THE ARCHITECTURE OF THE BABY BRAIN

GHISLAINE DEHAENE-LAMBERTZ

When we think 'education', we often have in mind formal teaching delivered at school. Yet, developmental researches have shown that infants are learning since the first days of life. This informal learning within the small family circle is at the basis of what makes us humans. Recognizing other fellow humans, understanding what she/he is saying, telling stories, walking, running, singing, figuring out space and number, recognizing 3D objects, etc., all essential skills, are the consequences of complex learning process which begins very early on. Because of the poverty of the behavioral repertoire during the first months of life, parents and researchers have difficult access to what an infant thinks, feels, and learns. These early learning capacities have thus long been neglected. Thanks to the development of non-invasive brain-imaging techniques, we can now understand the richness of this stage in life, when parents are their child's natural teachers. These new tools allow a better exploration of infant early capacities and of their cerebral bases. They reveal an early and already complex organization sustaining the first interactions with the outside world far away from the blooming buzzing confusion postulated by William James (1892). On the contrary, the early particular organization of the human brain provides infants with a remarkable tool to learn about the external world.

Humans have not only a long developmental period but also the different cortical regions have different maturational time-courses. This produces physical constraints on the spreading of information within the neural networks that evolve along childhood and endow the child brain with its functional characteristics. The infant brain has been for a long time described as a few islands of functional cortex among a vast space of barely functional immature regions. What brain imaging studies reveal is that all cortical regions are participating in the infant thoughts. However, the effectiveness of local processing and the speed of information spreading may vary from one region to the next thus explaining the particular dynamic of an infant's cognition. I would like to propose that our approaches on learning and development in humans should take advantage of the better description of the physical brain. Our hypotheses about learning algorithms should be constrained by the neural 'hardware', and take into account the computational properties provided at a given age by the activated networks. I will illustrate my point with language acquisition and show how the early brain organization promotes language learning in the human species.

Neuropsychology and brain-imaging studies have clearly defined the regions involved in speech processing in adults. They are largely left-lateralized and comprised the superior temporal and inferior frontal regions connected by two main pathways: first, a dorsal suprasylvian pathway consisting of the arcuate fasciculus and the superior longitudinal fasciculus linking the posterior temporal and inferior parietal region with area 44 and second, a ventral pathway running through the uncinate and the extreme capsule connecting the anterior temporal region with area 45 (Anwander, Tittgemeyer, von Cramon, Friederici, & Knosche, 2007; Frey, Campbell, Pike, & Petrides, 2008). Three models of development of this network can be considered. First, maturational models postulate that initially only the primary and secondary areas are sufficiently mature to respond to the complex and fast stimulus like speech. Brain imaging studies should thus show activations initially limited to the superior temporal region bordering Heschl's gyrus. Then, as maturation progresses, the efficient network converges into the adult's mature pattern giving the child more resources to process speech. In this model the behavioral progression observed during the first three years of life is thus related to the progressive involvement of regions able to deal with more and more complex computations. A connectionist alternative might propose that the infant's brain is heavily connected and that it is the competition between entries in the different regions that stabilizes the network in the adult configuration. This type of model postulates more diffuse activations in infants than in adults, and also that the same behavior may be sustained by different cortical layouts (Johnson, 2001). The third type of models postulates that an evolutionary change in brain organization is the critical factor that has provided humans with the language possibility and that infants are equipped with a toolbox facilitating language acquisition, this toolbox being based on a specific organization of the perisylvian areas.

Combining structural and functional studies, our results are in favor of the third model. They show that language learning is based on a tripod: First, an early asymmetric organization of the perisylvian areas biasing language processing toward the left side; Second, a linguistic network based on local connectivity within the temporal lobe but also involving long-distance connections with the parietal and notably the frontal areas; Third, this linguistic network is in strong interaction with the social system.

1. An asymmetric organization of the human brain

a. Morphological asymmetries

A striking particularity of the human brain is its asymmetrical organization climaxing around the posterior sylvian region. A torque movement

pushing the right frontal area forward and the left occipital region backward (petalias) bends the midline towards the right (Yakovlev, 1962) and raises the right Sylvian fissure over the left (LeMay, 1984). This creates a prominent shape difference between the left and right posterior temporal regions (Toga & Thompson, 2003; Van Essen, 2005) elongating the left planum temporale (Geschwind & Levitsky, 1968). Another important asymmetry revealed by brain imaging is a deeper right superior temporal sulcus at the base of Heschl's gyrus (Glasel *et al.*, submitted; Ochiai *et al.*, 2004). Finally Heschl's gyrus itself, where the primary auditory area is located, is thicker on the left side even in deaf people (Emmorey, Allen, Bruss, Schenker, & Damasio, 2003), suggesting that this asymmetry is constituent and not the consequence of an exposure to oral language.

