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ORIGINAL ARTICLE

The auditory environment drives superior temporal sulcus depth in the neonatal period

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Abstract

Premature birth impacts the development of superior temporal brain regions, including the superior temporal sulcus (STS), a key cortical area for language, voice recognition, and music processing. Using three distinct newborn imaging datasets, we examined the impact of premature birth on STS morphology at term-equivalent age. In the large cohort of the Developing Human Connectome Project (dHCP), we observed a linear relationship between gestational age at birth and STS depth, with earlier birth associated with a shallower STS. We hypothesized that this effect may have resulted from reduced structured auditory stimulation during a critical period of perisylvian network development. To test this hypothesis, we analyzed two additional published cohorts in which preterm neonates were exposed to contrasting auditory environments: either enhanced with structured music or minimized in quiet private rooms. We found that music exposure was associated with deeper STS, while a quieter environment was linked to further STS shallowing. Although the cross-sectional design limits causal inference, our findings suggest that early auditory experience—both in and ex utero—may influence the structural development of temporal brain regions. These results highlight the need to deepen our understanding of environmental influences in order to optimize postnatal settings that support the harmonious development of auditory and language networks.

Keywords Infant · Language · Prematurity · Noise · Plasticity · Learning · Brain · Music

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Introduction

Fetuses and preterm neonates have been shown to perceive sounds and respond to changes in their auditory environment as early as 30 weeks' gestation (wGA) (Draganova et al. 2005; Jardri et al. 2008; Mahmoudzadeh et al. 2013). Thanks to this early auditory sensitivity and learning capacity, full-term neonates recognize their mother's voice (Beauchemin et al. 2011; DeCasper and Fifer 1980; de Regnier et al. 2000), native language (Mehler et al. 1988), and melodies frequently encountered during pregnancy (Granier-Deferre et al. 2011). These auditory abilities rely on the superior temporal cortex, which is organized into multiple hierarchical and parallel pathways dedicated to processing various aspects of sound. These functional hierarchies extend from low-level auditory features in Heschl's gyrus and superior temporal gyrus to high-level representations essential for language, voice recognition, and music, primarily located in the superior temporal sulcus (STS) (Hein and Knight 2008).

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Because the STS and its associated networks undergo critical development during late gestation, they are particularly vulnerable to premature birth.

Multiple studies have reported associations between microstructural alterations in the linguistic tracts and superior temporal cortices of preterm neonates and their subsequent language development (Aeby et al. 2013; Bartha-Doering et al. 2023; Kersbergen et al. 2016; Salvan et al. 2017). Beyond potential microstructural lesions, direct modulation by the vastly different environment experienced by premature infants may also impact network maturation (Eyre et al. 2021), potentially contributing to their higher risk of language difficulties (Guarini et al. 2009; Nguyen et al. 2018; Putnick et al. 2017). Supporting this idea, our analysis of the large-scale dHCP cohort of neonates scanned at term age revealed a linear relationship between length of gestation and functional connectivity in the right superior temporal region. We tentatively related this observation to the longer exposure to low-frequency sounds of the fetal auditory environment favoring right-hemisphere processing, compared to an aerial sound environment prematurely experienced by preterm neonates (Mancuso et al. 2024).

Several interventions aim to improve the care and prognosis for preterm infants (see Pineda et al. 2023 for a review). One auditory intervention involved placing preterm neonates in private rooms to reduce ambient noise (Pineda et al. 2014a), as standard NICUs often exceed the desired 45 dB threshold (Jabraeili et al. 2016). Paradoxically, this intervention did not produce the anticipated benefits: infants in private rooms exhibited language delays compared to those who remained in the open ward. The authors proposed that it might be related to the reduced speech exposure in private rooms, open wards providing greater exposure to human voices, including those of parents and healthcare professionals, throughout the day (Pineda et al. 2014a, 2017). In contrast, music-based interventions enrich the auditory environment by presenting preterm infants with musical excerpts designed to mitigate the mechanical NICU noise. These structured stimuli characterized by rhythm, pitch, and harmonic structure enhance the neonates' auditory experience and, in a recent study by one of us, were further attuned to the infants' daily rhythms, notably sleep-wake cycles (Lordier et al. 2019a, 2019b; Sa de Almeida et al. 2023). In this study, preterm infants exposed to music and tested at term-equivalent age exhibited significantly enhanced functional connectivity within key neural circuits, including the auditory and right temporal gyrus (Filippa et al. 2020; Lordier et al. 2019a; Sa de Almeida et al. 2023).

Therefore, we explored whether the auditory environment directly impacts temporal cortex sulcation by investigating how gestational length influences STS depth and whether early auditory interventions in the NICU might mitigate this effect. To explore a possible causal link, we analyzed three datasets: (1) the large cohort of the Developing Human Connectome Project (dHCP) (Hughes et al. 2017), which allowed us to show that STS depth at term-equivalent age is shallower in preterm infants compared to term-born neonates; (2) a dataset examining the impact of a silent room on preterm development (Pineda et al. 2014a) and (3) a dataset investigating the effects of a music exposure protocol between birth and term-equivalent age (Lordier et al. 2019b). We hypothesized that the shallower STS observed in preterm infants is due to an ex-utero auditory environment that lacks appropriate or structured stimulation during a crucial period for the development of temporal auditory and language networks, then this effect should be mitigated in the music intervention dataset and exacerbated in the silent room dataset.

