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Longitudinal associations between birth-to-six cortical growth and childhood neurocognitive function

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The human cortex undergoes immense change in the first years of life, doubling in thickness within the first year and evidencing the greatest change within the first 5 y. While substantial research has identified the early postnatal period as a sensitive period in cortical development, research to date lacks the temporal resolution necessary to identify which aspects of cortical change predict later neural and cognitive function. This study leveraged a rich longitudinal dataset of cortical thickness in 50 children who were scanned up to 11 times between birth and 6 y. We used nonlinear multilevel modeling to explore patterns of cortical change across the brain during this period and distinguish whether different phases of change would predict performance and brain activation during a working memory task children completed at approximately 9 y. Cortical thickness across the brain showed a large increase from birth through 12 mo, a decrease from 12 to 18 mo, and a small increase from 18 mo to 6 y, mirroring patterns of early neural proliferation, pruning, and sustained growth. Performance and neural activation during the working memory task were associated with smaller peak (i.e., 12 mo) thickness and a marginally less steep 12 to 18-mo decline in thickness in the middle frontal gyrus (MFG) of the frontal lobe, in line with evidence demonstrating concurrent links between frontal lobe structure and working memory. These findings validate theories of cortical growth developed in preclinical models using human data and demonstrate that prefrontal cortex development in infancy uniquely predicts neurocognitive function 9 y later.

brain development | working memory | cortical thickness | MRI

Significance

While the cortex undergoes rapid nonlinear change in the first years of life, it remains unclear how these changes, which occur prior to age five, are associated with later neurocognitive function. This is in part because little research to date has examined cortical growth frequently and over a long enough developmental window to characterize these changes and their long-term implications. We leveraged densely sampled longitudinal data and nonlinear modeling to identify patterns of brain-wide cortical thickness change across 11 time points from birth to age six. Further, we showed that frontal lobe thickness in infancy uniquely predicts age nine neurocognition, underscoring the impact of very early changes in the cortex on brain and behavior across development.

The early postnatal period is a critical stage of human brain development. Animal and human postmortem research suggests that during the first years of life, cortical development proceeds through two stages: an initial phase of neural proliferation during which dendritic and synaptic density rapidly increases, followed by a period of pruning synaptic connections (1, 2). While the specific timing of these processes differs across areas of cortex (3), the peak in thickness and shift toward thinning is largely complete by 5 y (4, 5). Structural neuroimaging studies in human infants document that cortical thickness increases at an incredibly rapid pace, more than doubling in the first year of life and peaking shortly after (6–8), though few studies characterize development beyond age two or with a sampling frequency that would allow documentation of both proliferation and pruning processes. In this study, we took advantage of richly sampled cortical thickness data measured across up to 11 time points in the first 6 y of life (with 5 time points occurring in the first year) to more closely chart trajectories of putative cortical thickness change than has previously been possible in human data.

Evidence from animal models (1, 2) and postmortem tissue studies in humans (3–5) show increases in the number of dendrites and synapses prenatally through approximately the first year of life in humans. After this peak in thickness, the cortex undergoes a protracted phase of thinning that continues throughout childhood (3, 4). Pinpointing the timing of these phases of cortical growth in humans has been difficult because most studies do not include the span and density of measurement necessary to characterize these trajectories, although recent efforts that combine data from multiple studies have advanced our understanding of cortical development (9).

Neurodevelopmental theories further argue that cortical structure changes during early childhood set the stage for brain development across the lifespan and that variability in these processes is one mechanism through which individual differences in later neurocognitive function develop (1, 10, 11). While past studies of concurrent structure–behavior associations in middle childhood suggest that thinner cortex (12), particularly in the frontal lobe (13–15) is associated with better working memory (16–18), research to date

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has not examined longitudinal associations between cortical development when peak thickness occurs and subsequent working memory, as would be predicted by these models. Support for the hypothesized longitudinal link between early cortical development and later function comes from substantial evidence from animal models (19–21) and numerous studies in humans demonstrating that environmental experiences between 0 to 4 y shape both cognitive function (22–26) and brain structure (27, 28) in middle childhood and adolescence. Thus, while we know early developmental change of cortical structure is important to future neurocognitive function (10, 29), we do not know which aspects of early cortical development predict later cognitive capacity and associated neural recruitment, a question we sought to answer in this study.

The present preregistered study leverages data from a densely sampled longitudinal study to address two main goals: 1) to examine changes in cortical thickness from birth through age six across the brain and 2) to explore how changes in cortical thickness predict working memory task performance and associated neural function in childhood. We utilized multilevel nonlinear statistical modeling techniques to capture variable changes in cortical thickness from birth to 6 across the brain. Using these models allowed us to probe how changes in thickness at different phases of development longitudinally predicted later behavioral and neural aspects of working memory when youth were approximately 9 y old. Our hypotheses and analytic plan were preregistered on Open Science Framework (https://doi.org/10.17605/OSF.IO/BUWRJ).