Human brain development is also strongly asymmetric. Several right sulci appear one or two weeks earlier than their left counterparts (Chi *et al.*, 1977; Dubois *et al.*, 2008). The raising and shortening of the right sylvian scissure and a larger left *planum temporale* are also observed during the fetal life (Chi, Dooling, & Gilles, 1977; Cunningham, 1892; Wada, Clarke, & Hamm, 1975; Witelson & Pallie, 1973). Thus at birth, the main asymmetries observed in the adult perisylvian are already present, i.e. first the raising and shortening of the right sylvian fissure, due to the Yakovlean torque, second an elongated left *planum temporale*, third a thicker Heschl's gyrus and finally a deeper right superior temporal sulcus (Figure 1, p. 256, Glasel *et al.*, submitted; Hill *et al.*, 2010)

Some of these asymmetries are also noticed in the primate brain. A longer left sylvian fissure (Yeni-Komshian & Benson, 1976), a larger left *planum temporale* (Cantalupo, Pilcher, & Hopkins, 2003; Gannon, Holloway, Broadfield, & Braun, 1998; Gilissen, 2001; Hopkins *et al.*, 2008), and a left-ward asymmetry in the inferior frontal regions (Cantalupo & Hopkins, 2001) have been described. No study has looked to the newly described deeper right STS. By contrast, the right frontal-left occipital torque is not observed in chimpanzees while the left occipital petalia is clearly seen in gorillas (Gilissen, 2001). However, when present, these asymmetries are never as systematic and strong as in humans, emphasizing that perisylvian regions have been the target of an evolutionary pressure increasing these characteristics in the human lineage.

Several genes with an asymmetric expression in the human brain have been described. For example, LMO4 is asymmetrically expressed toward the right side in the human brain between 12 and 14 weeks of gestation (Sun *et al.*, 2005). Although during convolution development gene expression has become globally symmetric (Johnson *et al.*, 2009), 76% of the human genes

are expressed in the fetal brain during the 18 to 23 weeks of gestation, and 44% of these are differentially regulated. It creates an intricate pattern of patchy regions with complex interactions and possibly locally asymmetrical gene expression that can regulate locally the size of the subventricular zone (Kriegstein, Noctor, & Martinez-Cerdeno, 2006) and thus subsequently impacting the shape of the cortical plate. It may also modulate fiber connectivity constraints that might more or less bend connected regions. In our work, we did not find correlation between the different asymmetries (*planum temporale*, Heschl's gyrus and STS). This suggests that these characteristics might be related to separate gene expressions (see Figure 1, p. 256).

b. Is there a functional impact of these anatomical left-right differences?

Although structural asymmetries are present early on, do they subserve functional asymmetries? Because of a better recovery from early lesions compared to what is observed in adults, authors such as Lenneberg (1967) have postulated that the brain might be equipotential at the beginning of life. Brain-imaging studies in normal infants have contradicted this hypothesis. In particular, the *planum temporale* shows hemispheric biases depending on the presented stimulus. When exposed to speech stimuli, its activation is greater on the left side in newborns (Pena *et al.*, 2003) and in two-month-old infants (Dehaene-Lambertz, Dehaene, & Hertz-Pannier, 2002; Dehaene-Lambertz *et al.*, 2010). This is not related to a bigger structure producing stronger activation for any auditory stimulus, responses to piano melodies being symmetric in both planum (see Figure 2, p. 256) (Dehaene-Lambertz *et al.*, 2010). Asymmetries toward the right side have also been observed with non-speech stimuli (Perani *et al.*; Telkemeyer *et al.*, 2009) and when abnormal speech (flattened or hummed speech) has been compared to normal speech (Homae, Watanabe, Nakano, Asakawa, & Taga, 2006). By contrast, Dehaene-Lambertz *et al.* (2002) did not observe difference in lateralization between the same sentences presented forward and backward. Although the prosodic information in backward speech is not usable by infants (e.g. they cannot discriminate backward French from backward Russian whereas they can do it with normal sentences), some phonetic information is preserved (e.g. fricatives, vowels) and the fast acoustic transitions characteristic of a speech stimulus are still present in backward speech but not in the hummed speech used by Homae *et coll.* (2006). Thus, this early bias toward the left side for speech stimuli can be related to the fast transitions present in this type of signal.

Indeed, at birth there is already an asymmetry at the cochlear level revealed by larger left otoacoustic emissions for tones and larger right otoacoustic