Methods

Materials

We utilized three different datasets: the public dHCP database and two published datasets allowing for a well-controlled analysis of two distinct auditory environments.

(1) **Developing Human Connectome Project Database (dHCP)**: To investigate the impact of prematurity on STS development, we analyzed MRI studies from the dHCP database (Hughes et al. 2017), which includes 558 brain MRI studies from neonates born between 24 and 42 weeks of gestation, scanned around term-age (mean = 40.4w, sd = 1.9w).

We rejected poor quality MRIs according to a systematic rating performed by a Senior Paediatric Radiologist on criterion published with the database. Regarding preterm infants, we considered only acquisitions performed after 37 wGA (term-equivalent age). For term newborns, we removed the scans performed too early after birth (< 48 h) to avoid confounding factors affecting the brain segmentation (cortisol peak and hydration status). For each twin pair present in the database, we randomly selected one individual among the two. We selected full-term neonates to match the selected preterm subjects for gender and gestational age at scan (Fig. 1). We ultimately included 184 infants in the analysis (Fig. 1). Their distribution across the gestational age intervals used for visualization in Fig. 2 was as follows: <27w: 5, [27, 29]w: 14, [29, 31]w: 10, [31, 33]w: 10, [33, 35]w: 11, [35, 37]w: 23, [37, 39]w: 52, [39,41]w: 45, >41: 14.

Data acquisition Acquisitions were performed during natural sleep on a 3 T Philips Achieva MRI with a 32-channels coil. We utilized the T2w anatomical image because of

