Neuroscience of Language Development

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Introduction

Language development is the consequence of a series of neural events, resulting in an increased complexity at different levels of language: phonological, lexical/semantic, grammatical, and pragmatic. During the first three months of life, babies have the ability to produce few basic sounds, to respond to auditory stimuli in the range of human language frequencies, and present a clear preference for verbal sounds (**DeCasper and Fifer, 1980**; **Slater, 1998**). Between four and six months, babbling develops, and between seven and 12 months, babies can understand words for common items and imitate speech sounds. Between years one and two, the child can follow simple commands and h/she starts to put words together (https://www.nidcd.nih.gov/health/speech-and-language). Phonological, lexical, grammatical, and pragmatic development will be particularly accelerated between two and five years of age. At around five to six years, the child will have basic language knowledge: s/he will be able to produce all the phonemes and phoneme combinations existing in his/her language, will have a basic vocabulary including some 2000–3000 words, will be able to use the basic grammar, and will also be able to adapt the language to the current context (**Fenson et al., 1994**; **Lorraine, 2008**; **Rosselli et al., 2014**). Further language development will be observed during the school years.

Language, like many other cognitive abilities, has an asymmetrical brain organization, with a preference for the left hemisphere. Functional hemispheric lateralization appears since birth, but this lateralization significantly increases with age (**Ressel et al., 2008**). To quantify brain asymmetry, a functional index of lateralization has been proposed (e.g., **Desmond et al., 1995**). This index is based on the difference between the number of activated pixels ("picture alements", as a measure of resolution) in the left (L) and right (R) hemispheres divided by the total number of activated pixels. Using functional magnetic resonance (fMRI; it is a measure brain activity by detecting changes associated with blood flow). Language is one of the cognitive functions with the highest degree of left hemisphere lateralization. Language lateralization correlates with the growth of the corpus callosum (**Allen et al., 1991**), the commissure connecting the association cortex of the left and right cerebral hemispheres.

This paper describes the neuro-motor maturation required for speech production followed by the neurological bases of language development. It also describes early language development corresponding to the pre-school years followed by the late development up to adolescence.

Development of Speech Motor Control

Primates communicate using diverse strategies, including vocalizations, gestures, and facial expressions (**Liebal et al., 2013**). These initial communication systems represent the origins of contemporary human language (**Ardila, 2015**; **Corballis, 2019**); however, humans are the only primate capable of vocal learning. Chimpanzees, even when living since childhood in a human environment, are unable to vocalize more than a handful of words (**Kellogg, 1968**). The ability for vocal learning in humans has been related to the existence of the arcuate fasciculus, a segment of the superior longitudinal fasciculus, connecting the receptive language area (Wernicke's area) with the speech production area (Broca's area). The arcuate fasciculus is absent in non-human primates (**Rilling et al., 2008**).

Phonation is controlled by a hierarchically distributed system, extending from the brainstem to the motor cortex (**Simonyan et al., 2016**). At the cortical level, the ventral sensorimotor cortex plays the most crucial role in coordination with some subcortical structures. Speech articulation muscles are under the control of several cranial nerves, including V (trigeminal), VII (facial), X (vagus), XI (accessory), and XII (hypoglossal). More than 100 different muscles situated at different levels participate in what is probably one of the most complex motor acts.

Two different brain circuits are involved in human vocal learning: the cortico-striatal and the cerebro-cerebellar motor loops (**Ziegler and Ackermann, 2017**). Therefore, in addition to the cortical sensorimotor system and the cerebellum, the basal ganglia play a significant role in the acquisition of motor skills included in speech articulation (**Doyon and Benali, 2005**) (**Fig. 1**). Basal ganglia pathologies, such as Parkinson's disease, are associated with speech articulation impairments, and cerebellar pathologies can be associated with articulation defects, usually known as cerebellar or ataxic dysarthria, observed in conditions such as the Friedreich's ataxia (**Spencer and Slocomb, 2007**).

Early Language Development: Pre-school Period

Neuroimaging studies support the idea that in newborns, the left hemisphere is involved in processing verbal stimuli and that since very early in life, human language is predominantly processed by the left hemisphere (for a review, see **Rosselli et al., 2014**). Like adults, fMRI studies suggest that babies also activate the left perisylvian brain area (particularly the temporal lobes) when listening to their mothers speaking (**Dehaene-Lambertz et al., 2002**).

