



## THE RELATIVITY OF ONTOGENETIC TIME ON PRIMATE EVOLUTION AND THE EMERGENCE OF LANGUAGE

### A RELATIVIDADE DO TEMPO ONTOGENÉTICO NA EVOLUÇÃO PRIMATA E NA EMERGÊNCIA DA LINGUAGEM

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**Resumo:** A maioria dos estudos em primatologia têm foco nas semelhanças entre as espécies remanescentes dos gêneros *Pan* (chimpanzés e bonobos) e *Homo* (*sapiens*). Neste artigo, revisamos a literatura sobre as diferenças heterocrônicas no desenvolvimento ontogenético das espécies como uma forma de levantar uma discussão sobre suas diferenças comportamentais, especialmente no que diz respeito ao sistema de comunicação humano. Um conceito-chave aqui é a neotenia, que se refere à desaceleração na taxa de desenvolvimento das espécies. A biologia humana é altamente neotênica e retarda o desenvolvimento durante a primeira década de vida pós-natal. A neotenia humana permite que o nosso cérebro se desenvolva junto com o ambiente, de modo que a biologia, o ambiente físico e o ambiente social não podem ser vistos como visões diferentes do mesmo processo, mas como processos interdependentes que trabalham em conjunto para o desenvolvimento normal dos seres humanos. Com o objetivo de levantar potenciais características biológicas que possam ter auxiliado a emergência da linguagem, ao longo deste artigo, discutimos como a neotenia pode ser um conceito explicativo potencial para algumas diferenças comportamentais entre espécies e como isso poderia se relacionar outros sistemas cognitivos, como a aquisição da linguagem em *Homo sapiens*.

**Palavras-chave:** neotenia; heterocronia; linguística evolucionária; biolinguística.

**Abstract:** Most reviews on primatology focus on the similarities between the species of *Pan* (chimpanzees and bonobos) and *Homo* (*sapiens*) genera. In this paper, however, we review the literature on heterochronic differences in ontogenetic development of species in order to raise a discussion about their behavioral differences, particularly in relation to the human communication system. A key concept discussed here is neoteny, which refers to the slowed rate of species development. Human biology exhibits high levels of neoteny, resulting in a prolonged period of development during the first decade of postnatal life. Human neoteny enables the brain to develop in conjunction with physical and social environments, emphasizing that biology and society should not be perceived as distinct perspectives of the same process, but rather as interdependent processes that collaborate for the normal development of human beings. In order to identify

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biological concepts that may have contributed to the emergence of language, throughout this paper we explore how neoteny can be a potential explanatory concept to some of the behavioral differences between species, and how this may relate to cognitive systems such as language acquisition in *Homo sapiens*.

**Keywords:** neoteny; heterochrony; evolutionary linguistics, biolinguistics;

## 1. INTRODUCTION

The cladogram of the great apes shows that, among the extant species, chimpanzees (*Pan Troglodytes*) and bonobos (*Pan Paniscus*) are the closest relatives to humans in terms of evolutionary scale. In addition to anatomical similarities, DNA hybridization studies and molecular clock analyses indicate genetic differences of approximately 0.7% between the DNA of the two Pan species, and about 1 to 2% between their DNA and that of *homo sapiens*. These findings suggest a recent common ancestry shared by both Pan and Homo species (Chen, Li 2001; Ebersberger *et al.* 2002).

We might question whether such genetic similarity implies that fundamental differences between *homo and pan* are primarily quantitative rather than qualitative. Pinker (1995) challenges the validity of this argument. He argues that even a genetic difference of 1% can endow beings with quite different characteristics, qualitatively speaking. In this sense, genetics should not be measured quantitatively, but rather qualitatively.

In general, in the literature there is a tendency to emphasize the evident similarities between *homo and pan* species to highlight their evolutionary path. In this paper, however, we take a different approach. We will concentrate on a selected set of differences, specifically those related to the deceleration of ontogenetic development - neoteny - compared to our Last Common Ancestor (LCA), to raise questions concerning the connection between physiological and anatomical changes in primate evolution and the extent of behavioral variability. In our view, these differences may have favored the emergence of language in humans.

Our goal is to shed light on language evolutionary emergence by central biological concepts related to the ontogenetic changes. In this sense, the initial sections serve as crucial background information on biological evolution. Section 2 introduces the concept of heterochrony, in particular neoteny, responsible for extending an organism's development timeframe in comparison to that of their ancestors. Section 3 discusses the evidence supporting that neoteny is particularly pronounced in humans. This is done by comparing the birth and development of human infants with those of non-human primate and of other species. Having set the biological background for our discussion, the fourth section will bring a discussion on the Social Brain Hypothesis and, the fifth section will finally introduce a discussion on the relationship between neoteny, evolution and language development in children. This will lead us to the concept of critical periods for language, which will be reviewed and developed in section 6, while section 7 delves into the neurophysiological characteristics of this relation. The eighth section presents our final thoughts.

## 2. ON THE CHRONOLOGICAL CHANGES IN SPECIES DEVELOPMENT

Our planet houses an estimate of 3-112 billion species (May 1988). Mora *et al.* (2011) estimates the existence of about 8.7 billion terrestrial species and 2.2 billion marine species. Despite this, only 3 billion species were catalogued until 2008. Among

the documented specimens, only in some species, such as arachnids and insects, were hatchlings very similar to adults, just differing in size.

With mammals, like zebras, for instance, foals can get up and walk within only 20 minutes after birth and can run by one hour later (Nuñez *et al.* 2009). This remarkable feature is likely due to genetic memory<sup>4</sup> and natural selection. Rhesus monkeys, in contrast, need more time to develop their ability to move around, about one week after birth (Dienske & De Jonge, 1982) while chimpanzees need about three months to start crawling (Balzamo *et al.* 1972).

Species tend to be ontogenetically similar to their ancestors. Nevertheless, some differences in their developmental rate can be observed. Haeckel (1875) identifies these differences by the term *Heterochrony*, and suggests that it can occur according to three primary parameters: (I) the onset, (II) the rate and (III) the offset of the species' development, new behaviors, or anatomical traits (such as tail growth or crawling behavior).

Regarding the onset, a change in the development window may occur. For instance, the development of the tail might start in a preceding phase (Predisplacement) or subsequent phase (Postdisplacement) compared to that of its ancestors. In such cases, the development rate and speed remain the same (Figure 1).

