had a cross-sectional, correlational design, which precludes causal inferences. Future studies should test these associations using longitudinal designs and randomized trials that aim to change socioeconomic circumstance or home language input directly. Such approaches would yield important insights into the causal contributions of these factors to the development of language and its underlying neural circuitry. Second, while the LENA system provides naturalistic data on the quantity and quality of adult–child speech, it does not provide fine-grained information about qualitative aspects of linguistic stimulation, such as lexical diversity and grammatical complexity. Future studies should carefully examine these more detailed aspects of the home language environment in relation to children's brain structure. Third, head motion has a negative effect on estimates of cortical structure, even after excluding low-quality scans, and younger participants generally move more during acquisition (Alexander-Bloch et al., 2016). Motion corrupted images were excluded from analyses and all statistical models controlled for age. Finally, although language input data were based on lengthy recordings of the family environment, they only capture a brief snapshot of family life, and thus these data are only valid to the extent that they reflect a typical day for the family. It is possible that families could have been more or less talkative than usual at the time of the recording.

With the increasing prevalence of children living in poverty and the growth of the income-achievement gap (Reardon, 2011), understanding the proximal environmental and neural mechanisms through which socioeconomic disadvantage affects children's cognitive development is crucial to designing targeted interventions and shaping policy. Here, we show for the first time that children who experience more conversations with adults or adult speech have patterns of cortical structure in language-supporting regions that are linked with greater reading proficiency. These findings reinforce the importance of programs and policies supporting parents in providing high-quality language experiences to their children.

References

Alexander-Bloch, A., Clasen, L., Stockman, M., Ronan, L., Lalonde, F., Giedd, J., & Raznahan, A. (2016). Subtle in-scanner motion biases automated measurement of brain anatomy from in vivo MRI. *Human Brain Mapping*, *37*, 2385–2397. https://doi.org/10.1002/hbm.23180

Bingham, G. E. (2007). Maternal literacy beliefs and the quality of mother–child book-reading interactions: Associations with children's early literacy development. *Early Education and Development*, *18*, 23–49. https://doi.org/10.1080/10409280701274428

Bronfenbrenner, U., & Morris, P. A. (1998). The ecology of developmental processes. In W. Damon & R. M. Lerner (Eds.), *Handbook of child psychology: Theoretical models of human development* (Vol. 1, 5th ed., pp. 993–1028). Hoboken, NJ: Wiley.

Bruner, J. (1981). The social context of language acquisition. *Language & Communication*, *1*, 155–178. https://doi.org/10.1016/0271-5309(81)90010-0

Conant, L. L., Liebenthal, E., Desai, A., & Binder, J. R. (2017). The relationship between maternal education and the neural substrates of phoneme perception in children: Interactions between socioeconomic status and proficiency level. *Brain and Language*, *171*, 14–22. https://doi.org/10.1016/j.bandl.2017.03.010

Dale, A. M., Fischl, B., & Sereno, M. I. (1999). Cortical surface-based analysis. I. Segmentation and surface reconstruction. *NeuroImage*, *9*, 179–194. https://doi.org/10.1006/nimg.1998.0395

Desikan, R. S., Ségonne, F., Fischl, B., Quinn, B. T., Dickerson, B. C., Blacker, D., . . . Killiany, R. J. (2006). An automated labeling system for subdividing the human cerebral cortex on MRI scans into gyral based regions of interest. *NeuroImage*, *31*, 968–980. https://doi.org/10.1016/j.neuroimage.2006.01.021

Dickinson, D. K., McCabe, A., Anastasopoulos, L., Peisner-Feinberg, E. S., & Poe, M. D. (2003). The comprehensive language approach to early literacy: The interrelationships among vocabulary, phonological sensitivity, and print knowledge among preschool-aged children. *Journal of Educational Psychology*, *95*, 465–481. https://doi.org/10.1037/0022-0663.95.3.465

Dickinson, D. K., & Porche, M. V. (2011). Relation between language experiences in preschool classrooms and children's kindergarten and fourth-grade language and reading abilities. *Child Development*, *82*, 870–886. https://doi.org/10.1111/j.1467-8624.2011.01576.x

