JNeurosci
THE JOURNAL OF NEUROSCIENCE

Research Articles: Behavioral/Cognitive

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https://doi.org/10.1523/JNEUROSCI.1034-22.2023

Cite as: J. Neurosci 2023; 10.1523/JNEUROSCI.1034-22.2023

Received: 30 May 2022
Revised: 3 March 2023
Accepted: 9 March 2023

Language exposure and brain myelination in early development

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Number of Pages: 19
Number of Figures: 3
Number of Tables: 6
Abstract = 175 words
Introduction = 111 words
Discussion = 1965 words

Acknowledgements

This work supported by R01HD083287 from the National Institutes of Health award to JP Spencer as well as by NIH grants R01MH111578 and P50HD103556 to VAM. We thank all the families and children that participated in this study as well as all the DDLab members, staff, students and volunteers that helped with this project.

Additional information

Open Access Supplementary Materials and Code.
The authors declare no competing interests.
Abbreviated title: Language exposure and brain myelination

Abstract

The language environment to which children are exposed has an impact on later language abilities as well as on brain development; however, it is unclear how early such impacts emerge. This study investigates the effects of children's early language environment and socioeconomic status (SES) on brain structure in infancy at 6 and 30 months of age (both sexes included). We used magnetic resonance imaging (MRI) to quantify concentrations of myelin in specific fiber tracts in the brain. Our central question was whether Language ENvironment Analysis (LENA^{TM}) measures from in-home recording devices and SES measures of maternal education, predicted myelin concentrations over development. Results indicate that 30-month-old children exposed to larger amounts of in-home adult input showed more myelination in the white matter tracts most associated with language. Right hemisphere regions also show an association with SES, with older children from more highly educated mothers and exposed to more adult input, showing greater myelin concentrations in language-related areas. We discuss these results in relation with the current literature and implications for future research.

Keywords: *brain development, LENA, MRI, language input, SES*

Significance Statement

This is the first study to look at how brain myelination is impacted by language input and socioeconomic status early in development. We find robust relationships of both factors in language-related brain areas at 30 months of age.

Introduction

Children's early language environment is crucial for their emerging language abilities (Hoff & Naigles, 2002; Weizman & Snow, 2001), which are in turn associated with later literacy skills (Rodriguez & Tamis-LeMonda, 2011; Vernon-Feagans et al., 2022). For instance, children exposed to a large quantity of high-quality language input – longer utterances, higher grammatical complexity, more vocabulary diversity – have larger vocabularies (Huttenlocher et al., 2010; Laing & Bergelson, 2019; Rowe, 2012). In addition, children who are exposed to more child-directed speech early in development have faster language processing abilities (Weisleder & Fernald, 2013), show larger vocabularies (Fernald et al., 2006), and have better language outcomes (Marchman & Fernald, 2008).

Critically, there are large individual differences in the quantity and quality of language input that children receive from their caregivers. This variation may be associated with the caregiver's socio-economic status (SES) (Golinkoff et al., 2019), a complex index of a family's social and financial resources often based on parental education and/or income. Some studies using manual annotation of children's in-home speech exposure report that parents from higher SES backgrounds talk more and use richer language input with their children (Hart & Risley, 1995; Hoff, 2003; Huttenlocher et al., 2010; Rowe, 2012). Such variations could be due to multiple contextual influences such as high parental stress and economic instability in low SES families (Hoff, 2006). However, recent research has questioned whether variations in input quantity and quality are strictly associated with SES, because there also seems to be substantial variation in children's language environments within each socioeconomic stratum (Sperry et al., 2019).

These findings have sparked a debate about the strength of the association between SES and children's language experiences. One focus of this debate is differences in the methods used to gather input quantity data. To overcome possible observer effects (Dudley-Marling & Lucas, 2009; Zegiob et al., 1975), a recent meta-analysis examined the strength of the relationship between SES and children's language experiences measured with the Language ENvironment Analysis (LENA^{TM}) system (Piot et al., 2022), a recorder and software that generates automatic analyses of the speech occurring in the child's home environment (Gilkerson et al., 2017). The meta-analysis found quantitative differences of SES on children's home language experiences showing it is possible to capture differences in children's language environments as a function of SES using automatized measures (Piot et al., 2022).

Recent research has also shown links between language exposure and brain development. One study used LENA^{TM} home audio recordings to measure children's language exposure and a story-listening functional MRI task to measure brain activation (Romeo, Leonard et al., 2018). Children between 4 and 6 years of age who had experienced more conversational turns with adults showed greater left inferior frontal activation near Broca's area in the fMRI task. Interestingly, these effects were independent of SES, IQ, and the quantity of adult-child utterances. A second study using diffusion tensor imaging (DTI) techniques (Romeo, Segaran et al., 2018) with the same sample of 4-to-6-year-old children also found a relationship between amount of conversational experience and FA values in white matter tracts most associated with language including the left Arcuate Fasciculus (AF) that connects Broca's area with Wernicke's area as well as the Superior Longitudinal Fasciculus (SLF). Once again, these relationships were independent of SES and the quantity of adult language input. Other literature also supports the role of the AF in language skill in adults (López-Barroso et al., 2015; Rodríguez-Fornells et al., 2009; Vaquero et al., 2017) as well as in 4-year-old children (François et al., 2019). The SLF has also been associated with language abilities in adults (Madhavan et al., 2014). The youngest children from these studies were 4 years of age; thus, an important question is whether these relationships hold earlier in development when language abilities are first emerging.

To our knowledge, there is only one study that has looked at relationships between children's language environment, SES and brain development in infancy. This study used LENA^{TM} home language input estimates and EEG activity in a diverse sample of 6- to 12-month-old infants. Home language environment, independent of SES, accounted for disparities in early language abilities (Brito et al., 2020). Interestingly, the relationships between language input and brain activity were negative. These negative associations may reflect a positive relationship between the amount of chaos in the home and the amount of language input to children. In particular, children living in high-chaos households who heard more adult words tended to have reduced brain activity (Brito et al., 2020).

The goal of the present study was to investigate the relationships among children's home language input, SES, and brain myelination in language-related brain regions early in development in a group of 6- and 30-month-old children learning British English. We gathered three types of data: day-long in-home recordings of language experience to infants using the LENA^{TM} system, SES information based on maternal education, and brain myelination using the mcDESPOT-MRI protocol (Deoni et al., 2012). We obtained individual myelin water fraction maps in all participants (Deoni & Kolind, 2015) and registered them to a common group space to extract myelin concentrations from white matter tracts most associated with language processing and cognitive control: the SLF and the AF.

We measured myelin concentration using the mcDESPOT protocol as this approach appears to measure changes in brain myelination more directly than traditional diffusion-weighted imaging, particularly in early development (Deoni et al., 2012; Gilmore et al., 2018). For example, early brain maturation is accompanied not only by the establishment of the myelin sheath itself, but also by the arrival of precursory lipid and proteins, compartmentalization of water, and iron within the oligodendrocytes. Each of these processes can lead to changes in both T1 and T2 relaxation (MacKay et al., 2006), while myelin water fraction appears to be more sensitive to changes in the embellishment of the myelin sheath itself (Deoni et al., 2012). Furthermore, the mcDESPOT method has been validated using multiple approaches (Deoni et al., 2012; Deoni et al., 2011; Hurley et al., 2010; Kitzler et al., 2012; Kolind et al., 2012).

Our emphasis on structural brain changes in early development reflects the very rapid changes in the brain in the first years of life. Brain volume increases dramatically in the first year, with brain volume about 80% of the adult size by age 2. In terms of white matter growth, myelination in infancy begins in the cerebellum, pons, and internal capsule and proceeds in a 'back to front' pattern from the optic radiations to the occipital and parietal lobes and then to the frontal and temporal lobes (Deoni et al., 2012; Deoni et al., 2011; Mori et al., 2008).