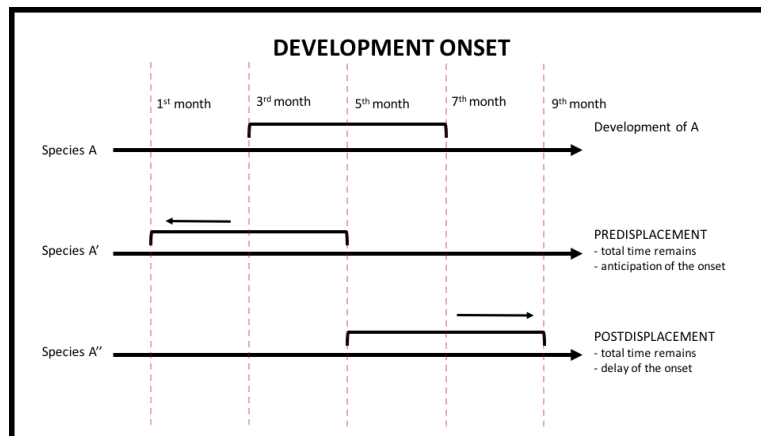


Figure 1: Modification in the onset of a species' ontogenetic development.

In terms of the development rate parameter, heterochronic changes result in a progenic or hypermorphic form. Progenesis involves a shortened maturational period, while hypermorphism entails an extended one (see Figure 2). In both cases, the developmental rate remains the same, and the altered trait completes its development, respectively, in a phase less or more advanced than that of its ancestor.

The third parameter of heterochrony concerns the rate of development (III), which can either be accelerated (*Peramorphosis/Gerontomorphosis*) or delayed (*Paedomorphosis/Neoteny*<sup>5</sup>), thereby modifying the offset of growth of specific characteristics within a species (see Figure 3).

<sup>4</sup> Over time, various mutations occur in individuals, slightly or drastically altering their internal functioning, anatomy or behavior. Mutations can be beneficial, neutral or harmful. Taking as an example that, in general, individuals who have natural fear of predators have a greater ability to run and hide, increasing probability of survival and, therefore, *reproduction*, so that feature becomes more and more common in species through genetic inheritance passed to offspring. This “natural fear” is an example of what is considered genetic memory in this paper.

<sup>5</sup> Some researchers classify neoteny (deceleration, Fig.3) and progenesis (shortening of duration, Fig.2) under the category of *paedomorphosis*, as both cases involve the retention of juvenile form in adulthood. In short, a progenic species retains an infant-like form because it reaches adulthood at a faster rate

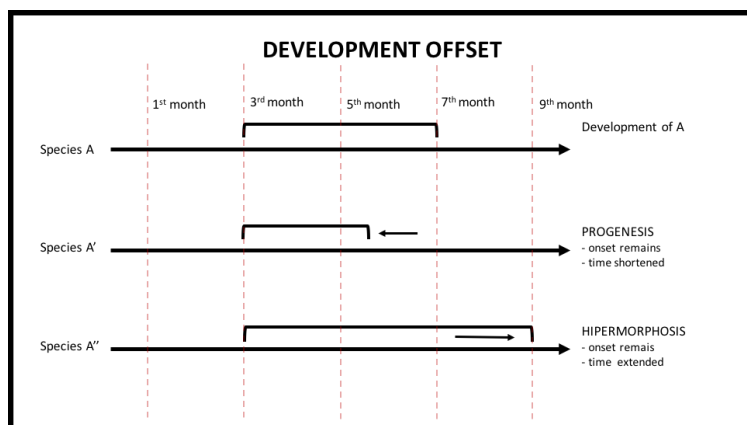


Figure 2: Modification in the offset of a species' ontogenetic development.

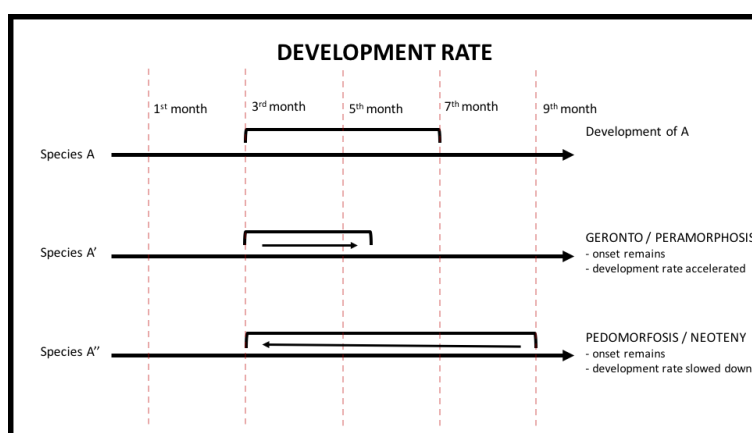


Figure 3: Modification in the rate of a species' ontogenetic development.

The term neoteny is used to describe the ontogenetic characteristic of a species that delays its reproductive development (Peirce, Smith, 1979), which is the case of humans. *Paedomorphosis*, however, derived from Karl Ernst von Baer's term *paedogenesis* (cf. Garstang, 1922) refers to a characteristic of the species that reaches its reproductive phase while its body is yet to attain physical maturity (i.e., early reproductive maturity).

One consequence of neoteny/paedomorphosis is the birth of highly incomplete individuals that may need from weeks to years to achieve their adult form and cognitive skills.

### 3. ON THE BIRTH OF "INCOMPLETE" PRIMATES

Having properly defined heterochrony, we can proceed to compare ontogenetic differences between homo and pan. It is important to remark that any hypothesis of human brain evolution needs to face three main questions: (i) the energetic/metabolic cost of a large brain, (ii) the differences between brains of human and non-human primates, and (iii) the anatomical problem of giving birth to a child with a large brain.

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(individuals mature quickly). On the other hand, a neotenic species retains an infant-like form because its juvenile stage lasts longer, resulting in adults that retain some immature traits (for instance, many dogs look similar to infant wolves).

Concerning the energetic/metabolic cost, Jared Diamond cites the amount of energy required daily so that men and women can meet their metabolic activity: “*Even if you spend all day lying on a bed, you need to ingest 1,640 calories a day if you’re a man (1,430 calories if a woman) just to keep your body*” (Diamond, 2010: 149). Neurons are cells of high metabolic activity, which means that beings with larger brains need larger quantities of food available to keep their neuronal activity. Aiello & Wheeler (1995), Aiello (1997) proposes that, for an organism to evolve a larger brain without a substantial rise in its basal metabolic rate, the organism needs to allocate less energy to other costly tissues (The Expensive-Tissue Hypothesis). The authors suggest that the secret of *homo sapiens*’ cognitive abilities (e.g., language, evaluative thinking, metacognition) is cooking<sup>6</sup>. It is important to mention that, prior to *sapiens*, *homo habilis* had cooking capabilities confined to food predigestion outside the body, that is, by cutting or tenderizing food. The control of fire and the advent of cooked meals, which came later, facilitated digestion, boosted energy extraction from a potential source and completely changed our relationship with nature (Herculano-Houzel, 2016). With this ability, the *Homo* lineage was able to withstand an increased brain density and metabolism, which likely contributed to the expansion of the individuals’ cognitive abilities.