emissions for clicks (Sininger & Cone-Wesson, 2004). Because these otoa-coustic emissions are modulated by the olivocochlear efferent neurons, which can themselves be modulated by the controlateral auditory cortex (Perrot *et al.*, 2006), it is not possible to disentangle a cortical or subcortical origin for these peripheral asymmetries. In adults, it is proposed that the left auditory cortex has a better temporal resolution (Boemio, Fromm, Braun, & Poeppel, 2005; Zatorre & Belin, 2001) and integrates incoming signal over short time periods (20–50 ms segments) corresponding roughly to the phoneme length. By contrast, the right auditory cortex preferentially integrating over a longer 100–300 ms time-period would be more sensitive to slower acoustic modu-lations (Giraud *et al.*, 2007). Because of the weak myelination of axons and the less efficient cortical networks, the infant's brain is relatively slow when compared to the adult's brain. Thus arguments based on a differential pro-cessing speed between hemispheres and on a tuning of the oscillatory activity of the left-hemisphere on the time-units of speech should first be tested in infants before being generalized to the early age. Furthermore, acoustical pa-rameters alone are not sufficient to explain all lateralized results. It is known in adults that the perception of tones or vowels for example, can be more or less left-lateralized depending on their linguistic value for the subject {Gan-dour, 2002 #3262; Jacquemot, 2003 #3123}. Similarly in infants, we have shown that the linguistic (vowel identity) and acoustical value (speaker iden-tity) of the same vowel are processed in parallel respectively in the left and right hemisphere in two-month-old infants (Bristow *et al.*, 2009) although both processing rely on spectral analyses. Thus, as in adults, the acoustical properties of the stimulus are not sufficient to explain the lateralization of the brain responses and we need more functional and structural studies to un-derstand what drives speech processing toward the left side. Structural markers and functional results point at least to an early different developmental tra-jectory of the right and left hemisphere that precedes and does not follow language development (see Figure 2, p. 256).

2. The early linguistic network

During resting, the spontaneous fluctuation of the MRI signal is syn-chronized across cortical regions and studies in adults have shown consistent patterns of correlated activity in different sensory regions but also in higher cognitive systems. Several studies in infants (Fransson *et al.*, 2009; Fransson *et al.*, 2007) and even preterms (Smyser *et al.*, 2010) have shown networks similar to what observed in adults. These results emphasize the fact that short and long distance connections are not only present but might be func-tional in the subplate before all neurons are even in place in the cortical

plate (Kostovic & Judas). The observation of regional networks in the earliest time of the preterm period (already around 26 weeks postmenstrual age) also emphasizes that the specific and basic functional organization of the human brain is determined early on during pregnancy contradicting a strong version of constructivist hypotheses.

a. A nested organization in the superior temporal lobe

Activations paradigms underscore the segregation of the brain in regions dealing with different functional properties. In response to speech, activations do not spread over the entire cortex but remain within the adult linguistic network, i.e. the perisylvian regions. This network involves not only the neighboring regions of the auditory cortex but also extends along the superior temporal region toward the parietal and frontal lobe. These regions are not functionally equivalent but present specific functional properties. First, the superior temporal region can be parsed into distinct regions based on their speed of activation (Dehaene- Lambertz, Hertz-Pannier *et al.*, 2006). The phase of the activation in response to a single sentence increases as one moves from the auditory primary cortex toward the posterior part of the superior temporal gyrus and toward the temporal poles and inferior frontal regions (Broca's area) (see Figure 3, p. 257). Given the size of the delays involved (several seconds), this organization is unlikely to solely reflect synaptic delays. Rather, this temporal gradient of activation might be the result of different cognitive operations that integrate over increasingly larger and possibly more abstract speech units, and may therefore require longer processing time or more sustained activity. We are currently testing this hypothesis in infants, and in adults we observed an increase in the size of the activation with an increase of the prosodic tree (Dehaene-Lambertz *et al.*, in preparation).

Second, the superior temporal can also be parsed in subregions depending on their response to repetition. When a sentence is immediately repeated, a repetition suppression effect is observed in the ventral part of the speech activation in infants (Dehaene-Lambertz *et al.*, 2010). A similar effect is present in adults (Dehaene-Lambertz, Dehaene *et al.*, 2006).

This suppression is interpreted as an indication that the upper region of the temporal lobe codes for acoustics or basic linguistic elements, such as phonemes or syllables, which are constantly changing in a sentence, or that the memory buffer is very short in these regions. By contrast, the lower regions of the superior temporal lobe are able to detect a full-sentence repetition indicating that they are coding at a more global level or that they able to maintain in memory a specific acoustic/linguistic element during several seconds to detect its repetition.

Finally, the superior temporal sulcus possesses speech cross-modal representation. The presentation of an auditory vowel congruent with previous presentation of an articulatory movement but without sound induced a decrease of the electrical response in comparison with an incongruent situation, again in the lower part of the superior temporal region whereas the upper part is indifferent to the visual information (Bristow *et al.*, 2009). These three experiments pointed to a hierarchy of regions coding for more and more complex sound representations along a dorsal ventral gradient and extending posteriorly toward the parieto-temporal junction and anteriorly toward the temporal pole. This hierarchical architecture of the human temporal lobes presents homologies with that of the monkey brain (Kaas & Hackett, 2000; Pandya & Yeterian, 1990). Thus it is possible that human speech recycles a pre-existing primate system for hierarchical auditory representations (Dehaene & Cohen, 2007). Such a nested organization of processing units with progressively longer temporal window of integration would provide infants with an adequate tool to segment the speech stream in its prosodic components.