In an initial analysis, we looked at the relationships between LENA™ measures (amount of adult words, conversational turns and child vocalizations) and children's SES based on maternal education. The aim was to see if the LENA™ output measures followed expected developmental trends across our two age groups. Next, we examined how early brain myelination is related to both language exposure and SES by measuring in-home language experience and structural brain development at 6 and 30 months of age. These ages are particularly important because 6-month-old children have high brain plasticity, relatively little brain myelin, and less experience with language. Thus, language input could have a smaller impact on brain structure at this early age. On the contrary, by 30 months of age, most children are able to understand and produce a large number of words (Frank et al., 2017). At 30 months, therefore, language input might have a strong influence on structural brain development, and there might be stronger associations with contextual factors such as SES. A final set of exploratory analyses considered whole-brain myelination in relation to children's home language experience.

Materials and Methods

Experimental Design and Pre-registration

This study was modelled after another study looking at the relationships between language input and myelination in the brain (Romeo, Segaran et al., 2018). In our case, we extended these results to a younger population. A priori hypotheses and main analyses were preregistered (see OSF Pre-registration). Our specific hypotheses were: H1) At both 6 months and 30 months, amount of adult input and measures of conversational experience will be positively related to white matter concentrations along fiber tracts known to be involved in language processing and cognitive control: SLF and AF (Catani et al., 2005). H2) Measures of conversational experience will be more relevant at older ages as language production increases at 30 months. This should boost the strength of the relationship between conversational turns and white matter concentrations in SLF and AF. We established that our confirmatory analyses would focus on the relationships between language input, SES, and myelin in the AF and the SLF fiber tracks in both hemispheres. We decided to include both hemispheres because at very early ages, brain function is less lateralized than later in development (Deoni et al., 2015). In a set of exploratory analyses, we planned to look at whole-brain myelination since this is the first study to measure language input, SES, and brain myelination early in development.

Participants

We collected language home input data for 163 children from two age groups: a 6-month-old group ($N = 87$, 42 girls between 4.28 and 13.77 months, $M = 6.75$, $SD = 1.54$) and a 30-month-old group ($N = 76$, 40 girls between 28.49 and 36.41 months, $M = 30.94$, $SD = 1.85$). For a subset of those participants ($N = 84$ children), we also collected measures of brain myelination using MRI at a similar time point (difference between the age of LENA™ collection and MRI collection was $M = 0.73$ months, $SD = 1.94$ months, range -4.05 to 7.13). This subsample included 38 6-month-olds (14 girls; MRIs collected between 4.93 and 10 months of age) and 46 30-months-olds (22 girls; MRIs collected between 28.61 and 35.15 months of age). These participants were white (N = 79, 94.05%), mixed (N = 4, 4.76%) and african (N = 1, 1.2%). All children were native speakers of British English and were not exposed to another primary language at home. Participants had no history of premature birth, neurological disorders or developmental delay (see Table 1 for more details).

Eight additional children were not included in these analyses because they did their LENA™ recording(s) when they were much older (3) than the other children in their cohort (older than 15 months for the 6-month-old group, and older than 37 months for the 30-months-old group) or they had myelin data but no language input data (5). All procedures used in this study were reviewed and approved by the UK NHS Health Research Authority Ethics committee (IRAS ID 196063). Parents signed an informed consent form and received £20 for attending the MRI session. Children received a small toy of their choosing and a t-shirt with the Lab logo for participating. The participants from this study are also part of a larger longitudinal project examining the early development of working memory and executive function. Note that the target sample size for each cohort (6 and 30 months) was 40 based on a power analysis conducted for the larger project (where power was estimated at .99 and .86 across two sample analyses). Due to the challenges of longitudinal designs and MRI data collection with young children as well as to protect against drop-out over time, we over-sampled yielding an N of approximately 80 for each cohort.

Table 1

Demographic Information of the Sample

Participant SES Related Variables (N = 84)	
Cohort (Average age between LENA™ and MRI)	*Mean(SD)*
6-months-old group	7.16 (1.46)
30-months-old group	31.35 (1.57)
Maternal Education (Main Caregiver)	*Total(Percent)*
Left School	1 (1.19%)
GCSE/O levels equivalent	13 (15.48%)
A levels or equivalent	8 (9.52%)
Trade apprenticeship	2 (2.38%)
Some University	10 (11.90%)
Bachelor's Degree	33 (39.28%)
Master's Degree	10 (11.90%)
Doctorate or Professional Degree	7 (8.33%)
Annual Household Income (Median in GBP)	*Total(Percent)*
5200	1 (1.19%)
7799.5	1 (1.19%)
12999.5	4 (4.76%)
18199.5	8 (9.52%)
28599.5	9 (9.64%)
33799.5	8 (9.64%)
38999.5	3 (3.61%)
44199.5	22 (27.71%)
52000	28 (34.94%)

Note. Participant's age is reported in months.

Socioeconomic Status Measures

We gathered information on the socioeconomic background of each participant and their family using a questionnaire that asked the main two caregivers to provide their level of education as well as the family annual household income. Studies have used multiple measures to calculate SES including family income, maternal education, average parental education or a composite score based on multiple measures (Romeo, Segaran et al., 2018). Our sample's SES was relatively homogeneous, especially regarding family income: 72.62% of our sample had an annual household income higher than 29,400 GBP which was the median household income in the UK in 2019 (Neill, 2019) when these data were primarily collected. However, our sample showed more variability in the level of maternal education with 59.52% of mothers having completed a higher education degree (see Table 1). Maternal education has been broadly used as a proxy for SES in many studies investigating SES in relation to language development, and it seems to be the component of SES most strongly related to child development outcomes (Pace et al., 2017). Here, we calculated the z-score for participants' maternal education as the primary SES variable.

Language Input Measures

The linguistic environment of the child was measured using the LENA^{TM} Pro system (Gilkerson et al., 2017). The LENA^{TM} system is composed of a recorder and associated analysis software. The small recorder can be worn in a vest by the target child at home and it can store up to 16 hours of audio recordings. The LENA^{TM} software automatically processes the recordings and estimates the number of words spoken by an adult in the child's vicinity which is referred to as adult word count (AWC), the number of vocalizations the target child made or child vocalizations count (CVC), and the number of dyadic conversational turns or conversational turn count (CTC), which is defined as a discrete pair of consecutive adult and child utterances in any order, with no more than 5 seconds of separation. Families took the LENA^{TM} recorder home on three different days when they did not attend nursery. During those days, the child wore the recorder in a specially constructed vest for a maximum of 16 hours (in total we gathered 6208.63 hours of LENA^{TM} recordings, with an average of 15.31 hours per day). Each child contributed between 1 and 3 days of recordings (M = 2.48, SD = 0.73). We processed the recordings using the LENA^{TM} Pro software, which automatically calculated the estimates for each measure (adult words, child vocalizations, and conversational turns). These data were then processed with R (R Core Team, 2021) using a similar approach as in previous studies (Romeo, Segaran et al., 2018). In particular, for each LENA^{TM} outcome measure and participant, we calculated the total count for each consecutive 60 min across all LENA^{TM} days, in 5 min increments. For example, we extracted the total amount of adult words that the child was exposed to between 7AM and 8AM, then we calculated the total amount of adult words between 7:05AM and 8:05AM, and so on. We then selected the hour with the highest number of adult words (i.e., the max hour). We used this procedure to extract the hour with the maximum adult word count, the hour with the maximum child vocalizations count, and the hour with the maximum turn count across the several days of home recordings that each participant provided. This maximum measure was used in all the analyses reported here.