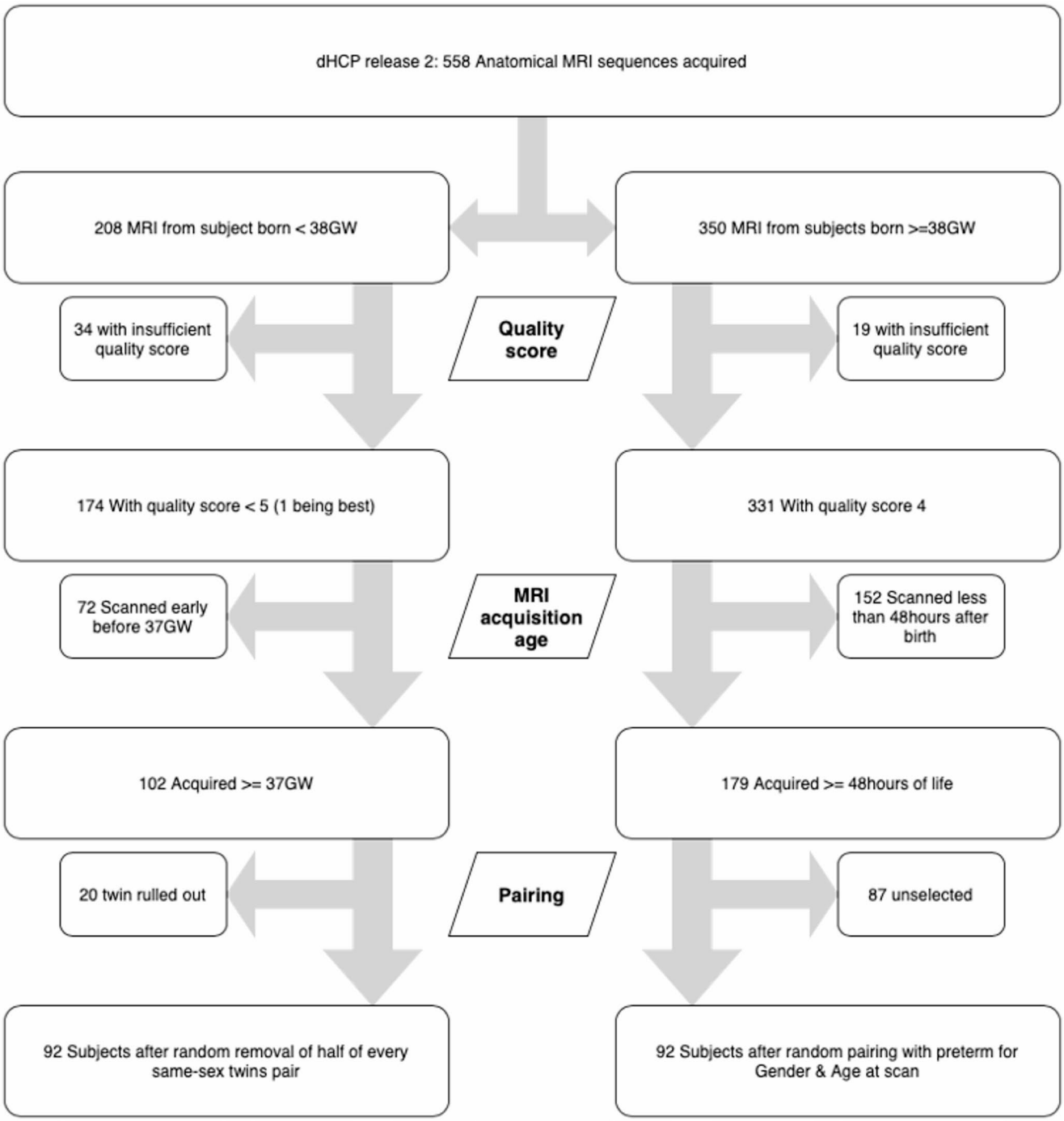

Fig. 1 Flowchart of the dHCP subject selection process. The dHCP database includes MRI scans accompanied by quality scores (1 = highest quality; 5 = lowest quality). Scans rated as poor quality (score = 5) were excluded from further analysis − 34 out of 208 preterm and 19 out of 350 term infants. Scans acquired within 48 h of birth were also excluded to avoid confounding factors that may affect brain segmentation accuracy, such as postnatal cortisol surges and hydration status. We applied a cut-off at 38 weeks of gestational age (wGA), as early-term births (< 38 wGA) are still associated with an increased risk of neurodevelopmental complications, particularly in verbal and non-verbal communication (Hochstedler et al. 2021; Sengupta et al. 2013)

its better signal-to-noise ratio for differentiating white and gray matter at birth compared to T1w images. Images were acquired in axial and sagittal planes with a $0.8 \times 0.8 \times 1.6 mm^2$ resolution and a 0.8 mm overlap (TR/TE = 12000/156ms, SENSE factor = 2.11).

(2) **Geneva hospital dataset**: To investigate the impact of enriched early acoustic environment on STS development