Results

Trajectories of Cortical Thickness Development. To examine how the cortex developed in the first 6 y, we fit growth curve models to the change in cortical thickness across each lobe of the brain (see ref. 30 for anonymized dataset). We supplemented these models by also examining change in thickness of the middle frontal gyrus (MFG), a region that has extensively been shown to play a fundamental role in the development of working memory (29, 31, 32). To account for the nonlinear change in the cortex during this stage, we used generalized additive modeling (GAM), a nonlinear modeling approach that approximates the shape of the data by combining multiple spline functions (Fig. 1). Across all four lobes and the MFG, there was evidence of a large initial increase in thickness during the first year followed by a small decrease in thickness from 12 to 18 mo and subsequently a protracted phase of slightly increasing cortical thickness through age six. Because we were interested in parsing whether changes in thickness at specific ages would predict subsequent working memory, we fit piecewise hierarchical linear models to cortical thickness data from each lobe and MFG that would allow us to separately examine associations with each phase of cortical growth. These models included fixed and random effects for the intercept and three separate slopes that allowed us to separately model putative proliferation (0 to 12 mo), pruning (12 to 18 mo), and sustained later growth (18 to 72 mo) of the cortex (Fig. 2) on average (via fixed effects) and for each participant (via random effects). Cortical thickness was centered at 12 mo so that the intercept reflected peak thickness. Results suggest that across all lobes and MFG, there was a significant intercept, significant increase from birth to 12 mo, significant decrease from 12 to 18 mo, and a significant increase from 18 to 72 mo (*SI Appendix*).

Cortical Thickness Development and Working Memory.
Predicting cortical thickness from n-back performance. In order to examine associations between cortical thickness development and later working memory, we examined whether performance on