Myelin Data Acquisition

The MRI scans were gathered at the Norfolk and Norwich University Hospital. Prior to scanning, children were brought to a 'sleepy room' adjacent to the MRI room to fall asleep (Deoni et al., 2011). This was a special quiet room where children were not disturbed, it included a bed with a comfortable blanket and several children's books, as well as an infant monitor and nightlight. The bed children slept on had a foam mattress on top of a plexiglas platform that was specially designed to fit into the head coil and scanner bore. Children slept on top of the foam mattress with a 'slippy sheet' under the top bedsheet (so the child could be easily shifted once asleep). Parents were encouraged to do their typical bedtime routine in the sleepy room, and then we waited until the child was asleep (which took anywhere from 5 minutes to 2-3 hours). The experimenters then quietly entered the room, adjusted the child so the head was positioned correctly on the plexiglas platform, lifted the platform onto an MRI-compatible plastic trolley, and then rolled the child into the scanning room. Finally, the child was positioned in the head coil, the child's ears were covered with noise-cancelling headphones, and the child was moved into the bore (all while the child was sleeping). An experimenter remained with the child throughout the scan to stop the scan if the child woke up or moved substantially. To maximize success, we additionally used these strategies: added a sound-insulating insert to the MR bore (Ultra Barrier, American Micro Industries), used electrodynamic headphones (MR Confon, Germany), and used customized 'quiet' imaging sequences (Deoni et al., 2011). Participants were scanned during natural sleep. Each participant was imaged using a 3T Discovery 750w MRI scanner (GE Healthcare, Milwaukee, WI, USA) equipped with an 8-channel head coil.

Myelin Data Protocol (mcDESPOT)

Myelin content was mapped using a multicomponent driven equilibrium single pulse observation of T_1 and T_2 (Deoni et al., 2008). Parameters were as follows: repetition time = 750 ms, echo time = 0.02 ms, inversion time = 650 ms, flip angle = 5°, receiver bandwidth = 244 Hz/ voxel, field-of-view = 200 mm x 200 mm, matrix size = 200 x 200, and section thickness = 1 mm. The sequences used as part of the mcDESPOT protocol were: two balanced steady-state free precession (bSSFP) series with phase-cycling increments 0 and 180° to allow for correction of off-resonance artifacts (Deoni, 2011); 8 spoiled gradient echo (SPGR) scans collected over different flip angles; two inversion-recovery SPGR (IR-SPGR) scans for accurate estimation of the B_1 transmit field. Further, all mcDESPOT data were acquired in pure sagittal or coronal orientation, with a field-of-view adjusted for head size and participant orientation, and a matrix size and section thickness chosen to give consistent isotropic resolution of 1.7 x 1.7 x 1.7 mm^3. To reduce acoustic noise, these scans were run with reduced gradient amplitudes and slew rates. This resulted in extended scan time. To minimize scan time, mcDESPOT data were acquired with a partial Fourier factor of 0.75 in k_y and with an ASSET parallel imaging factor of 1.5. The full protocol lasted less than 45 minutes. A member of the research team was present in the scanner suite to monitor the child at all times. The main motivation to use the mcDESPOT technique was that it is more specific to myelination and less sensitive to other biological factors such as axon packing density, axon caliber, microglia, inflammation, and tissue architecture. Moreover, mcDESPOT also allowed the data collection sequence to be quieter than other methods – such as diffusion tensor imaging (DTI) – and therefore, it was less likely to awaken sleeping infants.

Myelin Data Processing

First, the SPGR image with the highest flip angle was selected, and the individual SPGR, IR-SPGR and bSSFP images were all linearly coregistered to that image using *flirt* from FSL (Jenkinson et al., 2002). This accounted for small amounts of motion during the scans. Non-brain tissue and background were then removed from the images. Both the main (B_0) and transmit (B_1) magnetic field inhomogeneities were calculated. Myelin water fraction maps were then calculated in a voxel-wise manner for every subject using the three-pool model (Deoni et al., 2013). The resulting images were then aligned to a custom template using ANTS (Avants et al., 2011) and checked for registration quality. Core white matter tract masks were used to extract the values for the regions examined, namely the AF and the SLF so that only voxels contained in these masks were used for analyses. To create the masks, we used a white matter atlas based on the Providence data set (Deoni et al., 2012), except for the AF mask. For the AF, the white matter tracts were pulled from the atlas created by Figley and colleagues (Figley et al., 2015; Figley et al., 2017), which was based on adult data.

Statistical Analyses

Statistical analyses were conducted using the R software version *4.2.1* using the *lm* function from the stats package (R Core Team, 2021). We did three sets of analyses. Within each set, linear regression models followed a basic structure. Analysis 1 looked at relationships among the LENA™ output measures (number of adult words, conversational turns, and child vocalizations) set as the predicted variable and SES and age group set as the predictor variables. Analysis 2 (confirmatory) used linear regressions to assess whether language input measures predicted myelination in the SLF and AF. Analysis 3 (exploratory) measured the relationship between language input and other brain tracts that have been related to language in previous studies. The model basic structure used on Analyses 2 and 3 set mean myelin concentration on a specific region as the predicted variable and LENA™ measure as predictor variable. The models controlled for SES and age group set as fixed effects and interacting with each other. In all our models, SES was set as a continuous variable and age group was included as a categorical variable (6 months versus 30 months). These two age groups refer to the approximate age when the data were collected. This decision was based on the distribution of age in months, which showed two clusters around 6 and 30 months, and a gap in between. Age group was contrast coded with 6-month-olds set as -0.5 and 30-month-olds set at 0.5. Child gender was not included in the analyses because we did not find consistent effects during Analysis 1 using the LENA™ data only, and it did not significantly improve model fit when doing model comparison (AWC $F(4) = 0.496$, $p = 0.738$), CVC ($F(4) = 1.544$, $p = 0.192$) or CTC ($F(4) = 1.08$, $p = 0.367$). In our exploratory analyses (Analysis 3), we corrected for multiple comparisons, setting our alpha level for the family-wise error at 0.01. Thus, only p values less than 0.01 are considered significant.

Results

Analysis 1: Language Exposure at Home

Our initial analysis included three linear models, one per LENA™ measure. The LENA™ measure was the dependent variable and SES as well as age group were set as predictor variables interacting with each other. This means that we assumed that different values on SES and age group influence each of the LENA™ measures differently, depending on the values of the other interacting variables.

The linear model predicting the number of adult words showed main effects of SES and age group (see Table 2). As can be seen in Figure 1A, children from families with a higher SES score heard more adult words at home that children from families with lower SES scores. Moreover, the number of adult words decreased by age – older children heard fewer adult words than younger children. The linear model predicting child vocalizations also showed main effects of SES and age group. As can be seen in Figure 1C, children's vocalisations increased as a function of their mother's education. Moreover, children also vocalised more with age, as they developed better language skills. Finally, the linear model predicting amount of conversational

Table 2

Linear Regressions Estimates for the three LENA^{TM} outcome measures in relation to SES

LENA^{TM} measure	Term	Estimate	std.Error	*p*.Value
AWC	(Intercept)	4949.514	148.888	**0.001**
	AgeGroup	-1573.770	297.776	**0.001**
	SES	297.816	149.143	**0.048**
	AgeGroup:SES	377.271	298.287	0.208
CVC	(Intercept)	508.751	14.386	**0.001**
	AgeGroup	307.409	28.772	**0.001**
	SES	31.669	14.411	**0.029**
	AgeGroup:SES	30.491	28.822	0.292
CTC	(Intercept)	142.949	4.474	**0.001**
	AgeGroup	68.954	8.948	**0.001**
	SES	8.237	4.482	0.068
	AgeGroup:SES	9.294	8.963	0.301

Note. Results for the three linear models with LENA^{TM} measure as predicted variable: adult word count (AWC), child vocalizations count (CVC) and conversational turn count (CTC). Fixed effects are displayed including age group (6 or 30 months old) and SES. Significant effects are highlighted in bold.

turns only showed a main effect of age group with older children producing more turns than younger children (see Figure 1D).