Testimonies of the parcellisation of the superior temporal region are also encountered in the microstructure of the cortex. We used the magnetic resonance T2 weighted (T2w) signal as a direct window on the microstructure of the cortex and in particular on its maturation (see Figure 4, p. 257). Maturation processes, i.e. the proliferation of membranes (growth of axons and dendrites, proliferation and differentiation of glia cells), the increase of hydrophobic proteolipids constituting the myelin (Barkovich, 2000) and the deposits of ferritine (Fukunaga *et al.*, 2010), change the ratio of free to bound water and thus decrease the T2w signal. Using an index based on this signal, we have quantified maturation within the linguistic network in 14 1- to 4-month-old infants. There is a clear dorsal–ventral gradient of decreasing maturity along the superior temporal region (*planum temporale* > dorsal STS > ventral STS). Furthermore, there is a significant asymmetry of maturation with the left STS lagging behind the right STS (Leroy *et al.*, 2011). This observation may appear in conflict with the functional studies reported above in which the response to auditory stimuli is largely bilateral over temporal areas. The location of the functional asymmetry is more posterior, over the *planum temporale*. In this area, maturation is symmetric except for a segment close to Heschl's gyrus which is more mature on the right than on the left side. Thus the functional lateralization of the linguistic network does not appear as a direct consequence of a maturational lead of one side over the other. What does it mean? It is an early testimony of the differential fate of these two regions. Indeed, during the whole life-span, the

two superior temporal regions develop and age differently (Paus *et al.*, 1999; Sowell *et al.*, 2003; Sowell *et al.*, 2002). For the moment, we ignore how these structural differences are related to functional properties. However these observations emphasize the different genetic fate of the two STS. Because the STS hosts several important functions beside language such as social contact, biological motion perception and audio-visual integration (Hein & Knight, 2008), further studies are needed to understand how the asymmetric pattern of development of this region may favor the development of the verbal and non-verbal human communication system. One hypothesis might be that the left maturation lag might be useful to allow the environment to shape the linguistic representations (see Figure 4, p. 258).

b. Long-distance connections: storing sound patterns in the inferior parietal areas and memorizing them in the inferior frontal region

When infants listen to speech, activations are not limited to the temporal lobe. A larger network involving parietal and frontal areas is recruited providing other useful computational resources. When responses to forward and backward speech are compared, forward speech induces stronger activations in the temporal parietal junction. This region is activated more by words than non-words in adults (Binder *et al.*, 2000) and is described as a dictionary of the auditory forms encountered in the native language. Infants of this age have already learned the prosodic contour of their native language (Dehaene-Lambertz & Houston, 1998) and are able to recognize if a sentence comes or not from their native language. We might thus consider this region as a proto-lexicon of the forms of the native language, which stores the finest unit coded at this age (e.g. intonative contour). In adults, cortex is thicker in this same region either in the most fluent bilingual adults and/or in those who have learned a second language at an early age (Mechelli *et al.*, 2004). This confirms the role of this region in early/fluent language learning.

Another important region is the left inferior frontal region. Two-month-old infants can detect a change of phoneme in a series of syllable even after a 2mn delay (Jusczyk, Kennedy, & Jusczyk, 1995). They are thus able to maintain a series of sounds during a short time as adults are able to remember a phone number the time they dial it. In adults this short-term memory is based on the linguistic dorsal pathway connecting the temporo-parietal junction to the inferior frontal cortex through the arcuate fasciculus. In infants, we also observed that when a sentence or a syllable was repeated, an increase of activity was recorded in the left inferior frontal area for the repeated stimulus (Bristow *et al.*, 2009; Dehaene-Lambertz, Hertz-Pannier *et al.*, 2006). This repetition enhancement effect in the frontal region stands

in contrast with the repetition suppression effect in the superior temporal region and emphasizes the effort done by infants. Repetition enhancement is usually seen in adults when they should keep tracks of the repeated stimuli or when they have difficulties to perceive the stimuli.

In the past the frontal areas were considered immature, unable to sustain an efficient functional activity. This affirmation was based on post-mortem and PET/SPECT studies showing an important gap between these regions and the primary cortices for example. However, these studies are scarce and obtained from post-mortem studies in sick children, or they lack spatial resolution in metabolic studies. They are in contradiction with the results presented above (see also Grossman *et al.*, 2008) reporting anterior prefrontal activity when social cues are perceived by infants. Using the T2w normalized index defined above, we compared the degree of maturation of the frontal and temporal linguistic regions. We were surprised to observe that the most immature region was not the inferior frontal region but the left ventral superior temporal sulcus that stands behind all other structures we measured (see Figure 4, p. 258). The primary cortices (motor, sensory and auditory) are as expected the most mature regions. Then, the inferior frontal sulcus, the precentral and all Broca's rami were classified as belonging to the same intermediate maturational group than the planum. The most immature regions of this network are the dorsal and ventral bank of the superior temporal sulcus (STS), with the more immature region being the left ventral bank of the STS. Thus, there is no inconsistency between the functional and the structural results. It is perfectly explicable to observe infants' inferior frontal areas engaged in functional activities. Moreover, correlation analyses reveal that temporal and frontal regions are not developing independently but show correlated inter-individual variability over and above age-related changes between area 44 and the posterior ventral STS. A similar result has been reported in adolescents using cortical thickness as the variable (Lerch *et al.*, 2006). Covariations in cortical microstructure between distant brain areas have thus been proposed as revealing the architecture of the human brain (Chen, He, Rosa-Neto, Germann, & Evans, 2008).