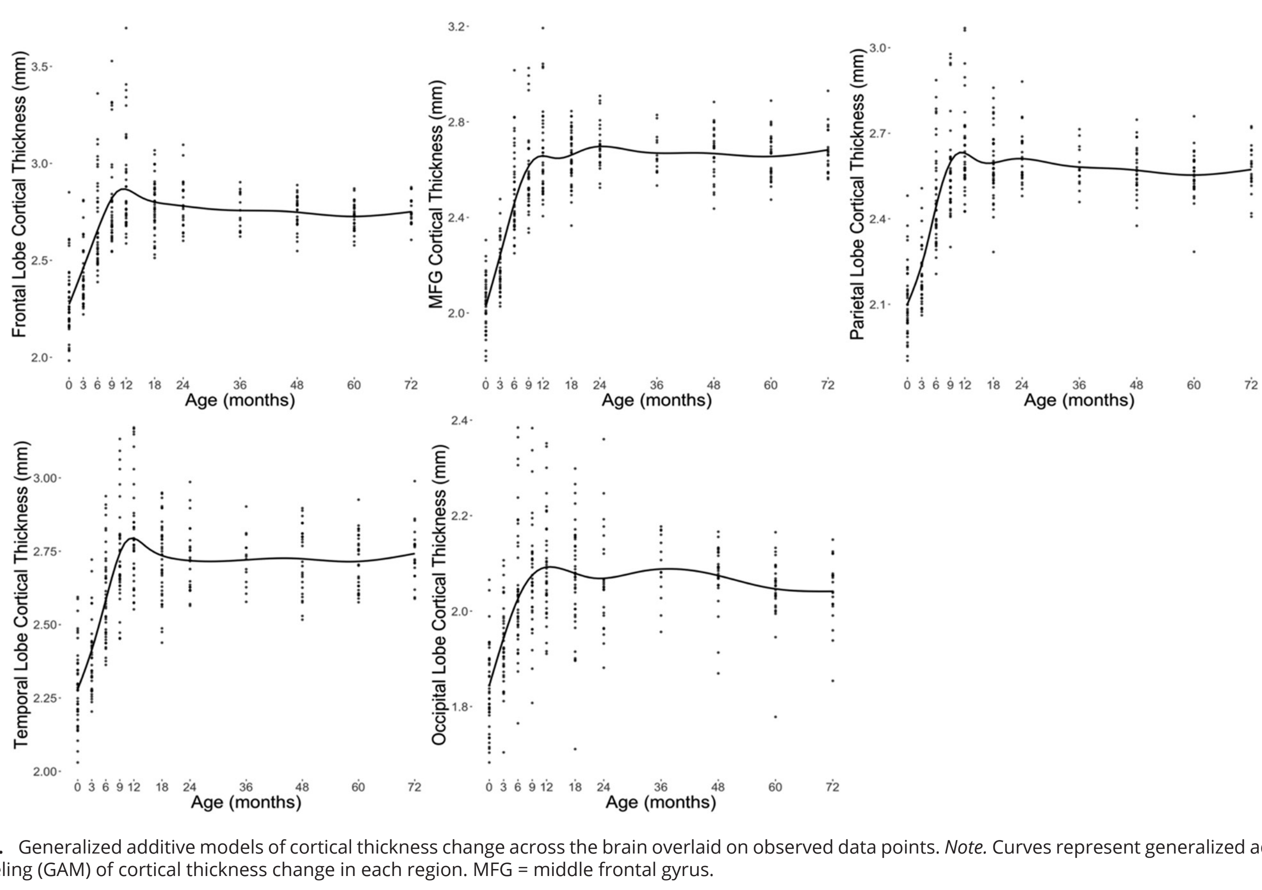

Fig. 1. Generalized additive models of cortical thickness change across the brain overlaid on observed data points. *Note.* Curves represent generalized additive modeling (GAM) of cortical thickness change in each region. MFG = middle frontal gyrus.

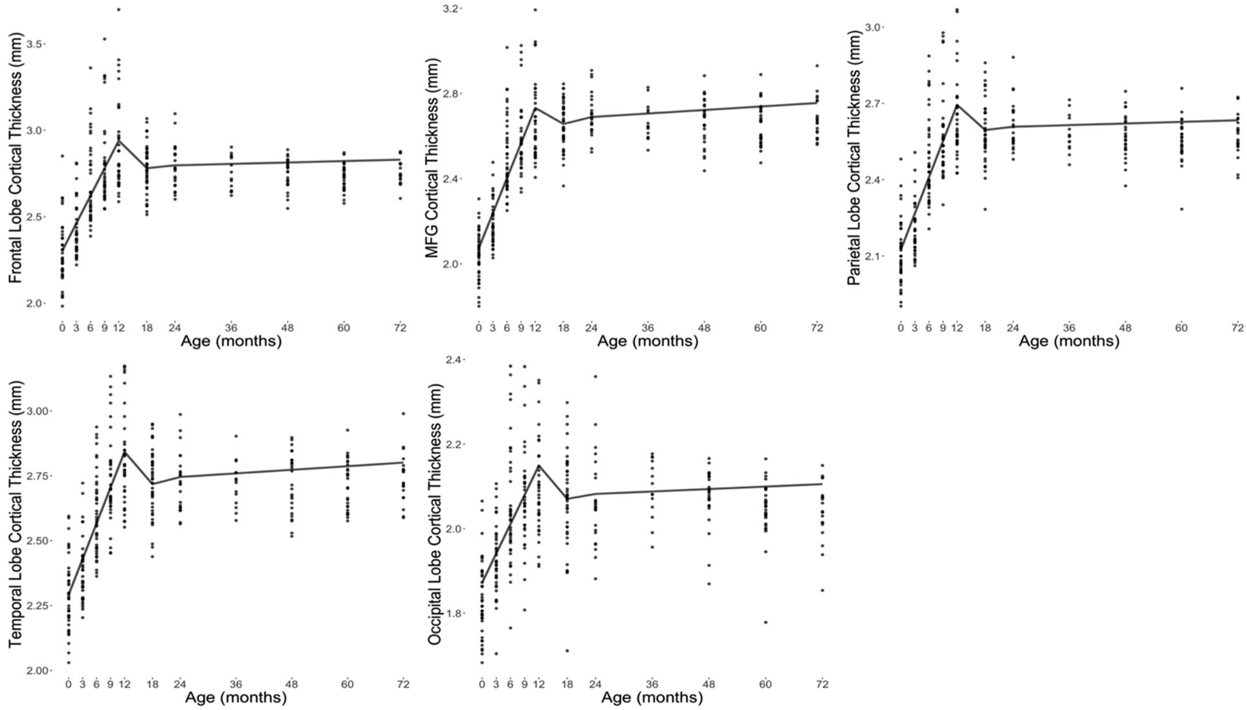

Fig. 2. Predicted trajectories from hierarchical linear models of cortical thickness change overlaid on observed data points. *Note*. Trajectories based on predicted values of intercept and slope from hierarchical linear models. MFG = middle frontal gyrus.