Analysis 2: Language Exposure and Myelin in Language-Related Fiber Tracts (AF and SLF)

Our second set of analyses used linear models to assess whether the three LENA^{TM} output measures predict myelination in the SLF and AF fiber tracts. We ran linear models with each language exposure measure (adult words, child vocalisations, and conversational turns) predicting mean myelination in the right and left AF and SLF. Models controlled for age group (6 versus 30-months-old) as well as SES (set as a continuous measure based on maternal education z-scores).

Results of our confirmatory analyses showed positive main effects of age group on the AF and the SLF for all the language measures, reflecting the increase in brain myelination with age in those white matter tracts. In our first set of models, we found positive relationships between the amount of adult input (AWC) and myelination in the AF and SLF. The models showed an interaction between the amount of adult input and children's age group on the AF and the right SLF, but not on the left SLF (see Table 3). In particular, larger amounts of adult word input were positively associated with higher quantities of myelin in the AF and SLF in the 30-month-old group (see darker shaded linear trends in the middle graphs in Figure 2). Thus, older children who were exposed to more adult speech had more myelinated language-related fiber tracts. At 6 months, this relationship was reversed: infants who were exposed to more adult speech had lower myelin concentrations in the regions of interest (see lighter color shading in the middle graphs in Figure 2). This pattern became stronger on the right hemispheric regions as family SES increased. This was indicated by a significant interaction between the number of adult words spoken around the child, age group, and SES on the right AF and right SLF (see Table 3). This SES effect can be seen in Figure 2: older children from families with a higher SES score, who were exposed to more adult words, showed greater myelin concentrations in these right hemisphere regions and younger children showed the reversed pattern.

The second set of linear models examining child vocalizations also showed significant relationships between language and myelin concentration. In particular, we found a significant main effect of child vocalizations on brain myelin concentration in the left SLF (see Table 4). As can be seen in Figure2, more vocalisations were associated with less myelin in the left SLF.

Table 3

Linear Regression Estimates for AWC predicting myelination in AF and SLF

Region	Term	Estimate	std.Error	*t*.Statistic	*p*.Value
Left AF	(Intercept)	0.071	0.006	12.390	**0.001**
	AWC	0.001	0.001	0.559	0.578
	AgeGroup	0.060	0.011	5.308	**0.001**
	SES	-0.009	0.005	-1.710	0.091
	AWC:AgeGroup	0.001	0.001	2.323	**0.023**
	AWC:SES	0.001	0.001	1.121	0.266
	AgeGroup:SES	-0.008	0.011	-0.729	0.468
	AWC:AgeGroup:SES	0.001	0.001	0.811	0.420
Right AF	(Intercept)	0.074	0.005	15.769	**0.001**
	AWC	0.001	0.001	-0.282	0.779
	AgeGroup	0.066	0.009	6.944	**0.001**
	SES	-0.006	0.005	-1.441	0.154
	AWC:AgeGroup	0.001	0.001	2.108	**0.038**
	AWC:SES	0.001	0.001	1.680	0.097
	AgeGroup:SES	-0.013	0.009	-1.471	0.146
	AWC:AgeGroup:SES	0.001	0.001	2.059	**0.043**
Left SLF	(Intercept)	0.094	0.007	14.090	**0.001**
	AWC	0.001	0.001	-0.020	0.984
	AgeGroup	0.085	0.013	6.353	**0.001**
	SES	-0.007	0.006	-1.136	0.260
	AWC:AgeGroup	0.001	0.001	1.415	0.161
	AWC:SES	0.001	0.001	0.721	0.473
	AgeGroup:SES	-0.013	0.013	-1.015	0.313
	AWC:AgeGroup:SES	0.001	0.001	1.130	0.262
Right SLF	(Intercept)	0.096	0.005	17.605	**0.001**
	AWC	0.001	0.001	-0.312	0.756
	AgeGroup	0.081	0.011	7.472	**0.001**
	SES	-0.004	0.005	-0.727	0.469
	AWC:AgeGroup	0.001	0.001	2.114	**0.038**
	AWC:SES	0.001	0.001	1.045	0.299
	AgeGroup:SES	-0.014	0.010	-1.392	0.168
	AWC:AgeGroup:SES	0.001	0.001	2.052	**0.044**

Note. Fixed effects are displayed including adult word count (AWC), age group (6 or 30 months) and maternal education z-score (SES). Alpha is set at 0.05 (significance level p<.05) effects below this threshold are highlighted in bold.

Our final set of confirmatory models examined brain myelination and conversational turns. Besides the main age group effects, we did not find any significant relationships between amount of conversational turns and myelin concentrations in the AF and SLF (see Table 5).

Finally, we also examined the intersection of the AF and SLF in a preliminary analysis. The overlap found between the AF and SLF was minimal. On the left side, there was a proportion voxel overlap of 0.138; on the right side, there was a proportion voxel overlap of 0.165. As a check, we re-run Analysis 2 on the non-overlapping masks. The results replicate all of our findings from Tables 3, 4, 5 except for the effects for the Right AF where the 2-way interaction between AWC and age group (p=0.054) and the 3-way interaction between AWC, age group and SES (p=0.050) Details from these analysis can be seen on our online Supplementary Materials.

Overall, results from the confirmatory analyses showed that the amount of adult language speech that children are exposed to at home is positively associated with brain myelination in the AF and SLF at 30 months. This partially confirms our first hypothesis (H1). However, we found negative associations between adult word input and brain myelination in younger children in the 6-month-old group. Our second hypothesis (H2) was that conversational experience would positively predict brain myelination at 30 months. This was not supported by our analyses.

Table 4

Linear Regression Estimates for CVC predicting myelination in AF and SLF

Region	Term	Estimate	std.Error	*t*.Statistic	*p*.Value
Left AF	(Intercept)	0.082	0.006	14.040	**0.001**
	CVC	0.001	0.001	-1.821	0.073
	AgeGroup	0.082	0.012	7.048	**0.001**
	SES	-0.007	0.007	-1.036	0.303
	CVC:AgeGroup	0.001	0.001	0.794	0.430
	CVC:SES	0.001	0.001	0.596	0.553
	AgeGroup:SES	-0.003	0.013	-0.224	0.823
	CVC:AgeGroup:SES	0.001	0.001	-0.085	0.932
Right AF	(Intercept)	0.073	0.005	14.804	**0.001**
	CVC	0.001	0.001	-0.507	0.614
	AgeGroup	0.078	0.010	7.874	**0.001**
	SES	0.001	0.006	0.168	0.867
	CVC:AgeGroup	0.001	0.001	0.974	0.333
	CVC:SES	0.001	0.001	0.096	0.924
	AgeGroup:SES	0.015	0.011	1.387	0.170
	CVC:AgeGroup:SES	0.001	0.001	-1.207	0.231
Left SLF	(Intercept)	0.105	0.007	15.868	**0.001**
	CVC	0.001	0.001	-2.098	**0.039**
	AgeGroup	0.097	0.013	7.305	**0.001**
	SES	-0.008	0.007	-1.124	0.264
	CVC:AgeGroup	0.001	0.001	1.094	0.277
	CVC:SES	0.001	0.001	0.761	0.449
	AgeGroup:SES	-0.002	0.015	-0.158	0.875
	CVC:AgeGroup:SES	0.001	0.001	-0.194	0.846
Right SLF	(Intercept)	0.097	0.006	17.199	**0.001**
	CVC	0.001	0.001	-1.049	0.297
	AgeGroup	0.095	0.011	8.436	**0.001**
	SES	0.001	0.006	-0.065	0.949
	CVC:AgeGroup	0.001	0.001	1.245	0.217
	CVC:SES	0.001	0.001	0.574	0.568
	AgeGroup:SES	0.025	0.013	1.954	0.054
	CVC:AgeGroup:SES	0.001	0.001	-1.724	0.089

Note. Fixed effects are displayed including child vocalisation count (CVC), age group (6 or 30 months) and maternal education z-score (SES). Alpha is set at 0.05 (significance level p<.05) effects below this threshold are highlighted in bold.