Dieterich, S. E., Assel, M. A., Swank, P., Smith, K. E., & Landry, S. H. (2006). The impact of early maternal verbal scaffolding and child language abilities on later decoding and reading comprehension skills. *Journal of School Psychology*, *43*, 481–494. https://doi.org/10.1016/j.jsp.2005.10.003

Duncan, G. J., & Magnuson, K. (2012). Socioeconomic status and cognitive functioning: Moving from correlation to causation. *Wiley Interdisciplinary Reviews: Cognitive Science*, *3*, 377–386. https://doi.org/10.1002/wcs.1176

Farah, M. J. (2017). The neuroscience of socioeconomic status: Correlates, causes, and consequences. *Neuron*, *96*, 56–71. https://doi.org/10.1016/j.neuron.2017.08.034

Fischl, B., & Dale, A. M. (2000). Measuring the thickness of the human cerebral cortex from magnetic resonance images. *Proceedings of the National Academy of Sciences of the United States of America*, *97*, 11050–11055. https://doi.org/10.1073/pnas.200033797

Fischl, B., van der Kouwe, A., Destrieux, C., Halgren, E., Ségonne, F., Salat, D. H., . . . Dale, A. M. (2004). Automatically parcellating the human cerebral cortex. *Cerebral Cortex*, *14*, 11–22. https://doi.org/10.1093/cercor/bhg087

Friederici, A. D. (2011). The brain basis of language processing: From structure to function. *Physiological Reviews*, *91*, 1357–1392. https://doi.org/10.1152/physrev.00006.2011

Ganek, H., & Eriks-Brophy, A. (2017). Language ENvironment Analysis (LENA) system investigation of day long recordings in children: A literature review. *Journal of Communication Disorders*. https://doi.org/10.1016/j.jcomdis.2017.12.005

Garcia-Sierra, A., Ramírez-Esparza, N., & Kuhl, P. K. (2016). Relationships between quantity of language input and brain responses in bilingual and monolingual infants. *International Journal of Psychophysiology*, *110*, 1–17. https://doi.org/10.1016/j.ijpsycho.2016.10.004

Garcia-Sierra, A., Rivera-Gaxiola, M., Percaccio, C. R., Conboy, B. T., Romo, H., Klarman, L., . . . Kuhl, P. K. (2011). Bilingual language learning: An ERP study relating early brain responses to speech, language input, and later word production. *Journal of Phonetics*, *39*, 546–557. https://doi.org/10.1016/j.wocn.2011.07.002

Gilkerson, J., Richards, J. A., Warren, S. F., Montgomery, J. K., Greenwood, C. R., Kimbrough Oller, D., . . . Paul, T. D. (2017). Mapping the early language environment using all-day recordings and automated analysis. *American Journal of Speech-Language Pathology*, *26*, 248–265. https://doi.org/10.1044/2016_AJSLP-15-0169

Hair, N. L., Hanson, J. L., Wolfe, B. L., & Pollak, S. D. (2015). Association of child poverty, brain development, and academic achievement. *JAMA Pediatrics*, *169*, 822–829. https://doi.org/10.1001/jamapediatrics.2015.1475

Hanson, J. L., Hair, N., Shen, D. G., Shi, F., Gilmore, J. H., Wolfe, B. L., & Pollak, S. D. (2013). Family poverty affects the rate of human infant brain growth. *PLoS ONE*, *8*, e80954. https://doi.org/10.1371/journal.pone.0080954

Hart, B., & Risley, T. R. (1995). *Meaningful differences in the everyday experience of young American children*. Baltimore, MD: Brookes.

Hayes, A. F. (2013). *Introduction to mediation, moderation, and conditional process analysis: A regression-based approach*. New York, NY: Guilford.