an n-back task in which participants had to identify whether or not a letter stimulus had been seen two trials previously (2-back blocks) or matched a target letter (0-back blocks) was associated with intercepts or slopes in the piecewise HLMs across all lobes and the MFG. We operationalized performance on the task via d' scores (which take into accounting correctly responding to both match and nonmatch trials) during two-back blocks of the task. We found that d' was significantly negatively associated with peak thickness in the frontal lobe (β = −0.19, $t = -2.18$, $P = 0.04$) and marginally negatively associated with peak thickness in the parietal

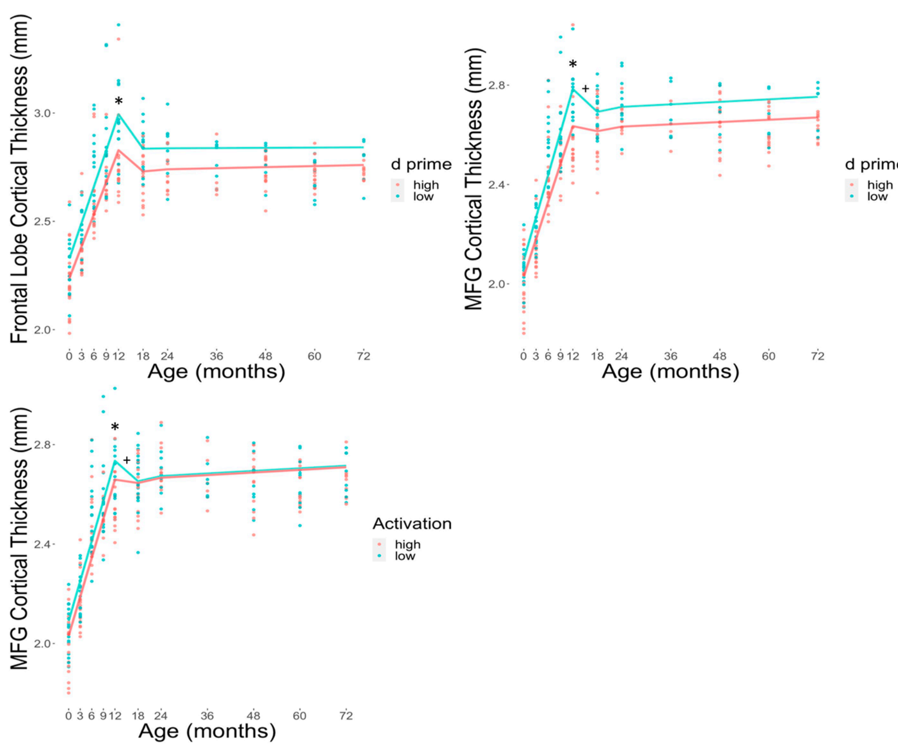

Fig. 3. Predicted Trajectories of Cortical Thickness Change based on n-back Task Performance (*Top*) and Activation (*Bottom*). *Note.* Trajectories based on predicted values from hierarchical linear models and overlaid on observed data. For visualization purposes, high and low represent those above and below the mean, respectively. Activation extracted from regions showing heightened activity in the 2-back vs. 0-back comparison that was predicted by d' scores. MFG = middle frontal gyrus. $^{+}P < 0.10$. $^{*}P < 0.05$.

Table 1. Regions showing heightened activation on the n-back task

Region label	k	z-stat	x	y	z
2-back > 0-back					
Right supramarginal gyrus	4,026	6.11	53.5	−44.5	39.5
Right middle frontal gyrus	3,888	6.66	29.5	5.5	63.5
Left middle frontal gyrus	2,202	5.99	−46.5	21.5	39.5
Paracingulate gyrus	1,941	7.4	7.5	31.5	31.5
Left supramarginal gyrus	1,548	6.1	−38.5	−54.5	49.5
Left frontal pole	512	5.43	−40.5	53.5	13.5
Right insula	443	6.25	35.5	21.5	−4.5
Left insula	387	6.34	−32.5	25.5	−0.5
Left anterior cerebellum	242	5.34	−44.5	−72.5	−26.5
Right anterior cerebellum	181	4.49	37.5	−48.5	−32.5
Left posterior cerebellum	95	4.57	−10.5	−78.5	−22.5
Right middle temporal gyrus	72	3.79	63.5	−26.5	−4.5
2-back > 0-back predicted by 2-back d′					
Right superior frontal gyrus	205	4.8	25.5	9.5	55.5
Right insula	103	4.46	29.5	27.5	3.5
Right supramarginal gyrus	96	4.01	41.5	−44.5	47.5
Right precuneus	83	4.16	11.5	−74.5	55.5

Note. k = cluster size. x, y, z correspond to MNI coordinates.

lobe ($\beta = -0.15$, $t = -1.95$, $P = 0.06$; Fig. 3). We also found that d′ was significantly negatively associated with peak thickness in the MFG ($\beta = -0.19$, $t = -2.64$, $P = 0.01$) and with a marginally slower decrease in MFG thickness from 12 to 18 mo ($\beta = 0.08$, $t = 1.71$, $P = 0.09$; Fig. 3). All other main effects of d′ and d′ x time interactions were nonsignificant (*SI Appendix*, Table S2).