Anterior and posterior linguistic regions are linked by the arcuate fasciculus through the dorsal linguistic pathway. Diffusion tensor imaging MR sequences can be used to follow the maturation of white matter tracts. As myelination progresses, water diffusivity decreases and fractional anisotropy (FA) increases inside the tracts. We measured an asymmetry in the parietal segment of the arcuate with an increase of FA in the left relative to the right tract, suggesting a faster myelination or a more compact tract on the left. This asymmetry was correlated with the asymmetry in maturation in the grey matter of area 44 and the posterior STS (see Figure 5, p. 258).

To summarize, we observe correlations between the maturation of regions belonging to the dorsal linguistic pathway. This dorsal pathway might thus provide the neural substrate behind the enhancement of activity observed in Broca's area when syllables (Bristow *et al.*, 2009) and sentences (Dehaene-Lambertz, Hertz-Pannier *et al.*, 2006) are repeated. Language acquisition has been mainly described as a bottom-up process with a progressive tuning to the characteristics of the native language through statistical analyses of the speech input. Can the early involvement of this dorsal pathway change our view? What new type of computational resources can this system provide? The arcuate fasciculus is prominent in humans compared to other primates (Rilling *et al.*, 2008) and is notably involved in the phonological loop underlying working memory. Working memory is not only useful for adults to remember a phone number but might be crucial at the beginning of language acquisition to increase the duration of the auditory buffer offering a longer temporal window to analyze the speech signal. The dorsal pathway also provides infants with an early interface between speech perception and production systems, through area 44, which is tightly connected with the motor and somato-sensory areas (Petrides & Pandya, 2006). Thus area 44 can be seen as a functional hub, containing amodal phonetic templates informed by auditory, visual, motor and proprioceptive stimuli. This crossroad region is thus at a correct location to fulfill two functions. First, it might drive infants' motor productions by sending mismatched signals about the auditory gap between the produced sound and the internal templates. Second, it might strengthen the auditory representations of the native phonetic contrasts through the infants' efforts to imitate the caregiver's productions and to decrease the gap with the target. Indeed, infants are rapidly engaged in social contact, seeking eye contact and imitating adults' movements, such as mouth opening from birth on. They also rapidly begin to emit sounds during these social interactions or in response to heard speech stimuli, that progressively fit better and better with the model (Kuhl & Meltzoff, 1996). Scott *et al.* (2009) have proposed that the inferior frontal region is crucial as conversational turn-taking in adults. Thus a virtuous circle would be precociously established between frontal and temporal areas through the arcuate to reinforce frequently used phonetic representations in perception and production. Congruent with this hypothesis, Imada *et al.* (2006), using MEG, reported a progressive emergence of a frontal response in response to a vowel in neonates, 6- and 12-month-old infants. This active and progressive attunement of amodal representations in area 44 might be supported by individual neurons described by Rizzolati and his collaborators in macaques as motor neurons (Kohler *et al.*, 2002; Rizzolatti & Craighero, 2004).

3. Interactions with the social network

Language is not a lonely occupation. Infants use language to communicate with others and are rapidly engaged in mutual exchange with caregivers. A mere exposure to speech is not sufficient to acquire a particular language as it has been elegantly confirmed by Kuhl *et coll.* (2003). These authors reported that English-speaking 9-month-old infants keep the capacity to discriminate a foreign (Cantonese) phonetic contrast only when they are playing with a Chinese speaker but not when they are just exposed to the video or audio recordings of the speaker. A passive exposure is thus not sufficient to maintain the discriminative value of a phonetic contrast without an active participation of the child in the communicative act. Indeed, our studies reveal that the linguistic network is in tied connections with other systems that might boost its efficiency. For example, awake infants display an increased activity in the right dorso-lateral frontal region when listening to their native language (see Figure 6, p. 259). This can be related either to an increase in vigilance stimulated by the recognition of a known stimulus or to a more specific linguistic memory recognition process in relation with the parietal storing of the intonative contour of the native language.

A second example is the wide activation induced by the mother's voice (see Figure 7, p. 259). Just after birth, behavioural studies indicate that infants already recognize their mother's voice (DeCasper & Fifer, 1980; Mehler, Bertoncini, & Barriere, 1978). Using fMRI, we observed several differences in the activations measured when infants are listening to their mother's voice and to the mother of the previous baby in the study. First, the mother's voice elicits higher activation in the left posterior part of the temporal lobe (see Figure 2, p. 256). This region, part of the dorsal linguistic pathway, is involved in phonological representations in adults (Caplan, Gow, & Makris, 1995) and is thought to be a plausible cortical source of phonetic mismatch responses that can be recorded with scalp event-related potentials in infants (Bristow *et al.*, 2009; Dehaene-Lambertz & Baillet, 1998). These results suggest that phonetic processing in infants is sensitive to talker characteristics and can be improved by listening to a highly familiar voice such as the mother's voice. This result is congruent with a behavioral study showing that, in the presence of distracting background speech, infants are better at learning words when they are spoken by the mother rather by an unfamiliar speaker (Barker & Newman, 2004). Our finding can also explain why the clarity of the mother's speech has a strong impact on infants' phoneme discrimination capacities (Liu, Kuhl, & Tsao, 2003). This also confirms our dynamic model presented above that phono-

logical representations are reinforced through active interactions with the care-givers thanks to top-down influences of frontal on temporal areas through the dorsal pathway.