Analysis 3. Language Experience and Overall Brain Myelination

Our last set of analyses aimed to explore the effect of in-home language exposure on overall brain development. We conducted exploratory analyses using a similar set of linear models as in Analysis 2, but now looking at a larger number of brain regions. As in the previous models, we controlled for age group (6 versus 30 months of age) and SES (using a continuous z-score based on maternal education). From a list of 21 brain region templates that we had available from the Deoni et al. (2012) study, we selected the 17 brain regions that have been previously associated with language. These areas consisted of the body and genu of the Corpus Callosum, as well as both the left and right areas of the Cerebellum, Cingulum, Corona Radiata, Internal Capsule and Frontal, Parietal and Temporal lobes. We decided to exclude the right and left Occipital lobes and the Optic Radiation because they seemed to be unrelated to language in previous studies. In addition, we only considered maximum adult words per hour (AWC) as a measure of language experience because this was the LENA™ measure that showed stronger relationships to myelin concentrations in our a priori regions of interest (Analysis 2). Also, recall that in Analysis 3, we set our alpha level at 0.01 to control the family-wise error rate.

All brain areas showed a strong positive age main effect, indicating that myelin concen-

Table 5

Linear Regression Estimates for CTC predicting myelination in AF and SLF

Region	Term	Estimate	std.Error	*t*.statistic	*p*.value
Left AF	(Intercept)	0.080	0.006	13.154	**0.001**
	CTC	0.001	0.001	-1.213	0.229
	AgeGroup	0.091	0.012	7.473	**0.001**
	SES	-0.012	0.010	-1.178	0.242
	CTC:AgeGroup	0.001	0.001	-0.138	0.891
	CTC:SES	0.001	0.001	0.742	0.460
	AgeGroup:SES	-0.002	0.020	-0.123	0.902
	CTC:AgeGroup:SES	0.001	0.001	-0.061	0.952
Right AF	(Intercept)	0.074	0.005	14.314	**0.001**
	CTC	0.001	0.001	-0.669	0.506
	AgeGroup	0.079	0.010	7.578	**0.001**
	SES	-0.011	0.008	-1.298	0.198
	CTC:AgeGroup	0.001	0.001	0.865	0.390
	CTC:SES	0.001	0.001	1.253	0.214
	AgeGroup:SES	0.018	0.017	1.060	0.293
	CTC:AgeGroup:SES	0.001	0.001	-1.085	0.281
Left SLF	(Intercept)	0.102	0.007	14.789	**0.001**
	CTC	0.001	0.001	-1.187	0.239
	AgeGroup	0.112	0.014	8.153	**0.001**
	SES	-0.015	0.011	-1.301	0.197
	CTC:AgeGroup	0.001	0.001	-0.338	0.736
	CTC:SES	0.001	0.001	0.815	0.418
	AgeGroup:SES	-0.009	0.022	-0.401	0.689
	CTC:AgeGroup:SES	0.001	0.001	0.178	0.859
Right SLF	(Intercept)	0.096	0.006	16.154	**0.001**
	CTC	0.001	0.001	-0.785	0.435
	AgeGroup	0.095	0.012	7.999	**0.001**
	SES	-0.013	0.010	-1.356	0.179
	CTC:AgeGroup	0.001	0.001	1.030	0.306
	CTC:SES	0.001	0.001	1.410	0.163
	AgeGroup:SES	0.028	0.019	1.437	0.155
	CTC:AgeGroup:SES	0.001	0.001	-1.348	0.182

Note. Fixed effects are displayed including conversational turn count (CTC), age group (6 or 30 months) and maternal education z-score (SES). Alpha is set at 0.05 (significance level $p<.05$) effects below this threshold are highlighted in bold.

trations increased with age. In addition, six regions showed significant variations in myelin concentrations below our threshold as a function of adult input and/or SES (see Table 6).

Results from the left Frontal region mimicked findings from the left AF (see Figure 3). In particular, we found positive relationships between myelin concentration and the amount of adult input for 30-month-old children in the left Frontal region, and negative relationships between myelin and adult input for 6-month-olds. Similarly, we found a statistical correspondence between the right Frontal region and the right AF in that both regions showed a significant 3-way interaction of adult word count by age group by SES. As can be seen in Figure 3, high SES 30-month-old children showed a positive relationship between myelin concentration and the amount of adult input, while 6-month-old infants showed a negative relationship. There was also a slight negative relationship between myelin concentration and adult input for low SES 30-month-olds.

This same pattern of results was evident for the right Corona Radiata, the left Internal Capsule, and the genu of the Corpus Callosum, with significant 3-way interactions in all cases (see Table 6 and Figure 3). The body of the Corpus Callosum showed a similar pattern; however, in this case, there was only a significant interaction between adult word count and SES, with

Table 6

Linear Regression Estimates for AWC predicting myelination in the brain

Side/Area	Region	Term	Estimate	std.Error	*t*.statistic	*p*.value
Left	Frontal	(Intercept)	0.064	0.005	13.636	**0.001**
		AWC	0.001	0.001	-0.063	0.950
		AgeGroup	0.061	0.009	6.503	**0.001**
		SES	-0.008	0.005	-1.669	0.099
		AWC:AgeGroup	0.001	0.001	2.824	**0.006**
		AWC:SES	0.001	0.001	1.594	0.115
		AgeGroup:SES	-0.013	0.009	-1.452	0.151
		AWC:AgeGroup:SES	0.001	0.001	1.681	0.097
Right	Frontal	(Intercept)	0.066	0.005	13.942	**0.001**
		AWC	0.001	0.001	-0.417	0.678
		AgeGroup	0.071	0.010	7.482	**0.001**
		SES	-0.012	0.005	-2.621	0.011
		AWC:AgeGroup	0.001	0.001	2.005	0.049
		AWC:SES	0.001	0.001	2.947	**0.004**
		AgeGroup:SES	-0.025	0.009	-2.752	**0.007**
		AWC:AgeGroup:SES	0.001	0.001	3.202	**0.002**
Left	Internal Capsule	(Intercept)	0.088	0.005	16.520	**0.001**
		AWC	0.001	0.001	-0.490	0.626
		AgeGroup	0.069	0.011	6.530	**0.001**
		SES	-0.008	0.005	-1.592	0.116
		AWC:AgeGroup	0.001	0.001	0.534	0.595
		AWC:SES	0.001	0.001	1.677	0.098
		AgeGroup:SES	-0.018	0.010	-1.818	0.073
		AWC:AgeGroup:SES	0.001	0.001	2.653	**0.010**
Right	Corona Radiata	(Intercept)	0.086	0.005	18.160	**0.001**
		AWC	0.001	0.001	-0.482	0.631
		AgeGroup	0.086	0.010	9.028	**0.001**
		SES	-0.010	0.005	-2.301	0.024
		AWC:AgeGroup	0.001	0.001	2.026	0.046
		AWC:SES	0.001	0.001	2.695	**0.009**
		AgeGroup:SES	-0.024	0.009	-2.594	0.011
		AWC:AgeGroup:SES	0.001	0.001	3.317	**0.001**
Body	Corpus Callosum	(Intercept)	0.079	0.005	15.426	**0.001**
		AWC	0.001	0.001	-1.007	0.317
		AgeGroup	0.084	0.010	8.138	**0.001**
		SES	-0.014	0.005	-2.767	**0.007**
		AWC:AgeGroup	0.001	0.001	1.534	0.129
		AWC:SES	0.001	0.001	2.735	**0.008**
		AgeGroup:SES	-0.016	0.010	-1.576	0.119
		AWC:AgeGroup:SES	0.001	0.001	2.217	0.030
Genu	Corpus Callosum	(Intercept)	0.081	0.005	14.959	**0.001**
		AWC	0.001	0.001	-0.941	0.350
		AgeGroup	0.098	0.011	9.054	**0.001**
		SES	-0.012	0.005	-2.246	0.028
		AWC:AgeGroup	0.001	0.001	1.669	0.099
		AWC:SES	0.001	0.001	2.738	**0.008**
		AgeGroup:SES	-0.023	0.010	-2.244	0.028
		AWC:AgeGroup:SES	0.001	0.001	2.923	**0.005**

Note. Fixed effects are displayed including adult word count (AWC), age group (6 or 30 months) and Maternal Education z-score (SES). Alpha is set at $p<0.01$, effects below this threshold are highlighted in bold.

higher SES children tending toward a positive relationship between myelin concentration and adult input while lower SES children showed a negative relationship.