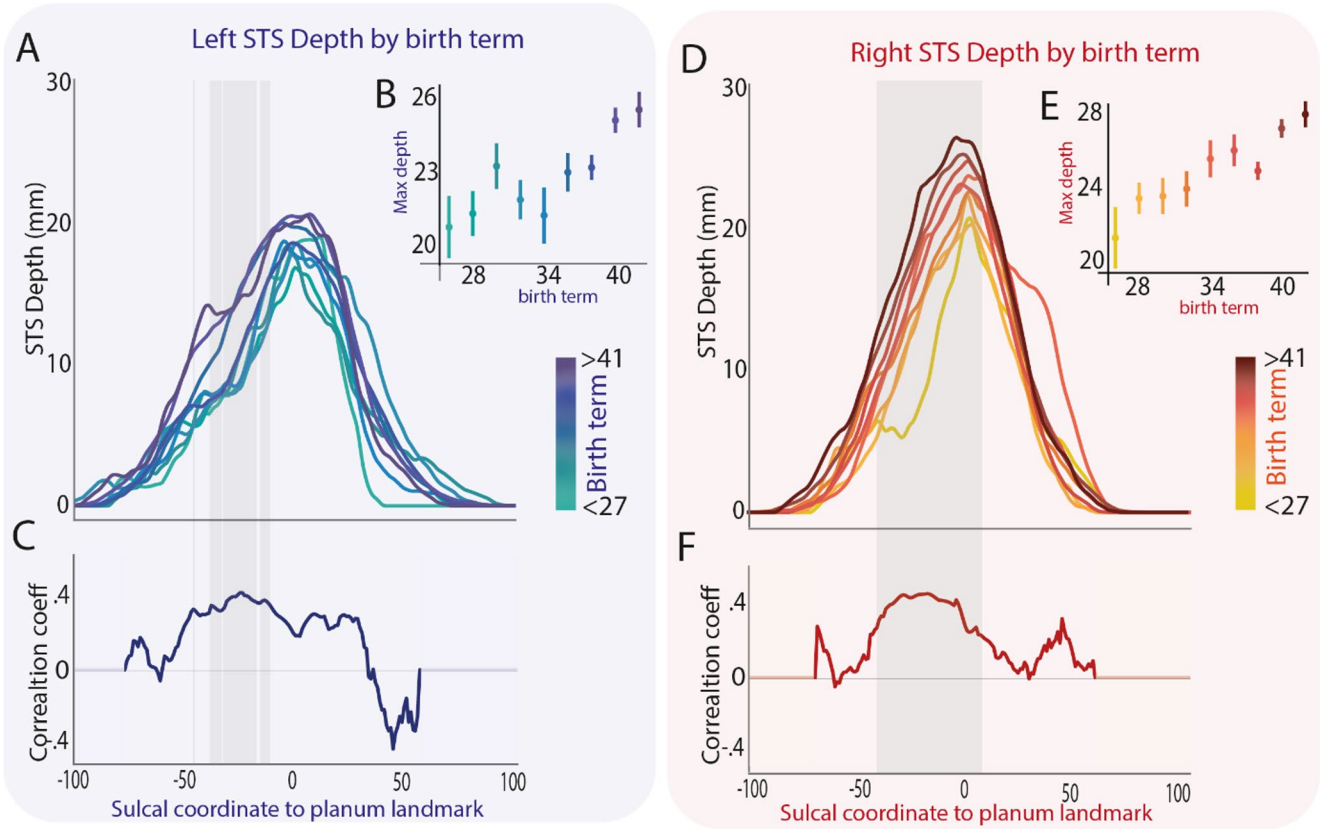

Fig. 2 Superior Temporal Sulcus (STS) depth profiles in neonates scanned at term, as a function of gestational age at birth in the dHCP database. **A**, **D** Mean left/right STS depth profiles grouped by 2-week gestational age intervals from <27 to >41 GW. The origin of the anterior-posterior STS axis corresponds to the coronal slice aligned with the posterior tip of the *planum temporale*. **B**, **E**. Maximum depth of the left/right STS extracted for each subject and averaged within each 2-week-interval group. **C**, **F** Linear regressions were performed at each coordinate along the depth profile, examining the relationship between STS depth and gestational age at birth, after regressing out central sulcus maximum depth as a regressor of non-interest. Shaded areas indicate coordinates where the relationship was statistically significant (Bonferroni corrected for 231 voxels). **D**–**F** correspond to the right STS and mirror panels **A**–**C** for the left STS. Note the consistently deeper right STS across all groups

in premature infants, we benefited from the musical protocol carried out at the Geneva university hospital (Lordier et al., 2019a, 2019b). MRI scans from 27 preterm neonates scanned at term-equivalent age were analyzed. It comprised two groups: 15 premature infants that received a music intervention and 12 premature infants in a sham control condition. The intervention featured slow music (bells, harps, flutes) in eight-minute sequences, tailored to the infant's state (falling asleep, waking up, or calm alert), five times a week from 33 weeks to term-equivalent age. The control group underwent the same procedure but music was not presented.

Data acquisition: Data were acquired on two 3 T scanners: a Siemens Trio using a 32-channel head coil (7PM, 8PC, 11 T) and a Siemens Prisma using a 64-channel head coil. The distribution of scanners/head coils were equally represented in each group. The T2w structural images for anatomy were acquired with the following parameters: 113 coronal slices, TR = 4990ms, TE = 151ms, flip angle = 150°, matrix = 256 × 164; voxel size = 0.78 × 0.78 × 1.2mm3.

(3) **St. Louis dataset** At the opposite, to investigate the effect of an early quiet auditory environment, we analyzed data from a separate cohort in which preterm infants were randomly assigned to receive clinical care in quiet private rooms or a noisier open bay environment in the NICU at St. Louis Children's Hospital (Pineda et al. 2014a, 2017). We analyzed MRI data collected from 40 preterm infants who received care in private rooms and 46 preterm infants in open ward beds during their hospital course. Single patient rooms were surrounded by solid walls so that outside noise was attenuated. In contrast, the open ward consisted of four large rooms with eight to twelve beds each.

Data acquisition: MRI data were acquired on a 3 T Trio scanner using a custom quadrature head coil. T2-weighted images were acquired using the following sequence parameters: TR/TE 8600/160 ms, voxel size 1 × 1 × 1 mm3, echo train length 17(Pineda et al. 2014b).

Methods

Realignment and segmentation

We used dHCP-preprocessed data that include realignment and brain tissue segmentations. Anterior and posterior commissures were manually marked, and affine registration towards the Talairach-MNI space was performed using Brainvisa (Rivière et al. 2009). Registered MRIs were visually inspected and corrected if needed, with the same transformation applied to tissue segmentations. This procedure was repeated for the other two datasets.

STS extraction and depth computation

We applied automated sulcal detection and recognition for each individual using BrainVISA morphologist toolbox (Perrot et al. 2011). We visually inspected the labeling and delineation of the STS and central sulcus, and corrected any inaccuracies. In addition, all STS segmentations were manually reviewed and corrected if necessary. As in our previous work, we computed a coordinate system attached along the sulcus based on heat diffusion (Leroy et al. 2015a). By simulating heat diffusion from one end of the STS, we obtained two diffusion gradients as a coordinate system attached to the particular geometry of each subject's STS. In order to align sulcus depth profiles across subjects, we manually defined a common reference, corresponding to the innermost border of the *planum temporale*. The coronal projection of this landmark on the subjacent STS corresponded to the zero of our coordinate system. This reference does not affect the depth profile itself (and therefore has no impact on the maximum depth). It only defines the zero coordinate used to align depth profiles across subjects.

We also ran the Brainvisa morphometric algorithm (https://brainvisa.info/web/morphologist.html) to automatically compute the maximum depth of the central sulcus. This provided a control measure of another large primary sulcus unrelated to the STS.

Impact of prematurity in the dHCP dataset

To explore the impact of premature birth on STS depth, we performed linear regressions of STS depth at term-equivalent age as a function of gestational age at birth, at each of the 231 coordinates along the depth profile. We then plotted the regression coefficients across the profile. The corresponding p_values from each regression were Bonferroni-corrected for 231 comparisons to identify coordinates where STS depth was significantly affected by the gestational age at birth.

