CellPress

The Infancy of the Human Brain

G. Dehaene-Lambertz[1,*] and E.S. Spelke[2]
[1]Cognitive Neuroimaging Unit, CEA DSV/I2BM, INSERM, CNRS, Université Paris-Sud, Université Paris-Saclay, NeuroSpin Center, 91191 Gif/Yvette, France
[2]Department of Psychology, Harvard University, Cambridge, MA 02138, USA
*Correspondence: ghislaine.dehaene@cea.fr
http://dx.doi.org/10.1016/j.neuron.2015.09.026

The human infant brain is the only known machine able to master a natural language and develop explicit, symbolic, and communicable systems of knowledge that deliver rich representations of the external world. With the emergence of noninvasive brain imaging, we now have access to the unique neural machinery underlying these early accomplishments. After describing early cognitive capacities in the domains of language and number, we review recent findings that underline the strong continuity between human infants' and adults' neural architecture, with notably early hemispheric asymmetries and involvement of frontal areas. Studies of the strengths and limitations of early learning, and of brain dynamics in relation to regional maturational stages, promise to yield a better understanding of the sources of human cognitive achievements.

The remarkable and complex cognitive functions observed in humans do not suddenly emerge in adulthood but are shaped by two decades of development. After centuries of considering infants' mental life as either empty or confused, research in cognitive development has repeatedly shown considerable cognitive competencies in the first months of life despite infants' highly limited motor behavior. This set of early capacities projects human infants on a learning pathway beyond the pathways available to other animals. This pathway already bears some of the hallmarks of learning and cognition in human adults. In some domains, such as language, human infants are even better learners than adults. In other domains, such as numerical cognition, infants lag far behind adults in the extended process of developing knowledge of mathematics, but are already beginning to build a path leading from a set of core capacities shared with other animals to uniquely human, abstract knowledge. The neural architecture underlying these early capacities has long been out of reach, but this is no longer the case, thanks to the development of noninvasive brain imaging techniques permitting careful comparisons of the brain's functional architecture in human infants, human adults, and nonhuman animals. Such comparisons promise to shed light on the key elements underlying human cognitive achievements.

Language in Infancy

Language is the paragon of human cognitive sophistication, and it is certainly from this domain that many of the best examples of human infants' early competencies can be drawn. Many of these capacities have been discovered only recently, because verbal production develops slowly: after a stage of vocalization, then babbling, human infants commonly produce their first words at the end of the first year, and they produce multiword utterances with a substantial vocabulary only at about two years of age. Carefully designed experiments have shown, however, that infants' receptive capacities are substantially better than their production and present three crucial features. First, long before any effective language production, infants are sensitive to the particular vocal sounds and combinations used by their native language to create words and sentences. They recognize their native language prosody at birth (Mehler et al., 1988) and establish the phonetic repertoire of their language during the first year of life, starting with sensitivity to the vowels of their native language (Kuhl et al., 1992) and progressing to consonants (Werker and Tees, 1984) and then to the combinations of phonemes allowed in native words (Jusczyk et al., 1994). These findings illustrate the adept and progressive analyses of the different levels of speech organization that allow infants to discover and learn familiar speech patterns.

A second line of competencies concerns infants' ability to infer the abstract structure of speech. Infants rapidly become sensitive to word categories, storing the most frequent function words of their native language by 6 months (Shi et al., 2006b) and using the higher frequency of some syllables in an artificial speech stream to parse the stream at 7 months (Bernard and Gervain, 2012). By 12 months, function words and grammatical suffixes have a different status for infants than open-class words and morphemes (Shi, 2014). Before they produce fully grammatical sentences, 24-month-old toddlers analyze the syntactic structure of sentences and display ‘‘error’’ event-related responses when the sentences are ungrammatical (Bernal et al., 2010; Oberecker and Friederici, 2006).

Finally, a third line of early competencies crucial for language acquisition has been reported: long before they speak, infants begin to connect words to the things to which they refer. Around 6 months, infants begin to understand some content words that refer to people (e.g., ‘‘mommy,’’ ‘‘daddy’’), objects (e.g., ‘‘bottle,’’ ‘‘foot’’), and action verbs (e.g., ‘‘hug,’’ ‘‘eat’’). When images of two objects (e.g., a foot and an apple) are presented side by side on a computer screen, 6-month-old infants look more to the object named by their mother in a sentence such as ‘‘Where is the X, look at the X’’ than to the other object (Bergelson and Swingley, 2012; Tincoff and Jusczyk, 1999, 2012); by the end of the first year of life, they understand about 50 words (Fenson et al., 1994). In the lab, infants associate words with visual shapes at 4 months (e.g., ‘‘bubu’’ with a curvy shape; ‘‘kiki’’ with an angular shape; Ozturk et al., 2013); by 6 months, they extract a nonce word from a sentence using prosodic and statistical cues and map it on a visual referent (Shukla et al., 2011). More generally, verbal labeling facilitates object categorization: after several exemplars of a category (dinosaurs or fishes) are presented to 3-month-old infants, the infants respond with greater attention to a new dinosaur or fish if it does not belong in the familiar category, provided that each of the familiar members of the category was accompanied by the same verbal label. Interestingly, verbal labels are more efficient in this task than tones and backward speech for these young infants (Ferry et al., 2010). Verbal labeling also aids 14-month-old infants' ability to hold representations of objects in working memory (Feigenson and Halberda, 2008). Thus, language begins early to foster human infants' processing of information about the surrounding world.