Hirsh-Pasek, K., Adamson, L. B., Bakeman, R., Owen, M. T., Golinkoff, R. M., Pace, A., . . . Suma, K. (2015). The contribution of early communication quality to low-income children's language success. *Psychological Science*, *26*, 1071–1083. https://doi.org/10.1177/0956797615581493

Hoff, E. (2003). The specificity of environmental influence: Socioeconomic status affects early vocabulary development via maternal speech. *Child Development*, *74*, 1368–1378. https://doi.org/10.1111/1467-8624.00612

Hoff, E. (2006). How social contexts support and shape language development. *Developmental Review*, *26*, 55–88. https://doi.org/10.1016/j.dr.2005.11.002

Hoff, E. (2013). Interpreting the early language trajectories of children from low SES and language minority homes: Implications for closing achievement gaps. *Developmental Psychology*, *49*, 4–14. https://doi.org/10.1037/a0027238

Hoff, E., & Naigles, L. (2002). How children use input to acquire a lexicon. *Child Development*, *73*, 418–433. https://doi.org/10.1111/1467-8624.00415

Hurtado, N., Marchman, V. A., & Fernald, A. (2008). Does input influence uptake? Links between maternal talk, processing speed and vocabulary size in Spanish-learning children. *Developmental Science*, *11*, F31–F39. https://doi.org/10.1111/j.1467-7687.2008.00768.x

Huttenlocher, J., Haight, W., Bryk, A., Seltzer, M., & Lyons, T. (1991). Early vocabulary growth: Relation to language input and gender. *Developmental Psychology*, *27*, 236–248. https://doi.org/10.1037/0012-1649.27.2.236

Huttenlocher, J., Waterfall, H., Vasilyeva, M., Vevea, J., & Hedges, L. V. (2010). Sources of variability in children's language growth. *Cognitive Psychology*, *61*, 343–365. https://doi.org/10.1016/j.cogpsych.2010.08.002

Jednoróg, K., Altarelli, I., Monzalvo, K., Fluss, J., Dubois, J., Billard, C., . . . Ramus, F. (2012). The influence of socioeconomic status on children's brain structure. *PLoS ONE*, *7*, e42486. https://doi.org/10.1371/journal.pone.0042486

Kuhl, P. K., Stevenson, J., Corrigan, N. M., van den Bosch, J. J. F., Can, D. D., & Richards, T. (2016). Neuroimaging of the bilingual brain: Structural brain correlates of listening and speaking in a second language. *Brain and Language*, *162*, 1–9. https://doi.org/10.1016/j.bandl.2016.07.004

Mackey, A. P., Finn, A. S., Leonard, J. A., Jacoby Senghor, D. S., West, M. R., Gabrieli, C. F. O., & Gabrieli, J. D. E. (2015). Neuroanatomical correlates of the income achievement gap. *Psychological Science*, *26*, 925–933. https://doi.org/10.1177/0956797615572233

Merz, E. C., Zucker, T. A., Landry, S. H., Williams, J. M., Assel, M., Taylor, H. B., . . . de Villiers, J. (2015). Parenting predictors of cognitive skills and emotion knowledge in socioeconomically disadvantaged preschoolers. *Journal of Experimental Child Psychology*, *132*, 14–31. https://doi.org/10.1016/j.jecp.2014.11.010

Mills, K. L., & Tamnes, C. K. (2014). Methods and considerations for longitudinal structural brain imaging analysis across development. *Developmental Cognitive Neuroscience*, *9*, 172–190. https://doi.org/10.1016/j.dcn.2014.04.004

Muter, V., Hulme, C., Snowling, M. J., & Stevenson, J. (2004). Phonemes, rimes, vocabulary, and grammatical skills as foundations of early reading development: Evidence from a longitudinal study. *Developmental Psychology*, *40*, 665–681. https://doi.org/10.1037/0012-1649.40.5.665

Neuman, S. B., Kaefer, T., & Pinkham, A. M. (2018). A double dose of disadvantage: Language experiences for low-income children in home and school. *Journal of Educational Psychology*, *110*, 102–118. https://doi.org/10.1037/edu0000201

NICHD Early Child Care Research Network. (2005). Pathways to reading: The role of oral language in the transition to reading. *Developmental Psychology*, *41*, 428–442. https://doi.org/10.1037/0012-1649.41.2.428

Noble, K. G., Houston, S. M., Brito, N. H., Bartsch, H., Kan, E., Kuperman, J. M., . . . Sowell, E. R. (2015). Family income, parental education and brain structure in children and adolescents. *Nature Neuroscience*, *18*, 773–778. https://doi.org/10.1038/nn.3983

Noble, K. G., Houston, S. M., Kan, E., & Sowell, E. R. (2012). Neural correlates of socioeconomic status in the developing human brain. *Developmental Science*, *15*, 516–527. https://doi.org/10.1111/j.1467-7687.2012.01147.x