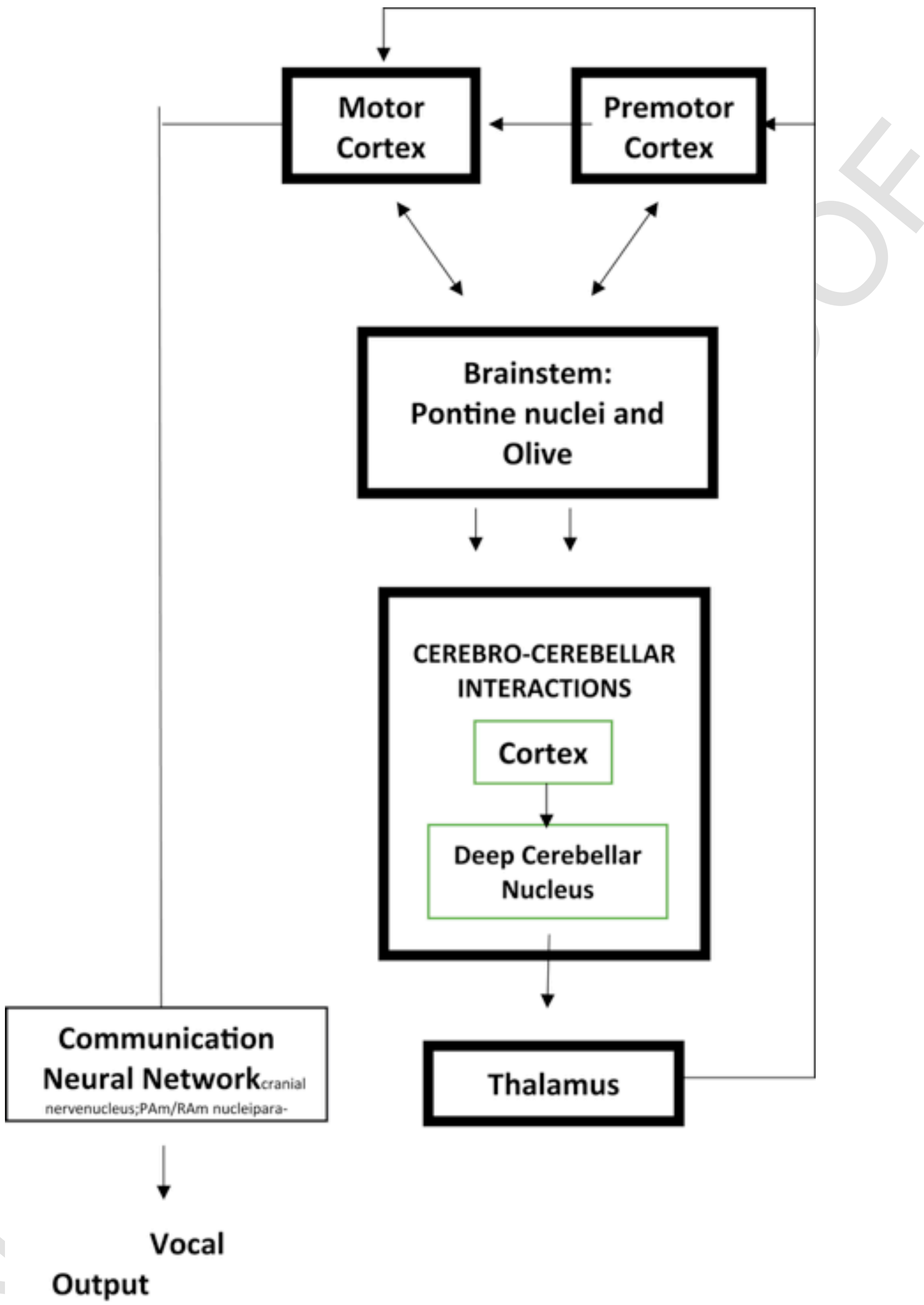

Figure 1 Cortico-pontocerebello-thalamocortical motor loops engage in the articulate speech of adult humans. Ad Adapted with permission from **Ziegler and Ackermann (2017)**.