Discussion

In this study, we examined the relationship between language experience, SES and myelination in the brain early in development. We hypothesized that more conversational turns and adult input would predict brain myelination in language-related areas, particularly at older ages. Toward that aim, we conducted three analyses with the purpose of quantifying the LENA™ measures (Analysis 1), confirming or refuting our hypotheses (Analysis 2) and, more broadly, exploring relationships between children's language experience, SES and overall brain myelination (Analysis 3).

Analysis 1 was used as a primary validation of the LENA™ system in our sample of participants with the variables of interest. We discovered that the number of adult words was related to children's SES, with children with more highly educated mothers being exposed to higher amounts of overall adult input than children with less educated mothers. Quantity of children's vocalizations was also associated with SES: children with more educated mothers produced more vocalizations. This finding was somewhat surprising given that our sample was relatively homogeneous with most children coming from middle and high SES backgrounds. This indicates that even small differences in SES (in this study indexed by maternal education) can have an effect on the amount of adult input children experience early in life and the amount of vocalizations that they produce.

Analysis 2 was the main focus of this study; quantifying the impact of early language experiences on myelination of the AF and SLF white matter tracts. Our findings showed that the amount of adult word input was the only language measure strongly associated with myelin concentration in the AF and SLF. In particular, the concentration of myelin in the AF and SLF was higher with more adult word input at 30 months of age. Therefore, this age group followed the pre-registered predicted pattern: more adult input was positively associated with greater myelin concentrations in the left and right AF and SLF. We did not have specific predictions regarding the effects of SES in our sample, as SES did not account for differences in neural connectivity in the brain in previous studies (Romeo, Segaran et al., 2018). However, we found relationships between myelin, age and SES in the right areas of the AF and the SLF with a stronger positive relationship between myelin concentration and adult input for higher SES 30-month-old children.

For the 6-month-old group, we generally found a negative relationship between amount of adult words and myelin concentration. These negative relationships should be interpreted with caution as myelin concentrations are quite low at the age of 6 months and might be susceptible to noise in the MRI data (Lankford & Does, 2013). Nevertheless, other studies have also found negative relationships between home language input and brain activity in children aged 6 to 12 months (Brito et al., 2020). These researchers related this effect to more chaos at home. We did not measure chaos at home; thus, future work will be needed to examine these relationships in more detail. Another possibility is that the negative relationships between myelin and adult input at 6 months reflect a delay in myelination in high functioning infants. Deoni et al. (2016) reported that higher cognitive ability in the first year of life was associated with slower initial development of myelin, followed by a prolonged period of rapid development thereafter. Based on this, they suggested that an early period of slowed myelination may coincide with increased synaptogenesis with a prolonged period of synaptic pruning after the first year. Thus, our findings may reflect slower initial development of myelin in high functioning 6-month-olds who receive more adult input.

Our results did not show an effect of conversational turns on AF and SLF myelination as previously reported in 4- to 6-year-olds (Romeo, Segaran et al., 2018). It is important to note, however, the our study had several methodological differences relative to this prior work. Romeo, Segaran et al. (2018) used DTI techniques and individually defined white matter tracts to assess brain myelination. By contrast, we measured average myelin concentration from specific brain regions defined using group templates. Note that it was not possible to acquire both DTI and myelin data in our sample because the mcDESPOT scans took 35-45 minutes to acquire at which point many children started to wake up. It is possible, therefore, that the absence of conversational turn effects in our study reflects these methodological differences. It is also possible that conversational turns have an effect on the brain later in development as children learn more language. In fact, studies looking at the relationships between quantity and quality of language input show that children might benefit from different aspects of language input at different time points depending on their language abilities (Rowe, 2012). Early in development, quantity of language input – which in our study was measured by the number of adult words – seems to be more relevant for children's emerging language skills. In contrast, quality of language input – richness of words, utterance length, and conversational experience – may be more relevant for children at older ages, consistent with effects reported in previous studies (Romeo, Segaran et al., 2018). This would explain why we found that amount of adult input is more strongly predictive of myelin in the AF and SLF at 30 months, while previous research shows that conversational turns are more relevant at 4 to 6 years of age (Romeo, Segaran et al., 2018). Another difference between our findings and prior work is that our results showed effects in both right and left hemispheres for the AF and only the right hemisphere for the SLF. This is consistent with work suggesting that the brain is less lateralized for language early in development, with left areas gaining more specialization for language as children gain language skills.

Our results also diverge in that we found SES effects in our sample, with children from more highly educated mothers being exposed to more adult words and showing higher myelin concentrations in the right AF and right SLF. It is possible that early in development, children are more sensitive to the effects of lower maternal education than later at 4 - 6 years of age (although note that Romeo, Segaran et al. (2018) only measured the left AF and SLF and used a different SES measure). Moreover, it could be that SES effects are more pronounced for amount of adult speech in comparison to conversational turns, in fact, we found a main effect of SES on amount of adult words but not on conversational turns in Analysis 1. It is particularly interesting that across our analyses, we found consistent differences with maternal education (especially when related to amount of adult speech) in a population that is relatively homogeneous. This suggests that SES might impact development even in less diverse contexts. That said, SES is a highly complex construct that should be interpreted carefully, even in an homogeneous population. This is because SES effects are likely to vary across populations and countries as well as based on how SES is captured (i.e., based on income, parental education or composite scores derived from those measures). Future work will be needed to address these open questions.

We also note that the current study is one piece of a larger longitudinal study which also includes behavioural tasks measuring language skill, attention and memory. Thus, further analyses using additional measures and at later time points will help disentangle how the 6-month-old and the 30-months-old findings are related, and how they might be associated to children's language abilities beyond input and output quantity. Ultimately, we hope to understand how language skill and brain myelination co-develop within individuals and what role language input and SES might play in that path. We also hope to clarify why our SES effects were largely focused in the right hemisphere and how these effects are modulated over development. It is possible that the role of SES changes throughout development as other individual differences and socio-cultural factors play out.

Our exploratory analyses looked at possible relationships between language experience and myelin concentrations in a broad range of brain regions. After family-wise correction, results showed relationships between the amount of adult input and myelin concentrations in the the left and right Frontal lobe, the left Internal Capsule and the right Corona Radiata, and the body and genu of the Corpus Callosum. These results largely followed the same pattern as our confirmatory analyses: more adult input was associated with more myelin in the 30-months-old group and this relationship was reversed in the 6 month-old group. These relationships where more pronounced in 30-month-old children from higher SES families, with some negative relationships found with 30-month-old children from lower SES families. It is not clear why we found inverse effects in some brain regions at 30 months of age.