Noble, K. G., Wolmetz, M. E., Ochs, L. G., Farah, M. J., & McCandliss, B. D. (2006). Brain-behavior relationships in reading acquisition are modulated by socioeconomic factors. *Developmental Science*, *9*, 642–654. https://doi.org/10.1111/j.1467-7687.2006.00542.x

Pace, A., Luo, R., Hirsh-Pasek, K., & Golinkoff, R. M. (2017). Identifying pathways between socioeconomic status and language development. *Annual Review of Linguistics*, *3*, 285–308. https://doi.org/10.1146/annurev-linguistics-011516-034226

Panizzon, M. S., Fennema-Notestine, C., Eyler, L. T., Jernigan, T. L., Prom-Wormley, E., Neale, M., . . . Kremen, W. S. (2009). Distinct genetic influences on cortical surface area and cortical thickness. *Cerebral Cortex*, *19*, 2728–2735. https://doi.org/10.1093/cercor/bhp026

Raizada, R. D. S., Richards, T. L., Meltzoff, A., & Kuhl, P. K. (2008). Socioeconomic status predicts hemispheric specialisation of the left inferior frontal gyrus in young children. *NeuroImage*, *40*, 1392–1401. https://doi.org/10.1016/j.neuroimage.2008.01.021

Ramírez-Esparza, N., García-Sierra, A., & Kuhl, P. K. (2014). Look who's talking: Speech style and social context in language input to infants are linked to concurrent and future speech development. *Developmental Science*, *17*, 880–891. https://doi.org/10.1111/desc.12172

Ramírez-Esparza, N., García-Sierra, A., & Kuhl, P. K. (2017). The impact of early social interactions on later language development in Spanish-English bilingual infants. *Child Development*, *88*, 1216–1234. https://doi.org/10.1111/cdev.12648

Raznahan, A., Shaw, P., Lalonde, F., Stockman, M., Wallace, G. L., Greenstein, D., . . . Giedd, J. N. (2011). How does your cortex grow? *The Journal of Neuroscience*, *31*, 7174–7177. https://doi.org/10.1523/JNEUROSCI.0054-11.2011

Reardon, S. F. (2011). The widening academic achievement gap between the rich and the poor: New evidence and possible explanations. In R. Murnane & G. Duncan (Eds.), *Whither opportunity?: Rising inequality, schools, and children's life chances* (pp. 91–116). New York, NY: Russell Sage Foundation.

Romeo, R. R., Christodoulou, J. A., Halverson, K. K., Murtagh, J., Cyr, A. B., Schimmel, C., . . . Gabrieli, J. D. E. (2017). Socioeconomic status and reading disability: Neuroanatomy and plasticity in response to intervention. *Cerebral Cortex*, *28*, 2297–2312. https://doi.org/10.1093/cercor/bhx131

Romeo, R. R., Leonard, J. A., Robinson, S. T., West, M. R., Mackey, A. P., Rowe, M. L., & Gabrieli, J. D. E. (2018). Beyond the 30-million-word gap: Children's conversational exposure is associated with language-related brain function. *Psychological Science*, *29*, 700–710. https://doi.org/10.1177/0956797617742725

Romeo, R. R., Segaran, J., Leonard, J. A., Robinson, S. T., West, M. R., Mackey, A. P., . . . Gabrieli, J. D. E. (2018). Language exposure relates to structural neural connectivity in childhood. *The Journal of Neuroscience*, *38*, 7870–7877. https://doi.org/10.1523/JNEUROSCI.0484-18.2018

Rowe, M. L. (2012). A longitudinal investigation of the role of quantity and quality of child-directed speech in vocabulary development. *Child Development*, *83*, 1762–1774. https://doi.org/10.1111/j.1467-8624.2012.01805.x

Schlaggar, B. L., & McCandliss, B. D. (2007). Development of neural systems for reading. *Annual Review of Neuroscience*, *30*, 475–503. https://doi.org/10.1146/annurev.neuro.28.061604.135645

Schwab, J. F., & Lew-Williams, C. (2016). Language learning, socioeconomic status, and child-directed speech. *Wiley Interdisciplinary Reviews: Cognitive Science*, *7*, 264–275. https://doi.org/10.1002/wcs.1393