As for the differences in brain development between human and non-human primates, Sakai *et al.* (2012) present a comparison of brain size using 3D ultrasonography on unborn humans and chimpanzees at gestational ages ranging from 14 to 34 weeks. The study found that both human and chimpanzee brains undergo a fast growth until approximately 22 weeks of gestation. After that, the chimpanzee brain suffers a brake on its growth while the human brain keeps its pace until around 30 months. At birth, non-human primates have a brain with 31-50%<sup>7</sup> of its final volume (Dieneske, 1986; Fragaszy, Bard, 1997; Desilva, Lesnik, 2006, 2008). On the other hand, human children are born with 25-30% of average volume of an adult brain (Lenneberg, 1967; Rice, 2001; Gonçalves 2006).

The prefrontal cortex (PFC) is immature in human and non-human primate babies, and is one of the last brain regions to develop. In a longitudinal experiment using magnetic resonance imaging (MRI), Sakai *et al.* (2011) demonstrate developmental differences in the PFC between humans and chimpanzees. The study found that in the postnatal period, the growth of white matter in the PFC of chimpanzee babies does not exhibit the same acceleration as it does in humans, suggesting that the PFC develops more intensively in human infants. At six months, chimps have about 25.5% of white matter volume in their PFC and 50.9% in non-PFC areas compared to adult values. In contrast, humans at one year of age have about 33% of white matter volume in the PFC and 53.4% in non-PFC areas. At the latter part of the juvenile stage, six-year-old non-human primates have approximately 60% of the white matter volume compared to the final volume in PFC and about 71% in non-PFC areas. In contrast, humans at approximately 10.5 years-old have about 85% of white matter in PFC and about 79% in non-PFC areas (Sakai *et al.* 2011).

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<sup>6</sup> See Gowlett (2016) and Cornelio *et al.* (2016) for other views concerning the cooking argument. Cornelio *et al.* employ a mathematical model to argue that brain growth in human lineage is independent of cooking. Gowlett argues that the brain growth in humans started about 1.9mya while evidence of fire control is more recent.

<sup>7</sup> The percentage of brain size varies according to primate species and, to a lesser extent, according to the study conducting the comparison. DeSilva & Lesnik (2006:207) mention an argument from Zuckerman (1928) questioning this type of comparison due to considerable variation in adult chimpanzee brain sizes, ranging from 290cc to 500cc. The authors also mention an argument from Tobias (1970) suggesting that the comparison between brain size and body mass is more suitable for an intraspecific study than an interspecific study.

Coincidentally or not, development of white matter in the prefrontal cortex (PFC) is closely related to linguistic processing. The ventromedial prefrontal area (vmPFC) is involved in specific linguistic tasks, such as the resolution of semantic incongruences (Pylkkänen, McElree, 2007) and discourse processing (Kuperberg *et al.* 2006) in adults. Additionally, various experiments indicate that the inferior frontal gyrus (IFG) and neighboring regions play a role in syntactic processing (Zacarella, Friederici, 2016 for a review). These areas are also involved in general cognitive processes activated during language processing such as decision-making (Fellows, Farah, 2007) and theory of mind (Gallagher, Frith, 2003). The communication between the PFC and other brain regions during language processing appears to rely on the white matter fibers (Friederici, 2009 for a review). It is worth noting that the classic Broca's and Wernicke's areas, which are involved in language production and comprehension respectively, also exhibit neotenic characteristics in terms of the development of their fiber pathways. More details about these areas will be addressed in section 6.

Based on the comparative information between *homo* and *pan*, we can say that the human brain, along with the human body, underwent a radical neoteny during its evolution. This means there was a radical increase in developmental period, which allowed the extension of our embryonic and juvenile forms to pre-puberty. This extended developmental period enables continued neuronal plasticity long after birth (Gould, 1977; Rice, 2001; Sakai *et al.* 2011, 2012). More recently, Gomez-Robles *et al.* (2015) provide evidence for this statement through neuroimaging experiments, demonstrating that the chimpanzee brain has strongly hereditary organization, while the organization of the human brain is much more susceptible to variation.

A question that arises at this point concerns possible causes, facilitators, and consequences of neoteny in the cohesion of a primate group. One hypothesis on the evolution of great primates<sup>8</sup> proposes that about four million years ago, bipedal walking brought morphological alterations to the primates living in the savannas. The upright posture led to anatomical adaptations that facilitated locomotion (Oliveira, 2003; Diamond, 2010). Pelvic format has changed, the iliac bone moved forward while the ischial bone shrank (Washburn, 1960; Rosenberg, Trevathan, 2002; Rosenberg, Desilva, 2017; Ruff, 2017). With these adaptations, the opening through which babies pass during childbirth has also changed, resulting in its narrowing in the last five million years of our evolutionary lineage. However, these changes would be quite convenient if it were not for one detail: anatomical adaptations for locomotion coincided with the increases in brain and in skull size, which presents a challenge during childbirth (Figure 4).

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<sup>8</sup> Although there are more accepted perspectives, at each stage of evolutionary history researchers may debate the potential inversions between cause and consequence regarding certain characteristics. Still, to not discuss each point specifically, one of these perspectives is assumed in this paper. This way, however, can be disregarded in the future. Depending on how this happens, arguments in this paper may have greater or lesser influence.

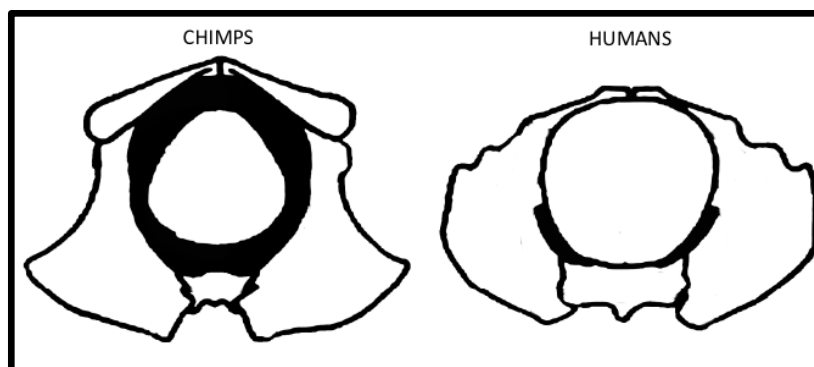


Figure 4: Representation of anatomical differences of chimpanzees and humans' pelvis and of birth of chimpanzees and humans according to opening of pelvis and babies' skull sizes. Images of first author, based on examples of Rosenberg & Trevathan (2002: 1204).