However, significant differences between early and adult brain language organization are reported. While in children the classic language areas are activated before the age of six, the functional connectivity among these regions is not completed at this age. Unlike adults, who present a clear intrahemispheric connectivity between the frontal and temporal language regions in the left hemisphere, the language network in children is characterized by a strong functional interhemispheric connectivity, mainly among superior temporal regions (**Friederici et al., 2011**).

Using fMRI, it has been observed that language lateralization continues increasing for several years, seemingly between the ages of 8–20 years (**Everts et al., 2009**). Language lateralization, as well as the lateralization of non-verbal spatial functions, represents a dynamic process extending for a long time, and significantly affected by individual experiences. Besides biological variables, experiential conditions affect language lateralization (**Blumstein and Amso, 2013**). Consequently, language lateralization should be understood as a dynamic process under the effect of diverse genetic and environmental variables.

The so-called "perceptual narrowing" illustrates the impact of environmental variables on language development. It is understood that babies can recognize all the language phonemes, and this phonemic recognition is not limited to those existing in the environmental language (**Kelly et al., 2007**). The child, however, is usually exposed to only a limited number of phonemes –those existing in the native language. A progressive decline in the recognition of those non-existing phonemes in the environmental language is observed; this decline is noted since the end of the first year. During the following years, the ability to recognize native language phoneme will be reinforced, whereas the ability to recognize non-native language phonemes continues declining (**Kuhl et al., 2008**). This "perceptual narrowing" could be explained either as a progressive elimination of certain connections (known as pruning) (**Faulkner et al., 2007**) or to the formation of new connections (**Lewkowicz and Ghazanfar, 2011**).

Three levels of language development are examined in pre-school children: phonology, lexicon, and grammar.

Phonology

Phoneme perception and phoneme production increase in a parallel way in children. Whereas the ability to discriminate the native language phonemes increases, the ability to recognize and distinguish the language sounds not included in the environmental language decreases ("perceptual narrowing"). **Table 1** presents the typical sequence of phoneme acquisition of English phonemes.

Some common characteristics in phoneme acquisition can be described: (1) The earliest phonemes to be acquired require simpler phonoarticulatory maneuvres (2) Anterior consonant phonemes (e.g., /p/) are developed before back phonemes (e.g., /k/) (3) In general, stop (e.g., /p/) and nasal (e.g., m) phonemes are learned before fricative (e.g., /s/) and affricate phonemes (e.g., /tʃ/; and (4), and there is a significant variability in the age of acquisition of different phonemes. For instance, whereas 50% of children can produce the phoneme /p/ at the age of one, at the age of three, 90% of children are able to produce this sound. It has been estimated that at age three, children can produce 5–7 consonant phonemes, at age four, 10–12 consonant phonemes, and at around age 6–8, all English phonemes can be produced (**Hoff, 2013**). At this age, it is expected that the child will have a basic language, enough for communicating external events and expressing personal conditions (**Gibson and Petersen, 2010**).

Phonological development correlates with the brain's progressive specialization for recognizing phonemes in the immediate environment (**Vihman, 1996**). During the second and third years of life, the ability not just to perceive, but also to produce native-language phonemes, increases in a significant way. Phonological development will typically be completed for any language around the age of 5 to 7 years, even though there are significant variations. For instance, phonological development, and in general language development, is significantly faster in urban than in rural children.

Walton et al. (2018) showed that a stronger phonological processing ability in preschool children is associated with increased white matter structure of the bilateral ventral language pathways (i.e., inferior fronto-occipital fasciculus). **Vigneau et al. (2006)** performed a large-scale meta-analysis of the neuroimaging literature dealing with the brain/language relationships to define the composition of the phonological,

Table 1 Consonant phoneme acquisition in English

Phonemes	*Age at which 50% produced the sound*	*Age at which 90% produced the sound*
/p/, /m/, /h/, /n/, /w/	1 year	3 years
/b/	1 year	4 years
/k/, /g/, /d/	2 years	4 years
/t/, /ŋ/	2 years	6 years
/f/	2.5 years	4 years
/r/, /l/	3 years	6 years
/s/	3 years	8 years
/tʃ/, /ʃ/	3.5 years	7 years
/z/	3.5 years	8 years
/j/	4 years	7 years
/v/	4 years	8 years
/θ/	4.5 years	7 years
/ð/	5 years	8 years
/ʒ/	6 years	8.5 years