To ensure that the observed correlation was STS-specific, and not reflective of general brain development, we checked that brain volume at scan age was not significantly correlated with gestational age at birth ($p = 0.12$). In addition, we repeated the regression after regressing out the maximum depth of the central sulcus for each subject, to control for overall gyrification effects (Fig. 2C/F). For visualization purposes, and to better illustrate the effect of gestational age at birth on STS depth at term-age, we divided the dHCP subjects into nine groups based on 2-week gestational age intervals : <27 weeks, 27–29 weeks, 29–31 weeks, 31–33 weeks, 33–35 weeks, 35–37 weeks, 37–39 weeks, 39–41 weeks, and >41 weeks. This grouping was used solely for visualization and not for statistical analysis. Average STS depth profiles were calculated in each group and separately for each hemisphere (Fig. 2A/D). We also extracted the maximum STS depth for each infant using the BrainVisa toolbox and averaged these values within the same gestational age intervals, providing a simpler proxy for STS depth (Fig. 2B/E). Impact of early sound environment.

We repeated the same procedure on the two other datasets to recover the STS depth profiles in each infant. These two datasets were purposely selected from the published literature to test the hypothesis that auditory environment influences the STS depth, as neonates in these two cohorts were exposed to contrasting auditory environments. However, both datasets were small. To reduce the burden of multiple comparisons and avoid overly conservative corrections, we guided our statistical approach based on results from the dHCP analysis: (1) Since prematurity affected the left and right STS similarly in the dHCP dataset (Correlations between prematurity and right–left depth difference, all $ps > 0.05$), we averaged the two depth profiles in our smaller datasets to increase the signal-to-noise ratio. This resulted in a single averaged depth profile per subject. (2) We used maximum STS depth as our main variable of interest, as this single measure was sufficient to detect an effect in the dHCP dataset. Focusing on the maximum also mitigates alignment issues and inter-subject variability in sulcal morphology. While this increases sensitivity, it limits voxel-wise group comparisons. Nonetheless, full depth profiles are shown in Fig. 3 for visualization. (3) Based on the interpretation that STS depth is influenced by auditory stimulation, we performed one-sided *t*-tests to test directional hypotheses. We predicted that a richer acoustic environment (music group, Geneva dataset) would lead to deeper STS compared to their control peers, while a quieter environment (private room group, St. Louis dataset) would result in shallower STS. (4) To assess whether the observed effects were specific to the STS, we applied the same statistical analysis to the maximum depth of the central sulcus.

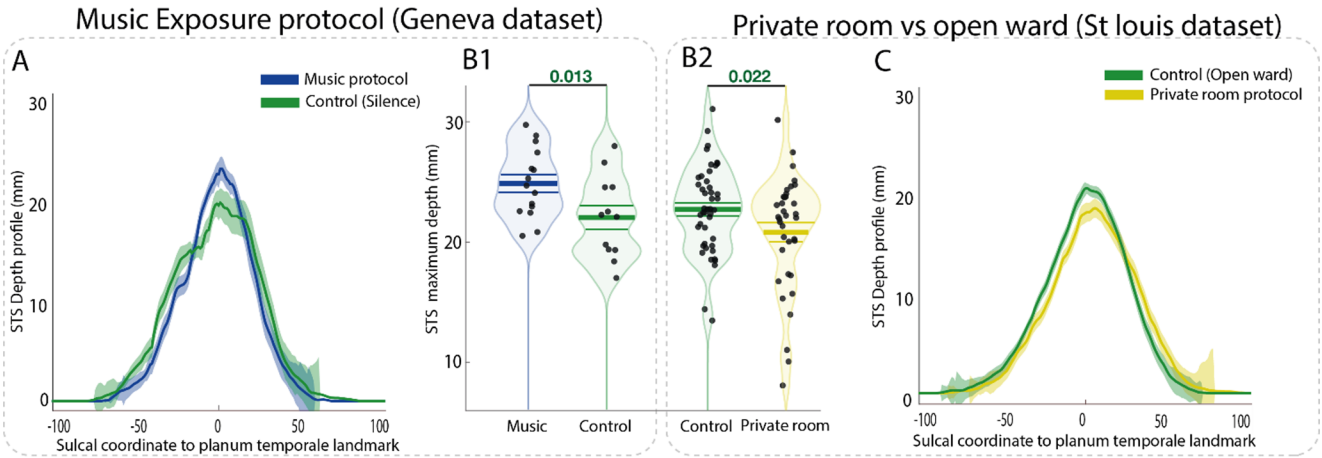

Fig. 3 Effect of the *ex-utero* acoustical environment on STS depth in preterm neonates scanned at term age. **A** Average STS depth profiles in preterm infants exposed, or not, to music. The shadow surrounding the line corresponds to the standard error of the mean. **B1** Maximum depth of the STS in each group. The thick bar represents the mean and the thin lines mean +-std. The music group shows a significantly deeper STS than the control group ($p=0.013$). **B2** Same analysis for the quiet room protocol. Preterm neonates placed in single patient rooms shows shallower STS than the control group remaining in the open ward ($p=0.022$). Note that the control groups from both datasets have the same STS depth despite different acquisition setups and populations, showing the robustness of the method. **C** Average STS depth profiles in preterm infants in single patient versus open ward rooms