Behavioral consequences can be observed from these morphological adaptations. While non-human females isolate themselves from the group to give birth, female humans need and look for aid in these moments. Behavioral change was essential to enable radical neoteny in humans. The birth of a baby with a skull measuring about one third of the adult mean size is quite complicated. It would be impossible for the species to postpone birth even more to maintain intrauterine development. Consequently, the human gestational period is “shortened” to about nine months. Many characteristics develop after birth, during the first twelve years. This may explain why human babies are born exceptionally immature compared to other animal species. This phenomenon has received from Washburn (1960) the name of the Obstetrical Dilemma.

It happens that this trade-off between selection for a larger birth canal, permitting successful passage of a big-brained human neonate, and the smaller pelvic dimensions required for bipedal locomotion directly constrain one of the hypotheses for the emergence of language, the social brain hypothesis, which, will be presented in the next chapter.

#### 4. THE SOCIAL AND THE CULTURAL BRAIN HYPOTHESES

As discussed in the previous section, it is possible to hypothesize about the conditions that allowed us to maintain a highly costly organ such as the brain, which most likely relates to the preparation of food by our ancestors. The time efficient increment facilitating the ingestion of sufficient calories provides a possible scenario for a concurrent explanation, that is the ‘Social Brain Hypothesis’ (Dunbar, 2009; Dunbar *et al.* 2009; Powell *et al.* 2012). In the authors' view, the human brain grew to meet the high demands of social life, such as keeping track of the behavior of each member of the group or to better understand our close friends and family. The hypothesis is based on an interesting correlation between the proportion of the neocortex size and the average size of groups for each species.

Anthropology and evolutionary psychology propose the concept of *grooming*, to refer, for instance, to the exchange of caresses that releases endorphins in the brain, stimulating affection among individuals in a group (Dunbar *et al.* 2007; Dunbar 2009). Grooming efficiency appears to have been expanded among humans. Regarding our offspring, unlike chimpanzees, where cubs are cared for by females, human babies generally are under the care of both parents. Other family members and friends can also share responsibility for children of the group, depending on family or culture (Fitch 2010; Rosenberg, Trevathan, 2002). Regarding the relation to other people, humans can

maintain connections with approximately 147.8 individuals, mapped in our social and digital life interactions (Gonçalves *et al.* 2011; Dunbar *et al.* 2015). Some researchers have been trying to model the mechanisms behind this relationship (Dávid-Barrett, Dunbar, 2013; Gavrillets, Vose, 2006). Language, in this sense, could be viewed as an evolution of social grooming, allowing us to develop exponential interaction with different individuals at the same time.

There are other instigating conjectures under investigation, such as the Cultural Brain Hypothesis (Henrich, McElreath, 2003; Pradhan, *et al.* 2012; van Schaik, *et al.* 2012). The broader idea behind this view is that our brain did not necessarily grow to meet with the high demands of social life, but rather to store and manage general information about the environment, which includes, among other things, social information related to other group members (social learning, Hoppitt, Laland, 2013) and also data pertaining to non-social problem-solving possibilities. This hybrid functionality is, in our opinion, a more feasible explanation. Despite the highly structured social net that we form, nowadays online and off, most of our language time is spent with incessant internal problem-solving, memory retrieval and thought organizing<sup>9</sup>.

For sure, difficulty in childbirth and extreme dependence of human babies have been facilitated by the strengthening of social bounds. However, it is not possible to affirm the directionality between cause and consequence of this dilemma: did our brain increase due to the cognitive demands of our social interaction (*i.e.* our high level of social interaction came first increasing the fitness of a large brain), or was our level of social interaction allowed by the evolutionary history of our brain (*i.e.* our brain increased in size enabled by the efficiency of cooking and, consequently, a larger brain allowed our socio-cognitive abilities to increase)? Or maybe both (our brain and our socio-cognitive abilities) grew together in a continuous way?

Nevertheless, we return to our discussion of the radical neoteny that allows humans to develop our nervous system outside the womb, in contact with stimuli from the world and social stimuli.

## 5. ON COMMUNICATION OF HUMAN AND NON-HUMAN PRIMATES

Along with changes in pelvis shape, which helped bipedal locomotion, other morphological changes were underway. Bipedalism would release front legs, which would specialize in manual activities that would be required for creating tools, a common feature among great primates (Van Schaik *et al.* 1996; Van Schaik 2003; Pruett *et al.* 2015). These manual activities and tools helped humans to control the fire.

Hands free to hold food, added to the possibility of cooking to make it softer, may have led to morphological adaptations in the jaw structure, resulting in a smoother and less prognathic facial appearance. Additionally, other morphological alterations occurred in the vocal tract. While chimpanzees have vocal cords located close to the mouth<sup>10</sup>, human evolution involved a migration of the larynx and the hyoid bone to a lower position, increasing the space for air handling and making it easier to control the articulation of speech sounds (Lieberman *et al.* 1969; Bluestone, 2008; Fitch, 2010;).

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<sup>9</sup> Furthermore, it is worth consulting the Cognitive Tradeoff Hypothesis (Matsuzawa, 2007) for an argument centered on the selection of specific cognitive abilities, such as the increased efficiency of symbolic thinking, over others such as short-term memory, as a crucial factor in the emergence of language.

<sup>10</sup> This characteristic is not exclusive to non-human primates. Neanderthals and even human children have vocal cords in high positions in the larynx.



For at least 40 years, many researchers believed that the reason chimpanzees do not speak as humans was the non-flattening of the face and the higher position of the larynx, which would decrease ability to manipulate speech sounds. In light of recent research by Fitch *et al.* (2016) and the following discussions by Lieberman (2017) and Fitch *et al.* (2017), that argument does not hold. Fitch and his team used x-ray technology, to examine the mouth of a *macaca fascicularis* and recorded 99 possible configurations in order to model their ability to produce speech sounds. While it is true that their anatomy hampers production of sounds, it would not stop them from generating consonants and at least five vowels, which in thesis would allow them to produce language.

Thus, according to these results, macaques have speech-ready vocal tracts despite their anatomical differences. There is a growing body of evidence suggesting that the inability to communicate through language originates in differences in the brain, not in the vocal apparatus (Fitch *et al.* 2016; Fitch *et al.* 2017; Lieberman, 2017; Papadimitriou; Vempala, 2019).