Adapted from **Sanders (1972)**.

semantic, and sentence processing networks in the frontal, temporal, and inferior parietal regions of the left cerebral hemisphere. From a sample of 730 activation peaks extracted from 129 scientific reports, the authors selected 30 activation clusters. The authors argue that this meta-analysis illustrates the fine-scale functional architecture of the inferior frontal gyrus for phonological and semantic processing. The meta-analysis also demonstrated areas of overlap between phonological and semantic processing, and a cortical area in the *pars opercularis* of the inferior frontal gyrus (Broca's area) dedicated to syntactic processing. On the other hand, the posterior part of the superior temporal gyrus was selectively activated by sentence and text processing. Results from this study also support the hypothesis that different working memory perception–action loops are identifiable for different language components. The authors concluded there are large-scale architecture networks rather than modular organization of language in the left hemisphere.

Lexicon

Active vocabulary development usually begins around the age of 12 to 18 months. Language understanding progresses significantly faster than language expression (**Fenson et al., 2000**). The number of words that the child can understand is several times higher than the number of words than the child can produce (**Fig. 2**).

During the following months, a significant increase in the child's vocabulary is observed. The ability to understand words out of context also progresses. Words begin to be combined, and from the one-word stage (holophrastic stage), the child moves to the two-word stage. In the two-word stage, one of the two words is a functional salient word and the other is usually a noun, for example: “more water”, “more play”, “more milk”, etc. This is the first step toward the development of grammar, illustrating that the increase in vocabulary correlates with grammar development (**Goodman, 1997**).

Vocabulary increases are particularly rapid after 18 months. Whereas at the age of two years, a child's vocabulary may include approximately 200 words, at the age of three it is close to 1000 words, and at the age of five, approximately 2000 words. At the age of six, the child can produce approximately 2500 active words, but s/he will understand close to 20,000 words (**Fenson et al., 1994**; **Lorraine, 2008**).

Specific neural changes support the rapid language development observed between the age of two and five years. These neural changes include not only structural changes (such as axon growth) but also some functional changes, including faster neural conduction due to myelination processes (**Courchesne and Pierce, 2005**).

Pujol et al. (2006) selected 100 children (mean age 16.6 months) and examined them using MRI, and a subgroup of 40 children were evaluated behaviorally. The authors measured the volume of myelinated white matter in the language-related areas in the temporal and frontal regions, and in the central sensorimotor area. It was observed that myelination changes started in sensorimotor white matter and the Heschl's gyrus and ultimately reached the language-related temporal and frontal areas. Both temporal and frontal regions showed a very similar myelination course. The language analysis suggested an accelerated rate of development in children's vocabulary after 18 months, once a rapid myelination phase was attained in the language brain.

Su et al. (2008) selected 241 normal neonates and young children (0 to 429 weeks) who underwent MRI and histopathological studies. Twenty-five adolescents and adults (aged 14 to 83 years) were included as controls. Seven language-related regions were analyzed: Broca's area, Wernicke's area, the arcuate fasciculus, and the angular gyrus, as well as their right hemisphere homologous regions, as well as the auditory cortex, the motor cortex, and the visual cortex. The authors reported that myelination in all seven language-correlated regions shared the same curve pattern: no myelination was observed at birth, it reached maturation at about 1.5 years of age, and it continued to progress slowly after that into adult life. No gender or hemispheric differences between homologous regions were found. The authors concluded that secondary cortical areas mature later than the primary cortical areas, and the arcuate fasciculus matured last. The observation that myelination reaches maturity after 18 months suggests that myelination may be a reason for the acceleration in vocabulary acquisition observed in children at that age (**Rosselli et al., 2014**).