Predicting cortical thickness from neural activation during the n-back. We then examined activation during the 2-back > 0-back contrast of the n-back task as a measure of working memory recruitment. Table 1 and Fig. 4 display regions with suprathreshold activation during this comparison. We observed significantly greater activation to 2-back vs. 0-back in bilateral MFG, bilateral insula, bilateral supramarginal gyrus, paracingulate gyrus, right middle temporal gyrus, and bilateral cerebellum. Average activation extracted across all of these regions was not significantly associated with peak cortical thickness or change in thickness in any regions (*SI Appendix*, Table S3).

Next, we conducted exploratory analyses to examine activation during the 2-back > 0-back contrast regressed on d′ (Table 1 and Fig. 4). We found that better performance (higher d′) predicted more activation in right superior frontal gyrus, right insula, right supramarginal gyrus, and right precuneus. Average activation extracted across all of these regions predicted a significantly lower MFG 12-month peak ($\beta = -0.16$, $t = -2.28$, $P = 0.03$) and a marginally slower decrease in thickness from 12 to 18 mo ($\beta = 0.09$, $t = 1.97$, $P = 0.05$; Fig. 3 and *SI Appendix*, Table S4).

Discussion

In this paper, we used data from a densely sampled longitudinal neuroimaging study to characterize trajectories of cortical thickness from birth through early childhood (0 to 6 y) and subsequently identify whether these trajectories predict working memory task performance and associated neural activation when participants were approximately 9 y old. When examining changes in thickness across lobes of the brain, we found an initial increase that peaked by 12 mo and then decreased until approximately 18 mo, after which minimally increasing change was observed. This pattern lines up with periods of neural proliferation and pruning that have been proposed to occur in early postnatal life and complete prior to 2 y of age (3, 18, 33). Although studies are mixed in finding evidence of increasing (6) or decreasing cortical thickness across childhood (34), nearly all of these studies focused on children over the age of 5; thus, our finding of slight increases from 18 mo to 6 y captures an understudied period despite its importance for the development of working memory (11). Interestingly, our results diverge slightly from recent meta-analytic findings which suggest a thickness peak closer to 18 mo (9); however, the overall pattern of thickness change summarized in this meta-analysis appears very similar to our results, which were particularly well-suited to identify small changes in thickness in the first 2 y. Additionally, this research fits with findings in humans showing rapid changes in early postnatal cortical thickness, albeit using less dense sampling (6, 8). The number of timepoints in this study allowed us to fit unique slopes to the distinct phases of cortical thickness increase and decrease, addressing challenges of capturing the nonlinear development of the cortex (34, 35). We observed that the rapid increase and decrease in thickness within the first 2 y was consistent across all lobes of the brain, even the frontal lobe, which has a protracted development across childhood (3, 5). This pattern of findings is consistent with human tissue research demonstrating that dendritic branching and synaptogenesis increase in the first year of life before decreasing across the subsequent year (3, 4, 36). The similarity of our findings to animal and human tissue research demonstrate the possibility of observing proliferation and pruning in vivo, which has numerous critical implications, including making it possible to explore how these processes relate to phenotypic variation in human cognition and behavior and predict the emergence of developmental competencies in different contexts.

When considering working memory outcomes, we found that children with higher d′ on 2-back blocks of the n-back task had significantly lower peak thickness in the frontal lobe generally and MFG specifically, as well as a marginally lower peak in the parietal lobe and a marginally less steep decline in MFG thickness from 12 to 18 mo. Past research has identified a link between the thinner frontoparietal cortex and better working memory concurrently (12, 14) and over time (15) in mid-to-late childhood. Significantly, this study additionally finds that having a thinner frontal cortex at one year—when the cortex reaches its peak thickness—longitudinally predicts working memory in middle childhood. As predicted, we found an association between cortical change and later working memory specifically in the frontal lobe. A wealth of past work has identified the crucial role played by the frontal lobe generally and the MFG specifically in the development of working memory (11, 16, 18) and demonstrated that the first years of life represent a sensitive period during which variance in the