A counter argument could come from research on chimpanzees (and, to some extent, gorillas) and their ability to communicate with humans through sign language. Yang (2013), however, rebates this argument, analyzing language production data in sign language by Nim Chimpsky, the single corpus of a primate using sign language available for that study. Yang's results show that, unlike humans, Nim's production does not follow Zipf's Law<sup>11</sup>, nor was his signing spontaneous. Nim was unable to use words conversationally or to form sentences creatively. These results support the hypothesis that language *strictu sensu* (*c.f.* Hauser, Chomsky, Fitch, 2002) is a unique feature of *Homo sapiens*.

Since chimpanzees use their own form of vocalization to communicate, in our view it is much too anthropocentric to judge chimpanzees' ability to use languages by comparing it to humans' abilities. They have their own natural communication, which has been observed and widely studied by primatologists. Since humans and chimpanzees suffered speciation from the LCA, it is expected that their communication systems have also suffered different evolutionary pressures in the last million years.

At this point, it is worth remembering that it is not our goal to raise the undeniable similarities between humans and chimpanzees, but rather to argue that both species must possess unique characteristics. Communication, in our view, is one of them. Evidence supporting our arguments can be observed in social communication characteristics of offspring within their groups. Although it is true that variation in communication exists among different groups of the same species (Schlingloff, Moore 2018; Cantor *et al.* 2015), this variation still looks small when compared to the 6,000+ languages and variations humans use nowadays.

A second difference relates to function. Birds, for instance, have a system of songs organized syntactically and song learning shares some neural and behavioral parallels with language acquisition (Bolhuis *et al.* 2010; 2013). Non-human primates and other mammals apparently have a pairing system between form and meaning and apparently have a very limited number of vocalizations that refer to issues relating to the tripod of animal life: danger, feeding and reproduction. They also appear to have limited capacity for combining elements in a hierarchical order, unlike the complexity observed in human communication (Hayashi, Matsuzawa, 2003; Fitch, Hauser, 2004; Yang, 2013).

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<sup>11</sup> Zipf's Law was proposed by the linguist George Kingsley Zipf in the 30's. By statistically analyzing the corpora of several languages, known or unknown, as well as written text and books, Zipf observed that they all respected a power law described as  $1/\text{ranking}$ . This means that the second most frequent word in language has a frequency of use of about half of the frequency of the most frequent word, the third of  $1/3$ , and so on.

Although human communication also relies on a limited number of linguistic units, its levels of representation (phonological, morphological, syntactic, semantic) exhibit greater structural complexity than a form-content matching with basic combinations. Some argue that this is a cognitive operation, known as ‘merge’, that takes pieces of language as computational atoms and combines them in structured expressions (Berwick, Chomsky, 2008). Others propose that merge could be the fusion, in the form of language, of two other existing communication systems from different animal species (Miyagawa *et al.* 2013, 2014). Human beings could have both systems working together, allowing for the integration of meaning into a syntactic computation.

It is important to mention that linguistic atoms exhibit a highly compositional and recursive nature, allowing for infinite combinations (referred to as ‘discrete infinity’; Chomsky, 1995; Bolhuis *et al.* 2018). This feature seems to be unique to humans, distinguishing human and animal communication systems (Hauser, Chomsky, Fitch, 2002). Furthermore, a human individual can achieve discrete infinity in multiple languages, which often have phonological, morphological, syntactic, and semantic features too far apart. Language acquisition will inevitably happen, whenever the baby is exposed to one or more languages within a certain time frame, called the *critical period*, a characteristic linked to neoteny, as we shall see in the following sections.

## **6. THE CRITICAL PERIOD AND ITS RELATIONSHIP WITH LINGUISTIC DEVELOPMENT**

The term ‘critical period’ is used in Linguistics in a similar sense as in neuroscience: a developmental period of uncommon plasticity in which stimulation received by the nervous system induces the perceptual system to develop. This period, although different among our sensory mechanisms and cognitive processes, coincides with the time when rapid development of part of the nervous system happens.

The critical period for binocular vision lasts from one to nine weeks in non-human primates and from one to three years in humans (Almli, Finger, 1987) while human vestibular system, responsible for balance, takes about three weeks after birth (Eugène *et al.* 2009). In terms of hearing, which includes the acquisition of phonetic traits, the critical period starts during intrauterine life and it can continue to specialize until around two years (Muenssinger *et al.* 2013; Minai *et al.* 2017).

Regarding the critical periods of language as a whole, their extensions are still under discussion. It is now understood that the critical period for the acquisition of acoustic patterns of the first language begins in intrauterine life, however, the end of that period is under discussion. Lenneberg (1969) argues that the window would close in two years. For Penfield & Roberts (1959), precursors of this line of research, this period would end in nine years.

Ruben (1997) suggests that language is not composed of a single system and that there are several critical periods depending on which system is being developed. Critical period of Phonetics/Phonology would start at six months of pregnancy and would extend until one year of the child’s life. For syntax, it would extend until four years, and, for semantics, it would extend until 16 years. Other proposals can be found at Scovel (1988), Johnson & Newport (1989), Long (1990), among others. See also Werker, Hensch, 2015 for a recent discussion of the biochemical processes involved in the modulation of such systems.

It is important to note that exposure to language in a critical period does not necessarily have to be oral or auditory. Deaf children acquire sign languages that are also natural languages with all the subsystems mentioned above (Bavelier *et al.* 2003).

Because it is a human trait, there is no way to conduct experiments to learn what happens when we lose a critical period. However, there are reports of children who have not had access to linguistic stimulation in early years of life. The best-known case is Genie's, a girl who was locked in the attic of her house and grew away from linguistic or social stimuli. The girl was found at 14 years old, after her blind mother managed to run away from home where she and Genie were captive. After her (re)socialization, Genie was followed by a linguist, Susan Curtiss, for about eight years. With training she managed to acquire a good level of linguistic understanding, although her production did not evolve the same way (Curtiss, 1977, 1981).

## 7. ON COGNITIVE DEVELOPMENT OF THE SPECIES

Neurophysiologically, the critical period is characterized by a series of brain changes in the organism. These changes are due, for example, in relation to synaptogenesis and myelination, resulting in greater energy efficiency and increased speed of cognitive processes. A notable phenomenon concerning synaptic organization occurs between 12 and 24 months. Despite a smaller brain volume, density of synaptic connections is about 50% above the level observed in adults (Huttenlocher, 1979; DiPietro, 2000; Johnson, 2001).