The degree of maturation in the linguistic network in 1-to-4-month-old infants was studied by **Leroy et al. (2011)**. Results demonstrated that the ventral superior temporal sulcus is the least mature perisylvian region. A significant difference of maturation in the superior temporal sulcus favoring the right side was also found. Asymmetries of maturation in Broca's area correlated with asymmetries in the posterior superior temporal sulcus and the parietal segment of the arcuate fasciculus, suggesting that an efficient frontotemporal dorsal pathway might provide infants with a phonological loop circuitry much earlier than expected. Furthermore, asymmetries in the maturation of Broca's area correlated with asymmetries in the frontotemporal dorsal pathway. **Qi et al. (2019)** confirmed, through longitudinal structural MRI, that children from five to six years presented larger cortical thinning in the left triangular IFG compared to the right. This brain asymmetry was positively related to language comprehension at seven years.

Grammar

The beginning of grammatical development is usually observed at around the age of two to three years. Initially, the simple sentences are produced, but with time, utterances become progressively longer; the average utterance length increases from about 2.5 to 3.5 words (**Tomasello, 2003**). Using the mean length of utterance (corresponding to the number of words in a sentence), increases are reported from 2.91 at the age of 2.5–3.0 years, to 5.03 at the age of eight to nine years (**Rice et al., 2010**) (See **Table 2**).

Grammatical development is associated with increased lateralization of language abilities to the left cerebral hemisphere (**Hervé et al., 2013**). Greater systematic handedness preference is also observed, although handedness is definitively established approximately at four years of age. Superior grammatical abilities are correlated with increased activation in the left inferior frontal gyrus (Broca's area) independent of age, suggesting that increased specialization for language of the left inferior frontal gyrus is associated with increased grammar proficiency (**Nunez et al., 2011**). Significant increases are also reported in left frontal lateralization for verb generation with advancing age beginning at age five using magnetoencephalography (**Kadis et al., 2011**).

Table 2 Mean length of utterances in number of words (MLUw) according to the age

Age range (in years)	*MLUw*
2:6–2:11	2.91
3:0–3:11	3.57
4:0–4:11	4.19
5:00–5:11	4.42
6:00–6:11	4.63
7:00–7:11	4,83
8:00–8:11	5:03

Reported in Rosselli et al. (2014) and adapted from Rice et al. (2010).

Late Language Development: From Six Years to Adolescence

Language development continues to improve during the following years, both in volume and complexity (for a review, see Rosselli et al., 2014). During the school period, there is an increased analysis of the levels of the language, resulting in improved metalinguistic awareness, the ability to evaluate, think about, or handle language as an object separate from its meaning in or out of context (Roth et al., 1996). Metalinguistic awareness is significantly associated with learning written language. The child progressively understands that language includes different levels: phonological, lexical, semantic, grammatical, and pragmatic. Noteworthy, this school period between six and adolescence is coincidental with the Piaget's stage of concrete operations (Piaget, 1964). At the age of six, children usually have a basic language including approximately 3000 words, the phonology of the native language is virtually complete, and he/she can understand and use basic grammar (Hoff, 2013). During pre-adolescence, vocabulary will continue increasing, and the child will progressively develop the ability to use more sophisticated grammar; increased metalinguistic awareness will be evident (Warner-Rogers and Reed, 2008).

Using MRI studies, we can observe that language complexity is correlated with neural changes, specifically, the increased white matter volume observed throughout childhood and adolescence (Lenroot and Giedd, 2006). This increase is found not only in the left, but also in the right cerebral hemisphere; however, it is particularly evident in the brain language areas, specifically left frontotemporal areas (Paus et al., 1999).

Wilke et al. (2009) analyzed the networks underlying story processing in children between 6 and 15 years. A clear dominance of left-sided language regions was observed. Linguistic development, however, is also correlated with the development of non-linguistic abilities, such as attention, spatial skills, and memory (Gibson and Petersen, 2010). Other non-language related structures also maturate during childhood and adolescence, with increases in both gray and white matter (Toga et al., 2006).

Summing up, extended changes are observed in different intellectual abilities during the pre-adolescence period. Increases in gray matter and white matter are associated with the development of verbal and non-verbal abilities, approaching a level similar to that observed in adults (Sowell et al., 2002). Using fMRI, it has been demonstrated that the pattern of brain activation during speech production is more bilateral in childhood but becomes increasingly lateralized in the frontal cortex during adolescence (Lidzba et al., 2011).