Results

Impact of prematurity

In the dHCP dataset, scan age at term was similar between groups (Preterm = 40.3wGA, Full Term = 40.5wGA; t(182) = − 0.94, $p=0.35$), as was head circumference (Preterm = 34.4 cm, Full Term = 34.5 cm; t(182) = 0.33, $p=0.74$). Gestational age at birth showed no correlation with brain volume before ($p=0.93$) or after ($p=0.12$) realignment to the template.

As shown in Fig. 2, STS depth at term-equivalent age was shallower in preterm infants. Linear regression confirmed its association with gestational age at birth, despite all infants being scanned at term-equivalent age. This relationship remained significant when controlling for central sulcus depth, indicating a specific modulation of STS by prematurity. Notably, the effect persisted when using only the maximum sulcus depth per subject (left $R=0.34$ p = e-6; right $R=0.41$ p = e-9 - Fig. 2B/E).

Role of the ex-utero sound environment

We first ran an ANOVA to test group difference in STS max depth between the music group, the control group from Geneva database, the control group from StLouis database, and the quiet environment group. This revealed a significant group difference ($p=0.011$). We further confirmed our hypothesis on environmental richness impact with the following tests: (1) In the Geneva dataset, the STS was significantly deeper in the music group compared to controls (t(25) = 2.35, $p=0.013$; Fig. 3A/B1). (2) Conversely, in the St. Louis dataset, neonates in the quiet environment had shallower STS depth than controls (t(79) = 2.04, $p=0.023$; Fig. 3B2/C). In both datasets, gestational age at birth had no effect on the maximum depth of the central sulcus: St.