Second, the mother's voice elicits significant negative bold response in several regions involved in emotional processing in adults such as the orbito frontal cortex, the putamen and the amygdala. This points to a potentially interesting linkage of linguistic and emotional network in infants that might play an important role in learning. Finally, there is a balance between the anterior prefrontal cortex activated by the mother's voice and the orbito-frontal cortex activated by the unknown voice (Figure 7, p. 259). This reminds the spatial separation observed in adults' frontal area between activity elicited when thinking about the self and familiar other versus unknown others (Amodio & Frith, 2006), or when focusing toward external world vs internal state (Wicker, Ruby, Royet, & Fonlupt, 2003). Once again, the organization of the infant brain appears very close to what is described in adults. Anterior frontal activations have also been reported in four-month-old infants perceiving communication cues (Grossmann *et al.*, 2008) and in one-year-old infants looking at their smiling mother relative to an unknown face (Minagawa-Kawai *et al.*, 2009). Thus, this area may be important for mother-infant contact and emotional attachment.

To conclude, neuroimaging researches offer a new view on infant development. Contrary to constructivism assumptions, a structured organization is present from the first days on, even in very preterm infants (Smyser *et al.*, 2010). This particular organization offers to infants a Swiss army knife of computational tools to process the external world. We have seen here through the example of language that several particularities of the adult brain, such as asymmetries, pre-exist to the mature stage and that some of the already functional pathway (i.e. dorsal linguistic pathway) can explain how infants can easily learn their native language. This emphasis on neural structure is not a denial of the importance of environment. On the contrary, we have seen that the linguistic network is intrinsically connected with the emotional and attentional networks, emphasizing the fact that infants are engaged in both learning to talk and learning to talk to another human fellow. This initial architecture has been selected through human evolution as the most efficient to help infants to pick the correct cues in the environment in order to build the rich and large social groups seen in humans. Thanks to the development of brain imaging, we are at the beginning of a new approach of development in which a better understanding of the structural and functional properties of the developmental brain should help to better define the neuronal algorithms that sustain human thoughts.