Brain Maturation and Language Development

Functional and structural MRI studies have significantly contributed to the understanding of the neural architecture underlying language development (Dehaene-Lambertz, 2017). These studies show linear decreases in cortical gray matter and increases in white matter between the ages of four and 20. fMRI techniques show selective increases in brain connectivity from age five to age six in a cluster within the left posterior superior temporal gyrus and sulcus (Xiao et al., 2016). Youssofzadeh, Vannest, and Kadis (2018) studied the fMRI connectivity of expressive language in young children (age four–six) and adolescents (age 16–18) and reported significant interhemispheric connectivity in young children, with minimal connectivity of Broca's area to subcortical and cerebellar regions. However, the older group showed substantial connectivity between Broca's and the left perisylvian cortex, left caudate and putamen, and regions of the right cerebellum. Yin et al. (2019) used a data-driven approach based on individual brain functional connectivity to cluster typically developing children during the first two years of life. MRI without sedation was used. Three age groups were determined based on the distinction of brain functional connectivity patterns: 0–1 month (group 1), 2–7 months (group 2), and 8–24 (group 3). Between groups 1 and 2, connection density nearly doubled, while between groups 2 and 3, connection density increased slightly. Researchers identified 27 core brain areas that yielded clustering results that resemble those obtained using all brain regions. These core regions were largely associated with motor, visual, and language functional domains as well as regions associated with higher-order cognitive functional domains. Both visual and language functional domains exhibited a persistent and significant increase within domain connection from groups 1 to 3, while no changes were observed for the motor domain. Cusack et al. (2018) found that functional connectivity in speech networks is mature at three months; this observation suggests that the delay in the onset of language is not due to brain immaturity but to the time needed to develop representations through experience.

Changes in cortical gray matter following an inverted U are specific to each brain area. Developmental curves for the frontal and parietal lobe initially peak at approximately age 12, and for the temporal lobe, this peak is at about age 16. Nonetheless, there is a continuous increase in cortical gray matter in the occipital lobe through age 20 (**Giedd et al., 1999**). The age at which this gray matter decline begins varies across the cerebral cortex; the frontal system reaches its gray matter peak between the ages of 12–14 years, while in the temporal lobe, this occurs around age 17–18, and in the parietal at 10–12 years. Conversely, there is a continuous increase in white matter volume (**Gerber et al., 2009**).

Giorgio et al. (2008) used diffusion-weighted MRI to identify middle frontal and precentral gyri that showed an age-related decrease in gray matter density through adolescence; this cluster was connected with the tracts that showed age-related white matter increases. The gray matter density decrease was significantly correlated with the white matter increase in the connected cluster. Although age-related changes were less prominent in the young adult group of the same study, there were significant age-related increases in the right superior longitudinal fascicle, suggesting that structural development of this pathway continues into adulthood. White matter increases are much more evident than the decrease in gray matter. The most significant changes between the ages of 13.5 and 21 years were observed in the body of the corpus callosum and the right superior region of the corona radiata.

It is noteworthy that age-related changes in white matter continue beyond childhood. These changes are supposed to underlie an acquisition of new abilities and an increased learning ability (**Lebel and Beaulieu, 2011**). Interestingly, sex differences in the maturation rate of both gray and white matter have been identified. MRI images gave shown a significant male/female differences in the shapes of trajectories with total cerebral volume peaking at age 10.5 in females and 14.5 in males. In males, white matter increases have a steeper rate of increase during adolescence. Both cortical and subcortical gray matter trajectories follow an inverted U-shaped path with peak sizes 1 to 2 years earlier in females (**Lenroot et al., 2007**).

In addition to the patterns of increase and decrease in white and gray matter, modification in brain regional activation has also been associated with language development. Age-related increases in activity are observed in primarily newly recruited, later-stage processing regions, such as in left frontal and left parietal cortex. Decreases, on the other hand, include all positive activations that are attenuated with age and are found across a wider neuroanatomical range, including earlier processing regions such as the bilateral extrastriate cortex (**Brown et al., 2004**).