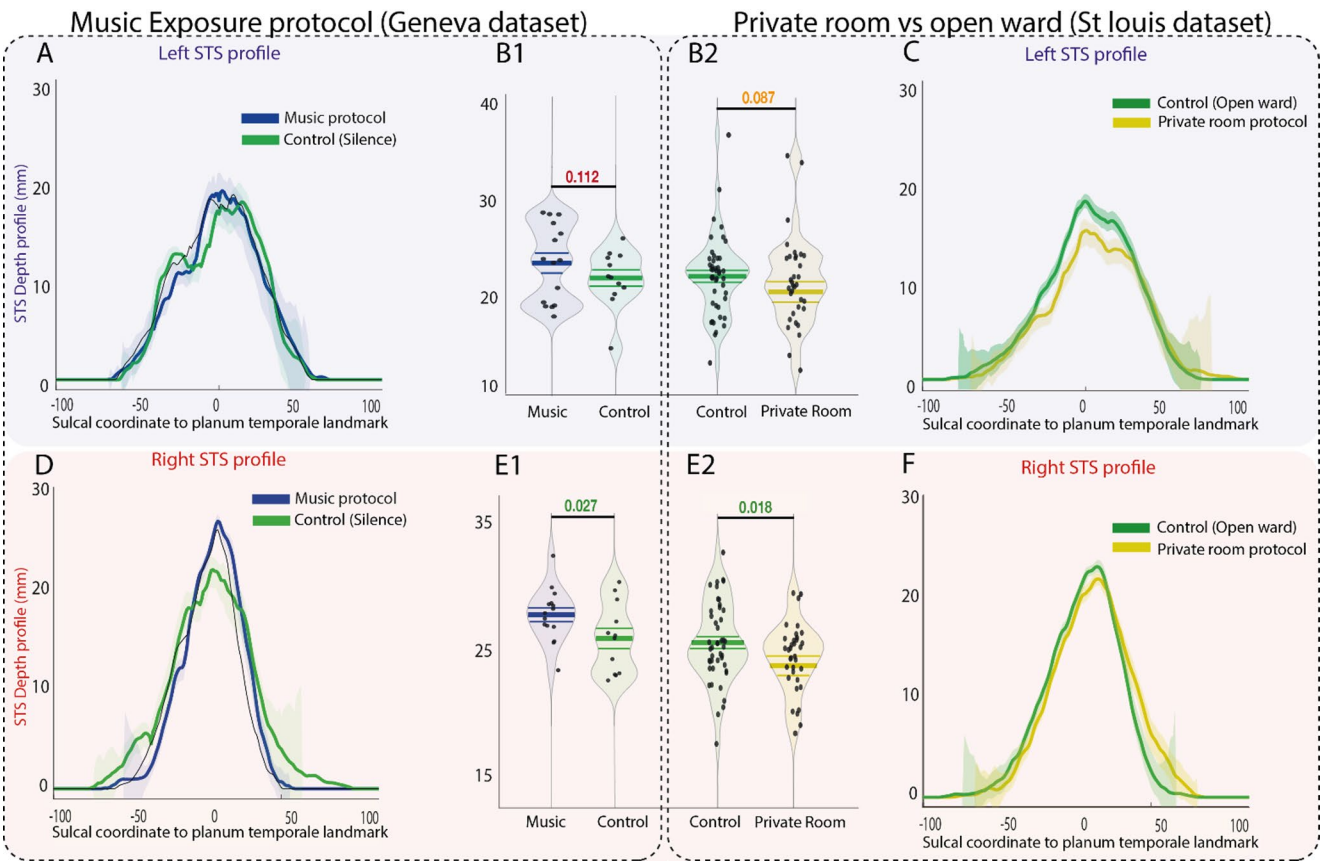

Fig. 4 Effect of the early sound environment on the left and right STS depth in the two datasets of preterm neonates. Reanalysis of the two protocols datasets (music and quiet room) for left and right STS independently. The main analysis with the average of both STS is presented in Fig. 3 of the main text

Louis dataset: left_t(25)<1; right_t(25)<1 and Geneva dataset: left_t(79)<1; right_t(79)=1.8, $p=0.96$. Moreover, as in the dHCP cohort, we regressed out the maximum central sulcus depth from the STS depth at the individual level. Both effects music>control ($p=0.046$) and quiet environment<control ($p=0.008$) remained statistically significant after this stringent control, further supporting the specificity of the auditory environment on the STS depth.

As a post-hoc analysis, we examined left and right STS depth profiles separately (Fig. 4). The pattern was similar in both hemispheres, but effects reached significance only in the right STS, which is typically less variable across individuals (Croxson et al. 2018; Leroy et al. 2015b) (Geneva dataset: Music vs. control: left_p=0.11 right_p=0.028; St. Louis dataset: private room vs. open ward: left_p=0.088 right_p=0.019).

Discussion

We demonstrated a linear relationship between STS development and gestational duration, with earlier birth associated with shallower STS depth at term-equivalent age. This finding appeared STS-specific, as it persisted even after controlling for central sulcus depth, despite the shared developmental timeline of these sulci (Chi et al. 1977; Habas et al. 2012; Kasprian et al. 2011) and common preterm risk factors (e.g., nutrition—Grotheer et al. 2023; hypoxia, stress). We hypothesized that this STS-specific alteration was primarily related to a reduced exposure to structured auditory stimulation during the weeks spent in the NICU, particularly a lack of exposure to the mother's voice. However, the STS might also be uniquely sensitive to a range of adverse exposures, making it difficult to isolate the role of auditory experience using the dHCP cohort alone. For instance, Kersbergen et al. (2016) observed reduced STS sulcation (confirmed in other studies - Dubois et al. 2019; Lefèvre et al. 2016), in preterm infants requiring prolonged mechanical ventilation (but note that this condition also alters auditory exposure).

To more directly assess our hypothesis concerning the impact of the richness of the auditory environment, we analyzed two supplementary datasets involving contrasting auditory environments: preterm infants exposed to music showed less alteration in STS depth, while those in quiet private rooms exhibited more pronounced changes. Together, these results support the idea that early auditory input contributes to the maturation of temporal networks, with downstream effects on macrostructural features such as the STS. The *ex-utero* environment offers distinct voices and enriched auditory input compared to the womb, potentially stimulating auditory development. However, constant mechanical noise from medical equipment, incubator white noise, and sudden alarms create an unpredictable soundscape, unlike the rhythmic fetal environment shaped by maternal heartbeats, vascular flow, and breathing. Moreover, voice frequencies are more attenuated in incubators than in the womb (Monson et al. 2020), and preterm neonates experience significantly less language exposure than fetuses (32 mn/day vs. 2.6 h/day—Monson et al. 2023).

Efforts to address these challenges led to the two protocols explored in this study. The first aimed to reduce the impact of harmful sounds by placing newborns in quiet private rooms, while the second focused on providing more structured and complex auditory input through music. However, while private-room infants were less exposed to noise as intended, they also experienced reduced exposure to speech and were more prone to language difficulties than those who remained in the open ward (Pineda et al. 2014b). In contrast, music exposure was expected to yield positive outcomes, as suggested by meta-analyses (Pineda et al. 2023). However, this specific protocol remained untested beyond its initial evaluation (Lejeune et al. 2019). Supporting our hypothesis that the linear effect on STS depth identified in the dHCP dataset reflects differences in auditory experience during the last trimester of gestation, we measured a macroscopic cortical effect in opposite directions across the two protocols with STS depth following the pattern: quietness < control < music. Such influence of environment on sulcal pattern has also been described in left-handers obliged to write with their right non-dominant hand. They presented a larger left than right central sulcus (Klöppel et al. 2010).