It is important to mention that the timing of reaching the peak of synaptic density varies across different cortical areas. For instance, between 4-12 months, synaptic density in the human primary visual cortex reaches a peak of 150% of adult levels and then starts to decrease. On the other hand, the synaptic density in the prefrontal cortex (PFC) does not reach its peak before eight months (Tau, Peterson, 2010). As seen in section 2, PFC is quite immature in both human and chimpanzee babies, being one of the last structures to develop. Besides, development of this area is related to cognitive tasks, including language processing (Kuperberg *et al.* 2006; Pykkänen, McElree, 2007).

During this development period, PFC also suffers an increase in synaptic density that seems related to language acquisition (Reed, 2005). This pile of neuronal connections undergoes a series of regressive processes, as part of normal development of the nervous system. One of those processes is synaptic pruning, which eliminates connections that are little used, making brain metabolism and communication between cells more efficient. According to Gopnik *et al.* (1999), this pruning happens with greater intensity until around the age of seven, when metabolic brain activity reaches levels of an adult brain.

One of the last steps in ontogenetic maturation of the nervous system is myelination, a process by which specialized cells produce a protective sheath called myelin around nerve fibers or axons. Myelin is composed of lipid-rich substance that wraps around the axons, forming an insulating layer. The main function of myelin is to facilitate the rapid and efficient conduction of electrical impulses along the nerve fibers.

Concerning human communication, at 18-20 months of age, Pujol *et al.* (2006) suggests that myelination happens in language-related regions in the temporal and frontal cortex. During this period, a lexical explosion is reported in children under acquisition phase. The authors also found a correlation between the development of the verbal system and the maturation and myelination of the temporofrontal language network. In addition, at the same time, it is reported an increase in density of the arcuate fasciculus, which connects Broca's and Wernicke's areas (Paus *et al.* 1999).

These data demonstrate that, for the neural circuits of linguistic representation and processing to be complete, stimulation is required during the critical period so that connections are not lost, and that speed of cellular communication is more efficient. This

stimulation is coined Primary Data since they are the first data received by developing organisms. If for some reason—as malformation of sensors like eye and ear—the brain does not receive that data, operation of this system and skills depending on it will be compromised.

Considering a critical period for language acquisition involves adopting a neotenic-based approach that recognizes language as a cognitive system influenced by both biological development and external stimulation.

Reviewing and sorting most of the arguments cited by now in this paper, Lenneberg (1967) still stands today: a comparison between children’s brain and language development, highlighting a strong correlation between them (Table 1).

<b>Linguistic development</b>	<b>Brain development</b>
Initial period, which lasts until 2 or 3 years of age, is the optimum period for language acquisition. Children who acquire and use any language until this age are considered native speakers.	Period from birth to 2 or 3 years is characterized by accelerated brain growth. In this period, the child's brain volume goes from 30% of the average adult values to about 70% to 80%.
By age of four, a child's linguistic system achieves stability, which can be further improved and restored until the beginning of puberty, by the age 12 or 13.	At about age 3 or 4, the rate of brain growth slows down gradually. Yet growth will follow until the beginning of puberty, around age 12 or 13.
From puberty, language acquisition without formal education seems impossible, and restoration of the acquired system is quite restricted.	At this age, the brain is almost mature, surpassing 95% of average values of adult brains. Its growth still progresses until the end of puberty.

Table 1: Comparative table of the stages of language and brain development. A summary of Lenneberg’s work (1967). This table presents some modifications from the original table, elaborated by Gonçalves (2006: 28).

In fact, the child only attains a level of development of certain cognitive functions over a period of exposure to data, and the brain reaches the level of development only after puberty. This suggests that, due to neoteny, human beings have some years of open neuronal circuits with heightened potential for plasticity, which even allows processes to be relocated in areas affected by injury. As early as the 50’s, Penfield and Roberts (1959) noticed that children can recover their linguistic skills using new brain regions or even the non-dominant hemisphere while adults have greater difficulty in brain reorganization.

Some researchers, including Gould (1977), Deacon (1997) and Johnson (2001), assign to this radical neoteny a key role in the emergence of *homo sapiens*’ cognition. More recently, Hill *et al.* (2010), in a comparative research between humans’ and other primates’ cortical fissures, indicate that important areas for cognition could benefit from an immature post-birth state, increasing the influence of external experiences.

Neoteny, as well as the continuous exposure to primary data, is necessary for assimilating patterns in our environment and for accumulating knowledge and skills. Among these, certainly are patterns and knowledge of sociocultural order, such as beliefs, accent, lexical inventory, among others, which are transmitted through generations when reproduced by human children. In this way, human biology not only allows, but makes necessary the assimilation of cultural factors that will influence both behavior and the variety of languages the child acquires. Still, the ability to acquire language is innate and only exists in *homo sapiens* (Chomsky, 1995; Hauser, Chomsky, Fitch, 2002; Fitch, 2010). Such factors do not diminish the importance of biology or of the environment in the development of the organism, but reinforce the combined work of these two factors

and the need to consider both for a comprehensible understanding of the faculty of language.

## 8. FINAL CONSIDERATIONS

Several studies, in different disciplines, seek to understand the leap *homo sapiens* would have taken in relation to other primates. Regardless of whether they consider these changes merely quantitative, it is undeniable that we, humans, have reached an evolutionary milestone, with cognitive and technological advancements that led us to seek for an understanding of our own nature and the nature of the universe we live in. As a result, we were able to inhabit most environments on the planet, without great morpho-anatomical nor genetic variability. In addition, we were able to understand many important phenomena for our survival, comfort, and culture.

The development of an organism does not start and does not end at birth. Thus, we must bear in mind that when comparing the cognitive development of two species, we cannot assume that the time of birth for species X is equivalent to the time of development of species Y only by tracking the time they were exposed to the world. Additional factors must be considered, such as the duration of the gestation period, the heterochronic configuration of each species, the extent of external stimulation even before birth, socialization capacity, life expectancy of each species and so on. In summary, when comparing the developmental time of two species, time itself is not an objective measure. The development time must be studied in relation to the species' heterochronic settings within its evolutionary lineage. Ontogenetic time is relative to each species.

If an individual is complete before its birth, it would tend to exhibit behavioral similarities to their parents, since the environment acts less decisively in its development, as Johnson (2001) states. On the other hand, if individuals are highly immature at birth, the environment has a large impact in neuronal and cognitive development, having more ground to act on and generating greater variability among the members of a species, as we can observe in primates and, specially, in humans.

By examining the size and cerebral organization of humans and chimpanzees Gómez-Robles *et al.* (2015) point out that, in terms of organization, while chimpanzee brains also exhibit neotenic characteristics, they are more strongly defined by their genetics than the human brains, which exhibit a greater degree of variability. The data suggest that human biology allows greater environmental influence on their development and brain organization than that of other great primates.