Sheridan, M. A., Sarsour, K., Jutte, D., D'Esposito, M., & Boyce, W. T. (2012). The impact of social disparity on prefrontal function in childhood. *PLoS ONE*, *7*, e35744. https://doi.org/10.1371/journal.pone.0035744

Storch, S. A., & Whitehurst, G. J. (2002). Oral language and code-related precursors to reading: Evidence from a longitudinal structural model. *Developmental Psychology*, *38*, 934–947. https://doi.org/10.1037/0012-1649.38.6.934

Tenenbaum, H. R., Snow, C. E., Roach, K. A., & Kurland, B. (2005). Talking and reading science: Longitudinal data on sex differences in mother–child conversations in low-income families. *Journal of Applied Developmental Psychology*, *26*, 1–19. https://doi.org/10.1016/j.appdev.2004.10.004

Turkeltaub, P. E., Gareau, L., Flowers, D. L., Zeffiro, T. A., & Eden, G. F. (2003). Development of neural mechanisms for reading. *Nature Neuroscience*, *6*, 767–773. https://doi.org/10.1038/nn1065

Vohr, B. R., Topol, D., Watson, V., St Pierre, L., & Tucker, R. (2014). The importance of language in the home for school-age children with permanent hearing loss. *Acta Paediatrica*, *103*, 62–69. https://doi.org/10.1111/apa.12441

Vul, E., Harris, C., Winkielman, P., & Pashler, H. (2009). Puzzlingly high correlations in fMRI studies of emotion, personality, and social cognition. *Perspectives on Psychological Science*, *4*, 274–290. https://doi.org/10.1111/j.1745-6924.2009.01125.x

Vygotsky, L. S. (1978). *Mind in society: The development of higher psychological processes*. Cambridge, MA: Harvard University Press.

Wang, Z., Pan, X., Miller, K. F., & Cortina, K. S. (2014). Automatic classification of activities in classroom discourse. *Computers & Education*, *78*, 115–123. https://doi.org/10.1016/j.compedu.2014.05.010

Weisleder, A., & Fernald, A. (2013). Talking to children matters: Early language experience strengthens processing and builds vocabulary. *Psychological Science*, *24*, 2143–2152. https://doi.org/10.1177/0956797613488145

Weizman, Z. O., & Snow, C. E. (2001). Lexical input as related to children's vocabulary acquisition: Effects of sophisticated exposure and support for meaning. *Developmental Psychology*, *37*, 265–279. https://doi.org/10.1037/0012-1649.37.2.265

Woodcock, R. W., McGrew, K. S., & Mather, N. (2001). *Woodcock-Johnson III*. Itasca, IL: Riverside Publishing.

Xu, D., Yapanel, U., & Gray, S. (2009). *Reliability of the LENA Language Environment Analysis System in young children's natural home environment* (pp. 1–16). Boulder, CO: LENA Foundation.

Supporting Information

Additional supporting information may be found in the online version of this article at the publisher's website:

Figure S1. (a) Language Input Significantly Mediated the Association Between Parental Education and Left Superior Temporal Gyrus Surface Area (SA), Anatomically-Defined, Indirect Effect = .20, 95% CI [.02, .52] (N = 42). (b) Language Input Was Not Significantly Indirectly Associated With Children's Reading Skills Via Left Superior Temporal Gyrus SA, Anatomically-Defined, Indirect Effect = .11, 95% CI [−.03, .30] (N = 42)

Figure S2. Results of QDEC Analyses of 34 Subjects With 10 or More Recorded Hours

Table S1. Associations Between Socioeconomic Factors and Language Input (N = 76)

Table S2. Associations Between Language Input and Left Perisylvian Cortical Surface Area (N = 42)

Table S3. Associations Between Socioeconomic Factors and Children's Left Perisylvian Cortical Surface Area (N = 42)

Table S4. Associations Between Home Language Input and Children's Reading Skills (N = 76)

Table S5. Associations Between Socioeconomic Factors and Children's Reading Skills (N = 94)

Table S6. Significant Clusters for Left Hemisphere Surface Area, Corrected for Multiple Comparisons (N = 34)