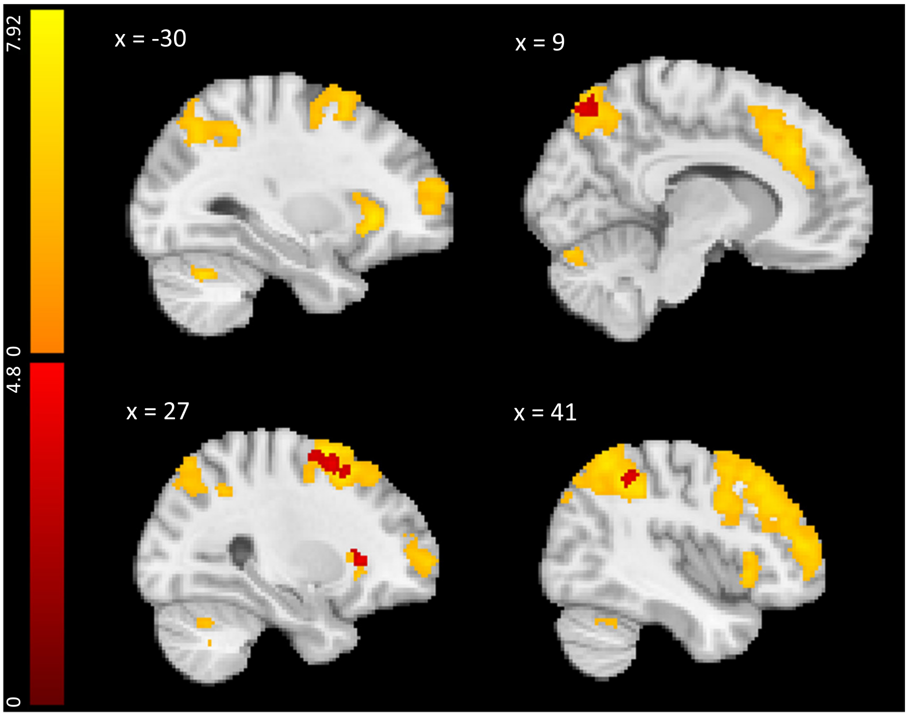

Fig. 4. Activation on the n-back task to the 2-back vs. 0-back comparison (in Yellow) and to the 2-back vs. 0-back comparison predicted by d′ scores (in Red) *Note.* Overall activation (in yellow) was extracted from 1-sample *t* test of 2-back > 0-back trials. Activation predicted by d′ (in red) was extracted from whole-brain regression of 2-back > 0-back activation regressed on standardized d′ scores.

developmental environment can impact the structure and function of this region (27). Here, we show that changes in frontal lobe structure during this key sensitive period predict neurocognitive function over 9 y later, identifying one mechanism through which variability in developmental trajectories emerges.

We also examined links between early cortical development and brain activation during the n-back task. When comparing 2-back vs. 0-back conditions, we observed activation across a range of regions consistently found to be responsive to working memory demands, including the MFG, supramarginal gyrus, insula, precuneus, paracingulate gyrus, and cerebellum (37–40). Examining patterns of activation that were predicted by better task performance, as indexed by d′ on the 2-back trials, revealed that higher d′ predicted more activation in a set of overlapping regions, including the right MFG, supramarginal gyrus, insula, and precuneus. We observed that the magnitude of activation of these regions was associated with a smaller MFG peak and marginally less steep MFG thinning from 12 to 18 mo, findings that mirrored what we observed using task performance as a predictor of cortical thickness change. These results provide evidence that early cortical maturation of the frontal lobe may predict future cognitive function via its impact on neural systems that instantiate these cognitive functions in middle childhood. It is possible that this very early development of the prefrontal cortex lays the groundwork for long-term prefrontal capacity. Interestingly, both task performance and neural function were associated with peak cortical thickness and decline in thickness from 12 to 18 mo, patterns of change which may reflect pruning processes that are the primary mechanisms of early plasticity.

Contributions and limitations

This study takes several steps to advance our understanding of how neural development proceeds during infancy and impacts later cognitive capacity. We implemented a longitudinal design with measurement of the same sample from birth through approximately 9 y of age, allowing us to demonstrate how early prefrontal development predicts later cognitive and neural function in the same youth. Further, we leveraged a sample with far denser and earlier assessment of cortical thickness than is typically available. Participants in the present project completed up to 11 scans by the age of six, with five of them occurring in the first year of life. We exploited the richness of early cortical thickness data using nonlinear and piecewise hierarchical linear models, which allowed us to more accurately model both peaks and changes in thickness over time. Through the use of these models, we were able to fit unique intercept and slope values for each participant, allowing us to demonstrate that individual differences specifically in prefrontal cortex development in infancy predict working memory task performance and associated neural activation in mid-childhood.