In short, similar to what happens to a computer, in the brain there is no internal processing without external data entering the system. Data cannot be processed without a system to organize and to interpret it. Both biological and environmental factors need to be addressed if, one day, we want to go deep into the genesis of speech, whose limits have not yet been defined. Exploring human neoteny seems to be a promising and enlightening path in our view.

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## REFERENCES

- AIELLO, Leslie C.; WHEELER, Peter. The Expensive-Tissue Hypothesis: The Brain and the Digestive System in Human and Primate Evolution. *Current Anthropology*, v. 36, p. 199–221, 1995.
- AIELLO, Leslie C. Brains and guts in human evolution: The Expensive Tissue Hypothesis. *Brazilian Journal of Genetics*, v. 20, p. 141–148, 1997.
- ALMLL, Robert C.; FINGER, Stanley. Neural insult and critical period concepts. In: BORNSTEIN, Marc H. (Ed.). *Sensitive Periods in Development: Interdisciplinary Perspectives*. Hillsdale, NJ: Lawrence Erlbaum, p.123-143, 1987.
- BALZAMO, Emmanuel; BRADLEY, Robert J; RHODES, John M. Sleep ontogeny in the chimpanzee: From two months to forty-one months. *Electroencephalography and Clinical Neurophysiology*, v. 33, n. 1, p. 47-60, 1972.
- BAVELIER, Daphne; NEWPORT, Elissa L.; SUPALLA, Ted. Signed or Spoken, Children need Natural Languages. *Cerebrum*, v. 5, p. 19-32, 2003.
- BERWICK, Robert; CHOMSKY, Noam. The biolinguistic program: the current state of its evolution and development. In: DI SCIULLO, A.; BOECKX, C. (Eds.). *The Biolinguistic Enterprise: New Perspectives on the Evolution and Nature of the Human Language Faculty*. Oxford: Oxford University Press, p. 19-41, 2011.
- BLUESTONE, Charles D. Impact of evolution on the eustachian tube. *Laryngoscope*, v. 118, n. 3, p. 522-527, 2008.
- BOLHUIS, Johan J.; OKANOYA, Kazuo; SCHARF, Constance. Twitter evolution: converging mechanisms in birdsong and human speech. *Nature Reviews Neuroscience*, v. 11, p. 747-759, 2010.
- BOLHUIS, Johan J.; EVERAERT, Martin. *Birdsong, speech, and language: Exploring the evolution of mind and brain*. Cambridge, MA: MIT Press, 2013.
- BOLHUIS, Johan; BECKERS, Gabriel J. L.; HUYBREGTS, Marinus A. C.; BERWICK, Robert; EVERAERT, Martin. Meaningful syntactic structure in songbird vocalizations? *PLOS Biology*, v. 16, 2018.
- CANTOR, Mauricio; SHOEMAKER, Lauren; CABRAL, Reniel; FLORES, Cesar O.; VARGA, Melinda; WHITEHEAD, Hal. Multilevel animal societies can emerge from cultural transmission. *Nature Communications*, v. 6, p. 8091, 2015.
- CHEN, Feng Chi; LI, Wen-Hsiung. Genomic Divergences between Humans and Other Hominoids and the Effective Population Size of the Common Ancestor of Humans and Chimpanzees. *The American Journal of Human Genetics*, v. 68, n. 2, p. 444-456, 2001.
- CHOMSKY, Noam *The Minimalist Program*. Cambridge, Massachusetts: MIT Press, 1995.
- CORNELIO, Alianda M.; BITTENCOURT-NAVARRETE, Ruben E.; BRUM, Ricardo B.; QUEIROZ, Claudio M.; COSTA, Marcos R. Human Brain Expansion during Evolution Is Independent of Fire Control and Cooking. *Frontiers in neuroscience*, v. 10, p. 167, 2016.
- CURTISS, Susan. *Genie: a psycholinguistic study of a modern-day 'wild child'*. New York, NY: Academic Press, 1977.
- CURTISS, Susan. Dissociations between language and cognition: cases and implications. *Journal of Autism and Developmental Disorders*, v. 11, n. 1, p. 15-29, 1981.

DÁVID-BARRET, Tamas; DUNBAR, Robin. Processing power limits social group size: computational evidence for the cognitive costs of sociality. *Proceedings of the Royal Society B: Biological Sciences*, v.280, 2013.

DEACON, Terrence W. *The symbolic species: the co-evolution of language and the brain*. New York, NY: W. W. Norton & Company, 1997.

DESILVA, Jeremy; LESNIK, Julie. Chimpanzee neonatal brain size: implications for brain growth in *Homo erectus*. *Journal of Human Evolution*, v. 51, p. 207-212, 2006.

DESILVA, Jeremy; LESNIK, Julie. Brain size at birth throughout human evolution: a new method for estimating neonatal brain size in hominins. *Journal of Human Evolution*, v. 55, p. 1064-1074, 2008.

DIAMOND, Jared M. *The third chimpanzee: the evolution and future of the human animal*. New York, NY: HarperCollins, 1992.

DIENSKE, Herman; DE JONGE, Gerrit. A Comparison of Development and Deprivation in Non-human Primates and Man. *Journal of Human Evolution*, v. 11, n. 6, p. 511-516, 1982.

DIENSKE, Herman. A comparative approach to the question of why human infants develop so slowly. In: ELSE, J. G.; LEE, P. C. (eds.). *Primate Ontogeny, Cognition and Social Behavior*. Cambridge: Cambridge University Press, 1986.

DIPETRO, Janet A. Baby and the Brain: Advances in Child Development. *Annual Review of Public Health*, v. 21, p. 455-471, 2000.

DUNBAR, Robin. The social brain hypothesis and its implications for social evolution. *Annals of Human Biology*, v. 36, n. 5, p. 562-572, 2009.

DUNBAR, Robin; BARRET, Louise; LYCET, John. *Evolutionary Psychology: a beginner's guide*. Human Behaviour, Evolution, and the mind. United Kingdom: OneWorld Publications, 2007.

DUNBAR, Robin I.M; ARNABOLDI, Valerio; CONTI, Marco; PASSARELLA, Andrea. The structure of online social networks mirrors those in the offline world, *Social Networks*, v. 43, p. 39-47, 2015.

EBERSBERGER, Ingo; METZLER, Dirk; SCHWARZ, Carsten; PÄÄBO, Svante. Genomewide comparison of DNA sequences between Humans and Chimpanzees. *The American Journal of Human Genetics*, v. 70, n. 6, p. 1490-1497, 2002.