At the end of the second year, toddlers can exploit the relations between words and things to learn aspects of the grammar of their language. In one experiment (Lany and Saffran, 2010), toddlers first listened to 32 sentences composed of four nonce words (e.g., ''erd deech ush coomo'') coming from two lists. One list consisted of monosyllabic nonce words always preceded by the syllables (''ong'' or ''erd,'' e.g., ''ong deech''); the second list consisted of bisyllabic nonce words preceded by ''alt'' or ''ush'' (e.g., ''ush coomo''). Then, six different pictures of animals or vehicles were presented, such that words in each category were consistently associated with one list (e.g., animals with the bisyllabic words). The toddlers were subsequently surprised (i.e., looked longer at the image) when an image was incorrectly associated with a word from the other list (a vehicle with a bisyllabic word in our example). This was not the case in a control group, for whom the only difference was that the syllables were inconsistently associated with the mono- or bisyllabic words during the initial presentation of the sentences. Once infants learned the conditions of application of the four syllables that preceded the nonce words, therefore, they were able to match these two complementary categories to visual categories. This example illustrates the versatility of infants' distributional analyses and their fast mapping of words to objects in different conceptual domains. A similar mechanism may underlie the matching of nouns to objects and of verbs to actions, because objects and actions are conceptually distinct, and nouns and verbs have complementary associations with the specific syllables representing articles and pronouns.

Mechanisms Underlying Early Language Learning

All these laboratory experiments are conducted in a few minutes, with no pretraining. They therefore reveal competencies that are readily available for language learning and cognitive development. Two main mechanisms have been proposed to explain infants' successes: statistical analyses of speech input and sensitivity to abstract patterns. A succession of experiments, beginning with the landmark study of Saffran et al. (1996), has demonstrated infants' powerful abilities to discover statistical properties of speech and thereby to uncover the phonetic inventory of their native language (Maye et al., 2002), to segment the continuous speech stream into words (Bortfeld et al., 2005; Ngon et al., 2013; Saffran et al., 1996), to establish long-distance relations between syllables (Friederici et al., 2011; Kabdebon et al., 2015), and to infer both the grammatical categories of words (Hochmann et al., 2010; Shi et al., 2006a) and word meanings (Xu and Tenenbaum, 2007).

Some of these capacities have also been reported in animals (e.g., tamarins [Hauser et al., 2001] and rats [Toro and Tobalón, 2005]), demonstrating the universality of distributional analyses. What is remarkable in human infants, however, is the simultaneous efficiency of these analyses at different levels of the speech hierarchy and the particular combination of speech cues that young children use. For example, to construct the closed-class word category, infants must note the co-occurrence of syllables sharing specific acoustic properties (low intensity, short duration, weak stress, particular distributions of phonemes) and their reproducible positions in prosodic domains. Children also associate the statistical structure of visual objects (cf. dinosaurs in Ferry et al., 2010) with the recovery of high-frequency speech events embedded in particular frame contexts (Mintz, 2003; Xu and Tenenbaum, 2007).

The strengths and limitations of infants' statistical learning expose how speech input is channeled in the infant brain, because the computational possibilities are framed by the neural architecture. For example, infants discover words in a speech stream only within a limited set of prosodic domains (Shukla et al., 2007) and only when statistical structure is weighted against other speech cues (Johnson and Seidl, 2009). Thus, the different levels of the prosodic hierarchy may correspond to different neural units. The superior temporal region, organized in areas of progressively longer temporal windows, is a likely substrate for this processing hierarchy (Dehaene-Lambertz et al., 2006). The precise description of the characteristics of speech statistical analyses in infants, together with increasingly realistic models of human infants' functional architecture, thus may inform models of language acquisition.

Another mechanism of language acquisition has been proposed by Marcus et al. (1999): 7-month-old infants are sensitive to the abstract pattern underlying syllable triplets. In this experiment, after a short familiarization with trisyllabic words sharing the same structure (*aab*, immediate repetition of the first syllable, or *aba*, delayed repetition of the first syllable after an intervening syllable), infants discriminated the two types of words over variation in the specific syllables presented. Because infants generalized their learning to new syllables, these findings were interpreted as showing infants' sensitivity to algebraic patterns. Subsequent research has revealed that infants' algebraic capacities might be limited at first to the detection of immediate repetitions (Endress et al., 2009), but their sensitivity to repetition can apply to abstract representations. In particular, 7-month-old infants can learn a hierarchical organization of repetitive structures (Kovács and Endress, 2014). In this experiment, infants first listened to sentences composed of three trisyllabic words, each word being either of the type *aba* or *abb*. These words were organized in a sentence with an ABB structure, for example *aba abb abb*, such that the two distinct words at the end of the sentence shared the same repetitive structure. When subsequently presented with sentences in which words were now organized with an AAB structure (*abb abb aba*), infants detected the second-order change in the repetitive structure, looking longer to the speaker when it played the new type of sentence. Although they detected the second-order regularity only when