While there are several strengths of this study, there are also noteworthy limitations. Notable among these is the small size of our sample. At the time parents were recruited into the study, the sample of 93 infants initially enrolled was considered large, and the number of structural scans collected was incredibly rare. Despite the impressive richness of the data, the sample size is underpowered to detect small individual difference effects, although the use of hierarchical models did allow us to leverage the large number of scans per participant to increase power. The sample of participants with usable n-back data during mid-childhood is smaller still due to attrition and ineligibility for an fMRI study, limiting our ability to detect small associations between cortical change and later brain or behavior. Our study is also limited in its use of cortical thickness derived from structural MRI as the sole measure of early neurocognitive development. Cortical thickness measures reflect dendritic and synaptic properties (6, 41) but are also affected by myelination (42) and even noise such as that from in-scanner motion (43). While our findings add to the field through in vivo replication of patterns of synaptic changes previously measured only in tissue samples, future work leveraging additional measures of neurocognitive development is warranted.

These limitations, coupled with the pattern of findings we observed, suggest several intriguing directions for future research. This work emphasizes the importance of dense sampling in longitudinal assessment of infant brain development, without which it is impossible to capture the immense amount of structural brain change that occurs across early life and that we have shown to be important for understanding later neurocognitive function. Studies that include assessment of both brain structure and cognitive function concurrently across infancy and childhood, such as the HEALthy Brain and Child Development (HBCD) Study, represent an important next step in this area. It will also be important to consider factors that influence brain development or interact with structural change to predict outcomes. A wealth of animal research (19, 20) and randomized trials in humans (27) identify sensitive periods during which experience irreversibly shapes brain development. Thus, it will be crucial for future work to consider the role of the environment within which brains are developing to understand the sources of variability in brain structure and function. While not a direct aim of this study, research has shown that variability in executive functions such as working memory is associated with myriad educational (44) and health (45) outcomes. Studies that consider these outcomes can clarify how early brain development may shape well-being through cognitive function and identify targets of and timing for policy, education, and health interventions.

Conclusion

The present study examined how cortical thickness develops across the first years of life and predicts later neural and cognitive correlates of working memory. We identified a trajectory of rapidly increasing thickness across the brain that peaked around 12 mo and decreased through 18 mo before marginally increasing through age six. However, only peak thickness in the frontal lobe, and specifically in the MFG, was associated with later performance and brain activation on a working memory task completed when youth were approximately 9 y old. These results provide a fine-grain view of cortical changes in the first years of life and highlight the importance of early changes in cortical thickness for understanding later cognitive development.

Materials and Methods

Participants and Procedures. We utilized data from a longitudinal neuroimaging study of 50 youth enrolled between birth and approximately 9 y of age. Mothers seen within the university healthcare system were recruited during their second trimester of pregnancy and their infants were enrolled in the study if they were born between 35- and 42-wk, at appropriate weight for gestational age, and if there were no pregnancy or delivery complications, congenital anomalies, neonatal hospitalization, significant maternal illness, or maternal substance use during pregnancy (see (46–48) for further recruitment details). Of the 93 newborns enrolled in the study, 10 had data that could not be processed and 33 did not complete the minimum three timepoints of data collection to allow for modeling, leaving a final sample of 50 (25 female). Participants varied in parent-reported race [13 (26%) African-American/Black, 31 (62%) White, 4 (8%) multiracial; 2 did not have data on race] and yearly family income (M = \$61,203, SD = \$45,650). Parents of participants ranged in age (M = 29.96, SD = 6.19) and years of education (M = 15.88, SD = 3.54; 16 corresponds to completion of college) at the time participants began the study. The 50 participants who completed at least three scans did not differ from the original sample of 93 in race [$\chi^2(3) = 2.62$, $P = 0.46$], gender [$\chi^2(1) = 0.01$, $P = 0.54$], family income [$t(80) = 0.52$, $P = 0.61$], or parental age or education (*ts*: 0.02 to 0.84, *ps*: 0.41 to 0.98). Parents provided written consent for all aspects of study participation, which were approved by the Institutional Review Board of the University of North Carolina at Chapel Hill. Participants completed a structural MRI session during natural sleep between birth and 2 y and during natural sleep or while watching a video between three and 6 y.

A subset of 56 of the original 93 participants completed an additional visit between 8 and 12 y of age. During this visit, children completed multiple tasks including an n-back working memory task while undergoing functional MRI (fMRI). Of the participants who returned for this visit, 41 ($M_{age} = 9.29$; 22 female) had three or more timepoints of usable data during the initial phase of structural MRI collection (i.e., birth–six) and are included in the final sample. In the present sample, parents identified youth as African American/Black (12, 29.27%), White (25, 60.98%), or multiracial (4, 9.76%).