How can the environment influence sulcal depth? Tract myelination and dendritic arborization affect tissue elastic properties and contribute to cortical sulcation (Wang et al. 2021). Concerning the auditory domain, the strong connectivity between the STS and auditory cortices matures significantly during this period (McMahon et al. 2012) and is highly sensitive to the structure of the auditory environment (Dahmen and King 2007). Music exposure might support these maturational processes. Preterm infants exposed to music showed advanced development in the acoustic radiations, interhemispheric auditory callosal fibers, uncinate fasciculus, and amygdala compared to controls (Sa de Almeida et al. 2023). They also showed a longitudinal increase in fiber cross-section in the right temporal gyrus compared to controls, reflecting microstructural maturation through multidirectional dendritic complexification and potentially pre-myelination processes (Sa de Almeida et al. 2023). Music-related changes were also noted in other brain areas, particularly in the left insulo-orbito-temporopolar complex of the paralimbic brain, a region involved in sensory integration and the processing of affective stimuli.

The STS is key to verbal and non-verbal communication networks, with genetically controlled functional and anatomical asymmetries unique to the human brain (Le Guen et al. 2020; Guen et al. 2018). The right STS is deeper than the left in humans (Leroy et al. 2015b), an asymmetry that we consistently observed in the datasets, regardless of the sound environment. Although the interaction between hemisphere and sound environment was not statistically significant, the effects of auditory environment appeared more pronounced in the right hemisphere. In the dHCP cohort, for example, the modulation of STS depth by gestational age also showed greater spatial consistency in the right STS (Fig. 2D). This asymmetry can be interpreted in two ways: either both hemispheres are similarly affected, but the effect is only significant on the right due to more reliable measurements, given the right STS's simpler and less variable morphology, which improves signal-to-noise ratio (Croxson et al. 2018); or there is indeed a true hemispheric asymmetry, but our sample lacked the statistical power to detect an interaction.

The latter interpretation is supported by numerous studies reporting functional asymmetries in early auditory processing, often favoring the right hemisphere (Mahmoudzadeh et al. 2013; Perani et al. 2010). For instance, in the same dHCP dataset, longer gestation was associated with a linear increase in functionally connected voxels within the right superior temporal lobe (Mancuso et al. 2024), which we tentatively attribute to the predominance of speech prosody in the fetal auditory environment. In our results, the administration of music stimulation clearly modulated the depth of the right STS, aligning with adult studies highlighting predominant right temporal cortex effects of musical experience (Jünemann et al. 2023).

Several hypotheses could account for this right bias. One is that the right superior temporal region matures earlier than the left during the perinatal period (Chiron 1997; Leroy et al. 2011), making it more sensitive to external input. Another possibility is that the asymmetry reflects intrinsic functional specialization, with the right hemisphere more attuned to prosodic and musical aspects of sound, and the

left to linguistic content (Albouy et al. 2020; Dehaene-Lambertz et al. 2010). A study directly comparing the effects of music and speech exposure during this period would be particularly informative in disentangling these possibilities.

Recent findings support this line of inquiry: for example, Loukas et al. (2024) reported stronger activation in the right posterior superior and middle temporal gyri in response to vocal compared to instrumental music in newborns. Ongoing research explores how parental vocalizations, singing and structured musical interventions can support development in preterm infants in NICUs (Filippa et al. 2020; Pineda et al. 2023). Together, these studies highlight the importance of early auditory experience and the need to better understand how specific sound properties may differentially shape the left and right temporal pathways.

A limitation of our study is the lack of longer-term cognitive follow-up to assess whether increased STS depth in the music group is associated with improved language or auditory outcomes. Previous research has shown links between STS development in the last trimester of gestation and later language acquisition (Bartha-Doering et al. 2023; Kersbergen et al. 2016). However, the extent to which instrumental music engages the language system remains unclear (Chen et al. 2021; Dehaene-Lambertz et al. 2010; Kosakowski et al. 2023; Norman-Haignere et al. 2015). Music may instead influence subcortical auditory processing, including the brainstem, in ways that support language development (Strait et al. 2012). Additionally, structured auditory stimuli might help shape higher-order auditory processing.

Other limitations relate to the retrospective nature of our analysis. While our study leveraged valuable publicly available datasets, a prospective design would allow for greater experimental control. Specifically, future studies should aim to disentangle the effects of music exposure from gestational age by varying the duration and type of auditory stimulation (e.g., music vs. speech) independently of prematurity. Such studies should also aim to standardize MRI scanner types and acquisition protocols to minimize variability and improve comparability across participants.

Our findings suggest that the maturation of auditory and language networks during the final weeks of gestation influences STS depth. This raises the possibility that STS depth may serve as a valuable clinical marker, not only for premature infants, as demonstrated in this study, but also in other neurodevelopmental conditions such as autism, particularly in cases involving language disorders. As a structural feature shaped by early network development, STS depth may signal disruptions in these systems and potentially provide insights into the timing of such alterations, thereby contributing to a better understanding of their origins.

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Author contributions Conceptualization: LB, MB, GDL. Data Analysis: LB, MB, FL, CM. Data Collection: LL, JSA, LG, CR, TI, CDS, PH. Manuscript first draft: LB, FL, GDL. Manuscript revision: all authors.

Data availability Data analysed in this study are available upon reasonable request to the authors.

Declarations

Competing interests The authors declare no competing interests.

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