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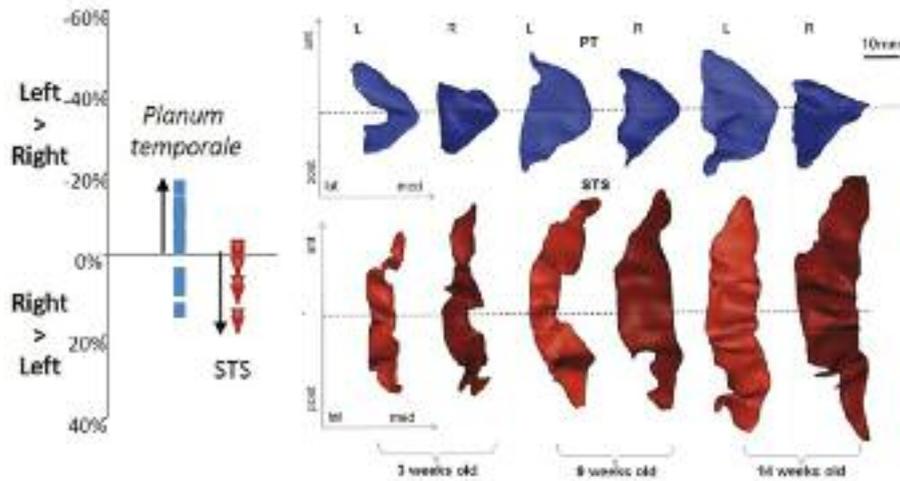
Figure 1. Structural asymmetries in human infants. A) Lateralization index (L-R/L+R) of the surface of the *planum temporale* and of the superior temporal sulcus (STS) in 14 infants. B) Individual examples showing the larger left *planum* and right STS in three infants spanning the time range considered (after Glasel *et al.*, submitted).
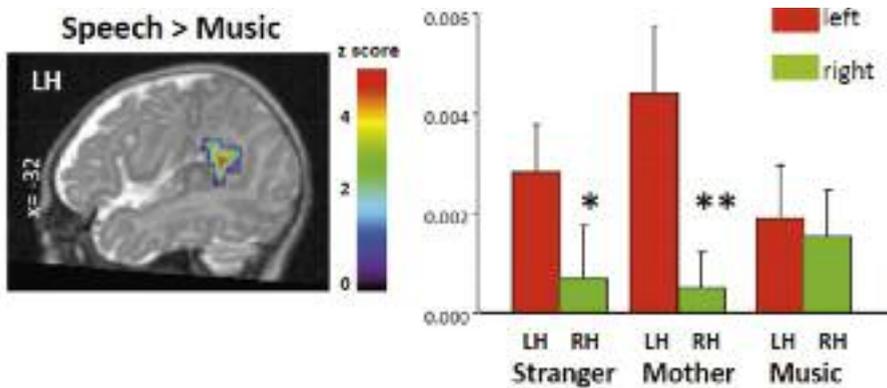
Figure 2. Hemispheric asymmetry for speech in the left *planum temporale*. (A) A comparison of the activations to speech and music in three-month-olds isolates a cluster in the left *planum temporale* (here projected on sagittal slices of a baby T2 anatomical image). (B) Boxplot of the individual activations averaged over the left and right *planum temporale* for three types of auditory stimulus: music, mother's voice and an unknown voice (arbitrary units). There is a significant left/right asymmetry for both speech conditions but not for music (** p<.01, *p<.05, after Dehaene-Lambertz *et al.*, 2010).
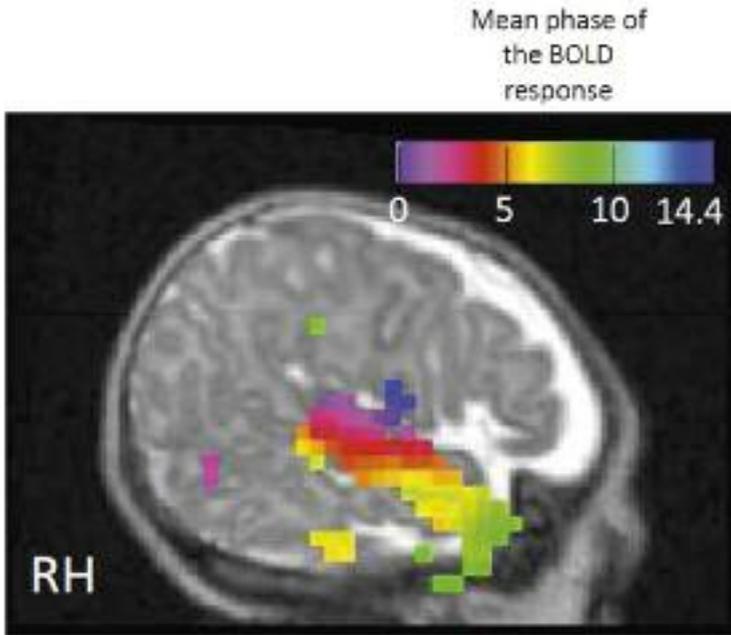
Figure 3. Phase measurement along the superior temporal region in three-month-old infants. The phase of the evoked fMRI responses to a single sentence was measured in 3- month-old infants (after Dehaene-Lambertz *et al.*, 2006b). A systematic gradient of response delays was found along both temporal regions, with fast on-line responses near Heschl gyrus (pink color), and increasingly slower responses as one moves either back into the *planum temporale* and Wernicke's area on the left side or forward along the STS toward the temporal pole and Broca's area (yellow-green color). A similar arrangement exists in adults (Dehaene- Lambertz *et al.*, 2006a), where it cannot be attributed purely to synaptic or hemodynamic delays, but may reflect integration and closure of speech segments of different lengths (phoneme, syllable, word, whole phrase). The presence of this gradient in very young infants, prior to any babbling, and its similarity to the hierarchical organization of anatomical projections in other primates (Kaas and Hackett, 2000; Pandya and Yeterian, 1990), suggests that it may constitute an innate bias that constrains language acquisition to a nested hierarchical structure.