Structural Brain Scans. Participants completed up to 11 T1- and T2-weighted structural MRI scans beginning as newborns (within two weeks of birth) and at 3, 6, 9, 12, and 18 mo and 2, 3, 4, 5, and 6 y of age (see *SI Appendix* for additional detail). Images were preprocessed using the infant Brain Extraction and Analysis [iBEAT (49)] pipeline that was designed to account for the rapid change in cortical thickness during the first years of life and validated using a longitudinal dataset with scans at the same ages as our sample. This pipeline includes resampling of T1- and T2-weighted images, brain extraction, and segmentation and registration to an atlas designed for infants and young children (50, 51). Segmentation leveraged a learning-based approach that incorporated infant brain templates constructed from T1, T2, and fractional anisotropy images and images from the same participant at multiple timepoints to improve identification of gray-white matter boundaries (49) (see *SI Appendix* for more detail). Cortical thickness was calculated as the minimum distance between the inner and outer cortical surface, reported as an average of vertices within 68 regions of interest (ROIs) based on the Desikan–Killiany atlas (52). Each participant's brain at each timepoint was aligned to the early developmental atlas using Freesurfer (31) and then mapped to the Desikan–Killiany atlas to ensure correct registration at each ROI (50, 51). Thickness was averaged across ROIs within the frontal, parietal, temporal, and occipital lobes to examine development across the whole brain. Additionally, we examined thickness specifically within the MFG, a region that has extensively been shown to play a fundamental role in the development of working memory (29, 32, 53).

Working Memory Task. When participants were between 8 and 12 y old, they completed an n-back task during fMRI. The n-back task had two conditions. In the 0-back condition, participants indicated a "match" for the letter X and a "nonmatch" for every other letter. In the 2-back condition, participants indicated whether letter stimuli presented sequentially were a "match" or a "nonmatch" to the letter presented two previously. Letters were presented for 1,000 ms with a 1,000 ms intertrial interval. There were 16 nonmatch and 4 match trials in each of four 0-back and four 2-back blocks. D-prime (d′) was calculated as the difference between z-transformed hit rate (correct matches) and z-transformed false alarm rate (incorrect nonmatches). D′ on 2-back trials of the task was used as an indicator of working memory performance.

Functional Brain Scans. During the n-back, fMRI data were collected and preprocessed using fMRIPrep version 20.0.7 (*SI Appendix*). A generalized linear model (GLM) was created using FSL (54) at the individual level that included 2-back, 0-back, and rest trials, as well as regressors of no interest for motion, global signal, white matter, and cerebrospinal fluid (*SI Appendix*). Each participant completed two runs of the n-back tasks, which were averaged in FSL to create a subject-level activation map. We conducted two group-level analyses of brain activation using mixed effect modeling with FLAME in FSL: a whole-brain one-sample t test comparing 2-back to 0-back conditions and a whole-brain regression examining activation during the 2-back to 0-back comparison that was predicted by higher d′ (reflecting activation associated with better task performance). Average activation from all regions showing supra-threshold (i.e., $z > 3.1$) activity in each analysis was used as a neural metric of working memory.

Analytic Plan. We preregistered our analytic plan on Open Science Framework (https://doi.org/10.17605/OSF.IO/BUWRJ). First, we examined the overall shape of cortical thickness across the brain using generalized additive models (GAMs). In order to assess when cortical thickness development was most predictive of later working memory, we then constructed piecewise hierarchical linear models (HLMs) of cortical thickness change over time using the lme4 package (55) in R. Each model included random intercepts and slopes to allow for differences in trajectories across individuals. Because HLM is well suited to modeling data with different numbers of observations at different waves (and only one wave had fewer than 20 participants), all available cortical thickness data were used in these models. Next, we added behavioral (i.e., d') and neural (i.e., activation in the 2-back vs. 0-back contrast) predictors into separate HLM models to predict peak levels of and changes in cortical thickness across each region. In order to control for the number of regions in each set of analyses, we calculated the harmonic mean *p*-value for five tests (four lobes plus MFG), which gave us a significant threshold of $p = 0.04$. This adjusted value did not change the significance of any test. We also examined whether sex would affect results; we found that there were no significant main effects of or interactions with child sex. Supplemental analyses not preregistered used activation from the n-back task regressed on d' as a predictor of CT change in an HLM model. Finally, in registered exploratory analyses, we extracted model parameters (intercepts and slopes) from the HLMs for each participant and entered them into whole-brain regression analyses to examine whether they would predict neural activation during the n-back task (*SI Appendix*).

Data, Materials, and Software Availability. Anonymized analysis code and data relevant to the present analyses are included in the OSF registration for this project. Data have been deposited in Open Science Framework (https://www.osf.io/mpr8v) (30).

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