Interestingly, structural brain development in these brain regions has been linked to aspects of language development in prior work. The genu is an early developing part of the Corpus Callosum. Myelin concentration in this tract has been related to receptive language in early development (O'Muircheartaigh et al., 2014). Similarly, the genu and body of the Corpus Callosum have been both linked to early cognitive scores measured using the Mullen Scales of Early Learning (Deoni et al., 2016). The structural development of the left Internal Capsule has also been related to language measures in prior work. In particular, white matter in the left Internal Capsule (measured using DTI) is related to reading scores in 7- to 10-year-old children ((Fletcher et al., 1992; Qiu et al., 2008). Similarly, less white matter in the right Corona Radiata has been linked to reading dysfluencies in 11-year-old children (Lebel et al., 2019). In this context, it is interesting to note that our study is one of the first to look at myelin and language development before the onset of formal reading; thus, our data suggest a role for these fiber tracts in processing language in pre-reading children. It would be interesting in this context to expand the number of regions we examined in future work to look at additional brain areas associated with language such as the Uncinate Fasciculus (Papagno, 2011), the Inferior Longitudinal Fasciculus (Del Tufo et al., 2019), the Inferior Fronto-Occipital Fasciculus (Almairac et al., 2015), or the Frontal Aslant Tract (Dick et al., 2019).

Finally, our home language input measures relied on the LENA™ automated estimates, which are a big advantage over high time consuming manual annotations of daylong recordings. However, a limitation of this method (and of this study) is that it is difficult to know precisely what the LENA™ estimates for adult words are capturing since they might contain both child-directed and overheard speech. Moreover, there are some open questions about the reliability of the LENA estimates, particularly for conversational turns which were found to have low-to-moderate correlations (CTC $r = .36$) when compared to human transcriptions, as opposed to higher correlations coefficients for adult words (AWC $r=.79$) and child vocalizations (CVC $r=.77$) (Cristia et al., 2020). Manual transcription techniques are not a feasible option when used over large amounts of daylong recording data. This is why, it is important that future research tools similar to the LENA™ are developed with a focus on even more reliable estimates, and that can make a distinction between child-directed speech and overheard speech. This is especially important because a recent meta-analysis comparing SES groups in terms of child-directed word counts and overall word counts, found a larger effect for child-directed estimates and lower effects for overall estimates, which would be equivalent to the AWC estimate used in our study. The results of this meta-analysis mostly relied on manually annotated naturalistic data rather than on automatic estimates of home input data, such as those derived by the LENA™. However, they suggest that SES may influence child-directed speech quantities even more than overall amount of speech (Dailey & Bergelson, 2022). Finally, the qualitative proprieties of children's language exposure also play an important role in language development. Conversational turns capture some of those qualitative aspects however, they seem to be the less reliable estimates from LENA™ (Cristia et al., 2020) and they are found in low amounts at early ages since they are highly dependent on children's own productions (a conversational turn necessarily needs a child vocalization). Future studies should look at other qualitative aspects of speech to children — such as word length, vocabulary richness or word repetition — in combination with myelin. It is possible that some of those qualitative aspects of children's language input are more meaningful at very early ages when children produce a limited set of words and sentences.

In summary, our findings suggest that early in development, the amount of adult speech that children hear is crucial for the myelination of language-related brain regions. Moreover, at this early ages, myelin quantity seems to be sensitive to SES differences based on maternal education in a quite homogeneous population. This study is the first to examine the association between socioeconomic status (SES), language development, and myelination in the first two and a half years of life. Therefore, it is essential to conduct further research across more diverse populations in order to gain a better understanding of the impact of SES on early childhood development.

figures/Figure1.pdf

Figure 1: LENA™ measure showing adult word count (AWC) on panel A, a child wearing the LENA™ vest with a LENA™ device inside a pocket on panel B, LENA™ measure showing child vocalization count (CVC) on panel C and conversational turn count (CTC) on panel D. All graphs are split by age group (6 months old versus 30 months old) and median SES (lower SES in light green and higher SES in dark green) based on maternal education.

figures/Figure2.pdf

Figure 2: Relationships between AWC (adult input) and myelin in the left AF (green), right AF (blue) and right SLF (red) as well as CVC (child vocalizations) and myelin concentrations on the left SLF (yellow). Dark shading shows data for the 30-months-old group; light shading shows data for the 6-months-old group. Scatter plots are divided by SES using a median split. Brain images were obtained using MRI scans

figures/Figure3.pdf

Figure 3: Significant relationships found between adult input (AWC) and myelin concentration in the brain. Brain region and tract overlays are shown on the left, each region and tract prior is highlighted in a different color. Right graphs are divided by SES using a median split, dark shading shows data from the 30-months-old group, light shading shows data from the 6-months-old group.