Szaflarski et al. (2006) analyzed progressive and regressive activation changes in brain development during the school years. They obtained fMRI data every year for a period of five years. Results showed a progressive participation in language processing by the inferior/middle frontal, middle temporal, and angular gyri of the left hemisphere and the lingual and inferior temporal gyri of the right hemisphere, accompanied by a regression in the participation of the left posterior insula/extrastriate cortex, the left superior frontal and right anterior cingulate gyri, and the left thalamus. The authors concluded that language development includes not only quantitative but also qualitative brain changes between the ages of five and 11. **Sreedharan et al. (2018)** analyzed language networks and lateralization using fMRI in 8–12 year olds. Two different paradigms were used: visual verb generation and word pairs. fMRI showed left language lateralization in 13 out of the 16 children in both paradigms and bilateral language lateralization in two subjects. With the visual verb generation paradigm, there was more activation in the left inferior triangular gyrus, left inferior opercular gyrus, left middle frontal gyrus, left and right dorsolateral prefrontal cortex. The left posterior superior temporal gyrus, left angular gyrus, and left supramarginal gyrus were significantly activated with the second paradigm.

Conclusions

Language production begins around the age of 12 months; however, language understanding is earlier and develops faster. Grammar begins developing around 2–3 years. At around 5 to 6 years, the child is expected to have a basic language with the following capabilities: to produce

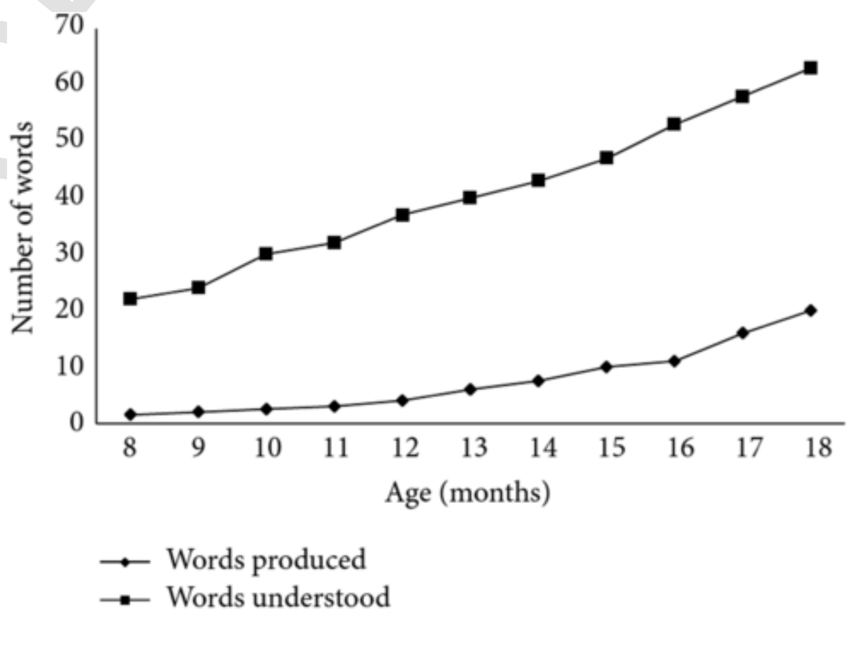

Figure 2 Number of words produced and understood by Spanish speakers in the 50th percentile. Presented in **Rosselli et al. (2014)** and adapted from **Jackson-Maldonado et al. (2013)**.

all the phonemes and phoneme combinations existing in his/her language, to have a basic vocabulary including approximately 2000–3000 words, to use the basic grammar, and to adapt the language to the current context. Language development will continue during the school years. In addition to the continuing development of vocabulary and grammar, metalinguistic awareness and written language abilities are progressively reinforced.

Language development is associated with specific changes in the brain, with changes in both gray and white matter observed. These changes in cortical gray and white matter are specific in each brain area and are evident in the language brain areas in the left hemisphere. Handedness is established around the age of 4–5 years. Furthermore, language development involves not only quantitative but also qualitative brain changes. During adolescence, in addition to increasing language complexity, the underlying neurological changes observed are similar to the level observed in adults. Nonetheless, further minor changes are also observed through adulthood.

Acknowledgments

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