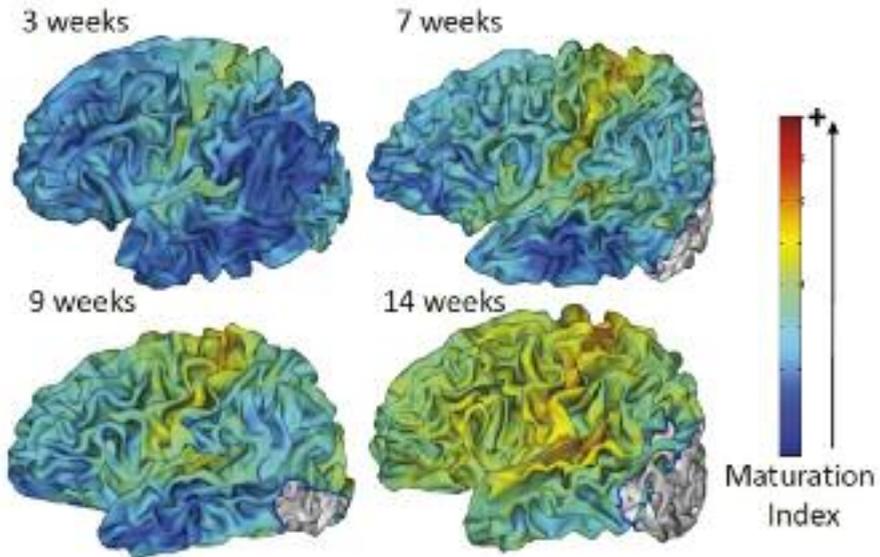
Figure 4. Cortical maturation during the first months of life. An index based on the T2w signal and measured at each cortical point is projected on 3D meshes (left hemisphere) at 4 different ages. No data (grey region) is presented where absence of CSF in the T2w image prevents the computation of the index. The primary cortices are clearly more mature than the other cortices. By contrast, the maturation is delayed in the temporal region, in particular relative to frontal areas.
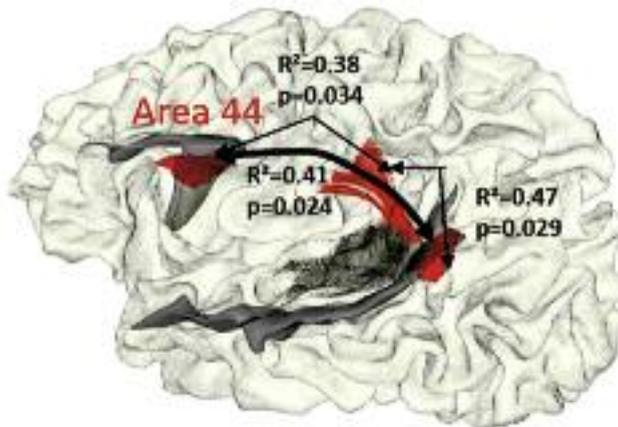
Figure 5. Correlations between white and gray matter maturation along the dorsal pathway. The STS, the precentral/inferior frontal sulci and the arcuate fasciculus of an individual infant are presented on his brain mesh. The arcuate fasciculus is limited to the parietal and temporal sections easily identifiable in infants. The regions significantly correlated at a group level are marked in red and correspond to the parietal part of the arcuate, the ventral part of the posterior STS and area 44 at the junction between the precentral and the inferior frontal sulcus (after Leroy *et al.*, 2011).
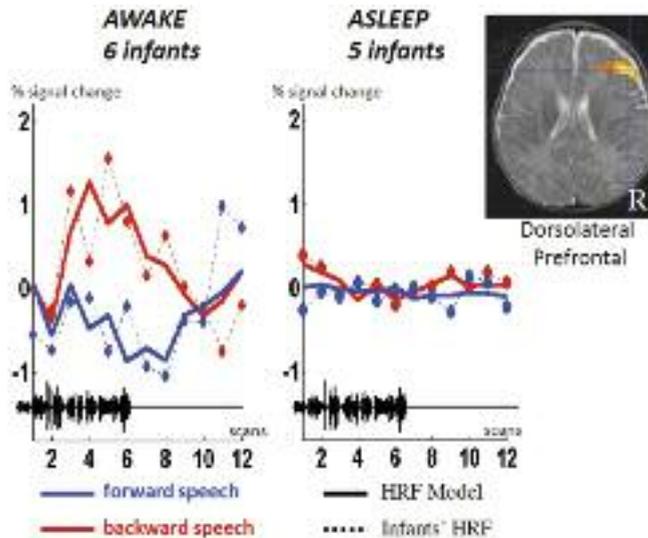
Figure 6. Responses to forward and backward speech in awake and asleep three- month-old infants. No response is seen in frontal regions in asleep infants although temporal areas are reacting to sound. In awake infants, there is a strong response to the native language (forward speech) which is not present for an impossible or unknown language (backward speech). These results underscore the participation of frontal regions in infants' cognition (after Dehaene-Lambertz *et al.*, 2002).
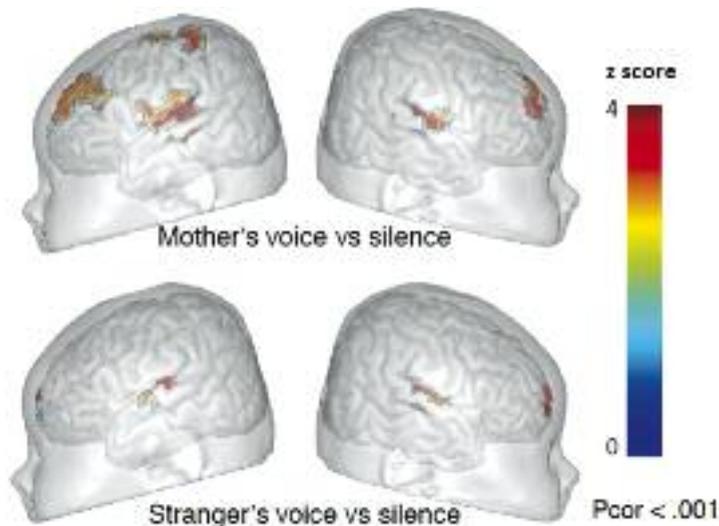
Figure 7. Activations in response to a known (the mother) and an unknown voice in two-month-old infants. The mother's voice elicits larger responses in the linguistic regions of the posterior temporal area, and also in the anterior prefrontal cortex and in the amygdala. The linguistic system is in tied connection with the attentional and emotional system (after Dehaene-Lambertz *et al.*, 2010).