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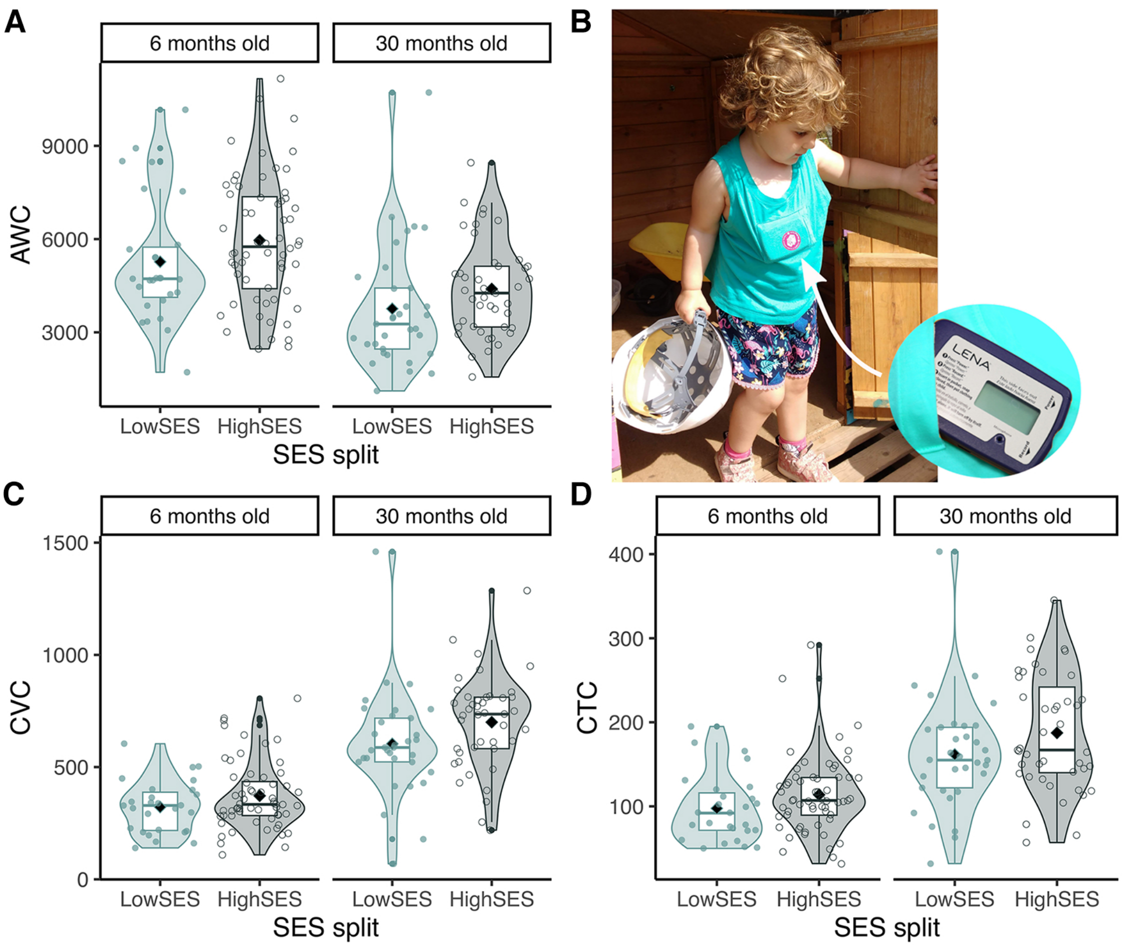
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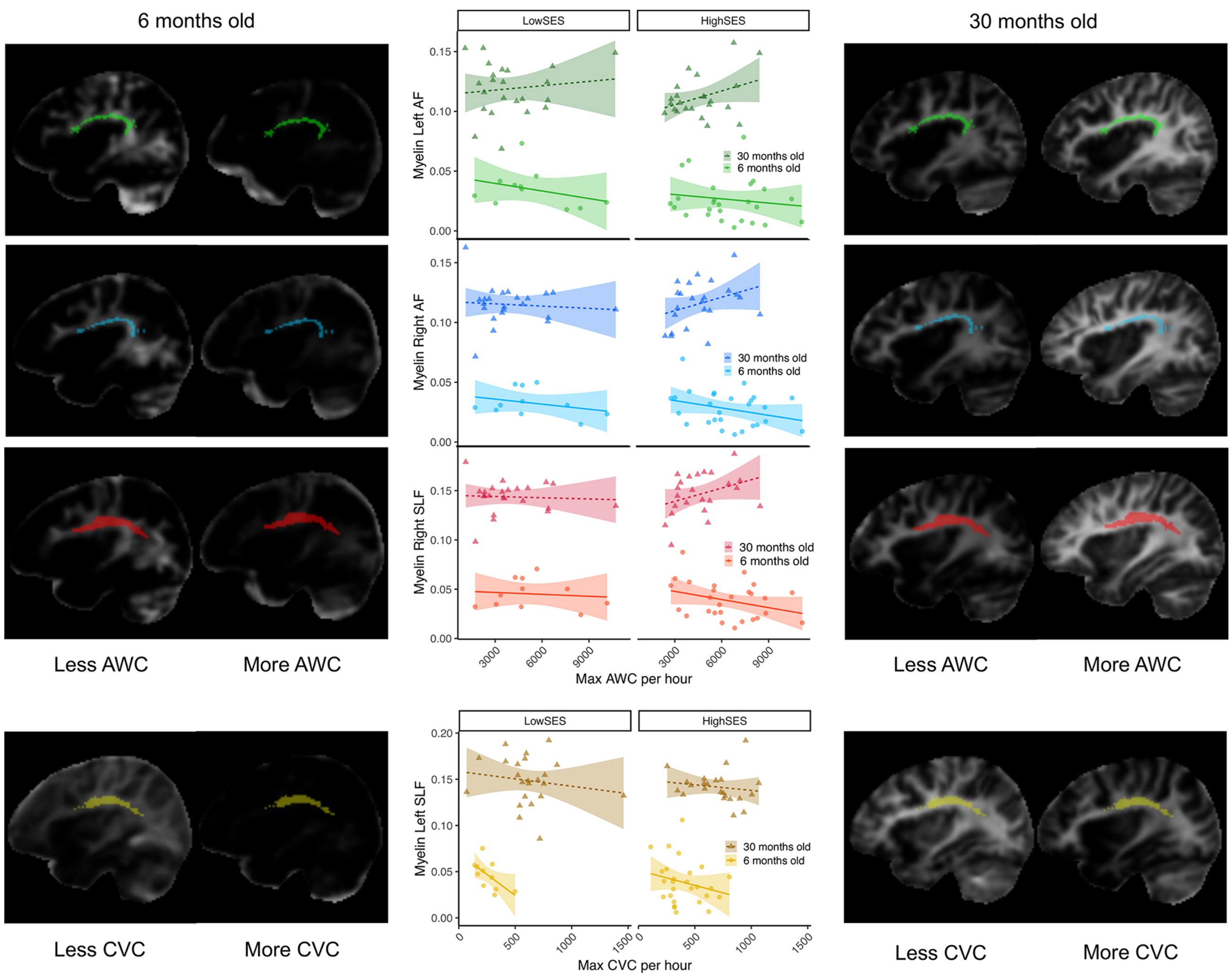
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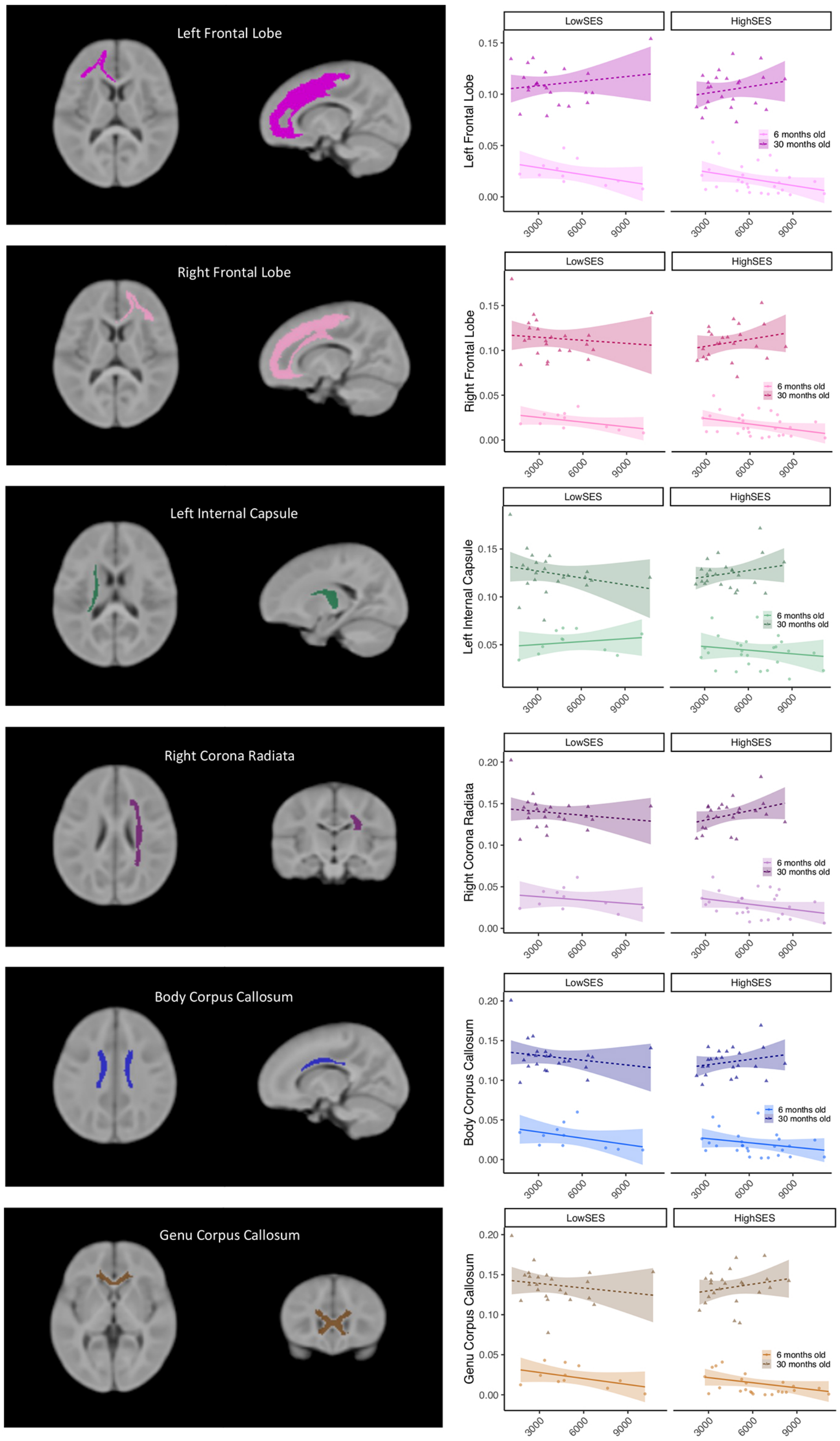

Left Frontal Lobe
Right Frontal Lobe
Left Internal Capsule
Right Corona Radiata
Body Corpus Callosum
Genu Corpus Callosum
LowSES
HighSES
6 months old
30 months old
Left Frontal Lobe
Right Frontal Lobe
Left Internal Capsule
Right Corona Radiata
Body Corpus Callosum
Genu Corpus Callosum
Max AWC per hour