EUGÈNE, Daniel; DEFORGES, Sèverine; VIBERT, Nicolas; VIDAL, Pierre P. Vestibular Critical Period, Maturation of Central Vestibular Neurons and Locomotor Control. *Annual New York Academy of Sciences*, v. 1164, p. 180-187, 2009.

FELLOWS, Lesley K.; FARAH, Martha J. The role of ventromedial prefrontal cortex in decision making: Judgment under uncertainty or judgment per se? *Cerebral Cortex*, v. 17, n. 11, p. 2669-2674, 2007.

FITCH, Tecumseh W.; HAUSER, Marc D. Computational constraints on syntactic processing in a nonhuman primate. *Science*, v. 303, n. 5656, p. 377-380, 2004.

FITCH, Tecumseh. W. *The Evolution of Language*. United Kingdom: Cambridge University Press, 2010.

FITCH, Tecumseh W.; DE BOER, Bart; MATHUR, Neil; GHAZANFAR, Asif A. Monkey vocal tracts are speech-ready. *Science Advances*, v. 2, n. 12, 2016.

FITCH, Tecumseh W.; DE BOER, Bart; MATHUR, Neil; GHAZANFAR, Asif A. Response to Lieberman on "Monkey vocal tracts are speech-ready". *Science Advances - Technical comments*, v. 3, n. 7, 2017.

FRAGASZY, Dorothy; BARD, Kim. Comparison of development and life history in Pan and Cebus. *International Journal of Primatology*, v. 18, p. 683-701, 1997.

- FRIEDERICI, Angela D. Pathways to language: fiber tracts in the human brain. *Trends in Cognitive Sciences*, v. 13, n. 4, 2009.
- GALLAGHER, Helen; FRITH, Christopher. Functional imaging of ‘theory of mind’. *Trends in Cognitive Sciences*, v. 7, n. 2, p. 77–83, 2003.
- GARSTANG, Walter. The theory of recapitulation: A critical restatement of the Biogenetic Law. *Proceedings of the Linnean Society of London*, v. 35, n. 232, p. 81-101, 1922.
- GAVRILETS, Sergey; VOSE, Aaron. The dynamics of Machiavellian intelligence. *Proceedings of the National Academy of Sciences*, v.103, 2006.
- GOMEZ-ROBLES, Aida; HOPKINS, William D.; SCHAPIRO, Steven J.; SHERWOOD, Chet C., Relaxed genetic control of cortical organization in human brains compared with chimpanzees. *Proceedings of the National Academy of Sciences USA*, v. 112, n. 48, p. 14799-14804, 2015.
- GONÇALVES, Renata R. F. *A Expressão do FoxP2: Uma introdução ao estudo das relações entre genes e linguagem*. Dissertação de Mestrado, Universidade Federal do Rio Grande do Sul, 2006.
- GONÇALVES, Bruno; PERRA, Nicola; VESPIGNANI, Alessandro. Modeling Users' Activity on Twitter Networks: Validation of Dunbar's Number. *PLoS ONE*, v. 6, 2011.
- GOPNIK, Alison; MELTZOFF, Andrew; KUHL, Patricia K. *How babies think: the science of childhood*. London: Orion, 1999.
- GOULD, Stephen Jay. *Ontogeny and Phylogeny*. Cambridge: Belknap Press, 1977.
- GOWLETT, John A. The discovery of fire by humans: a long and convoluted process. *Philosophical transactions of the Royal Society of London*. Series B, Biological sciences, v. 371, 2016.
- HAECKEL, Ernst. Die Gastrula und die Eifurchung der Thiere. *Jen. Zts. Naturwiss.*, v. 9, p. 402-508, 1875.
- HAUSER, Marc D.; CHOMSKY, Noam; FITCH, W. Tecumseh. The faculty of language: what is it, who has it, and how did it evolve? *Science*, v. 298, p. 1569-1579, 2002.
- HAYASHI, Misato; MATSUZAWA, Tetsuro. Cognitive development in object manipulations by infant chimpanzees. *Animal Cognition*, v. 6, p. 225-233, 2003.
- HENRICH, Joseph; MCELREATH, Richard. The evolution of cultural evolution. *Evolutionary Anthropology: Issues, News, and Reviews*, v.12, p.123-135, 2003.
- HENSCH, Takao. Critical period regulation. *Annual Review of Neuroscience*, v. 27, p. 549-579, 2004.
- HERCULANO-HOUZEL, Susana. *The human advantage: A new understanding of how our brain became remarkable*. Cambridge, MA, US: MIT Press, 2016.
- HILL, Jason; INDER, Terrie; NEIL, Jeffrey; DIERKER, Donna. HARWELL, John; VAN ESSEN, David. Similar patterns of cortical expansion during human development and evolution. *Proceedings of the National Academy of Sciences – USA*, v. 107, p. 13135-140, 2010.
- HOPPITT, William; LALAND, Kevin N. *Social Learning: An Introduction to Mechanisms, Methods, and Models*, Princeton University Press, 2013.
- HUTTENLOCHER, Peter R. Synaptic density in human frontal cortex – developmental changes and effects of aging. *Brain Research*, v. 163, n. 2, p. 195-205, 1979.
- JOHNSON, Jacqueline S.; NEWPORT, Elissa L. Critical period effects in second language learning: The influence of maturational state on the acquisition of ESL. *Cognitive Psychology*, v. 21, n. 1, p. 60–99, 1989.



- JOHNSON, Mark H. Functional brain development in humans. *Nature Reviews Neurosciences*, v. 2, p. 475-483, 2001.
- KUPERBERG, Gina R.; LAKSHMANAN, Balaji M.; CAPLAN, David N.; HOLCOMB, Phillip J. Making sense of discourse: An fMRI study of causal inferencing across sentences. *Neuroimage*, v. 33, n. 1, p. 343–361, 2006.
- LENNEBERG, Eric. *Biological Foundations of Language*. New York, NY: John Wiley & Sons, Inc, 1967.
- LIEBERMAN, Phillip H.; KLATT, Dennis H.; WILSON, William H. Vocal tract limitations on the vowel repertoires of rhesus monkey and other nonhuman primates. *Science*, v. 164, p. 1185-1187, 1969.
- LIEBERMAN, Phillip H. Comment on “Monkey vocal tracts are speech-ready”, *Science Advances - Technical comments*, v. 3, n. 7, 2017.
- LONG, Michael H. Maturation constraints on language development, *Studies in Second Language Acquisition*, v. 12, n. 3, p. 251–285, 1990.
- MATSUZAWA, Tetsuro Comparative cognitive development, *Developmental Science*, v. 10, p. 97–103, 2007.
- MAY, Robert. How many species are there on earth? *Science*, v. 241, p. 1441-1449, 1988.
- MAY, Robert. Tropical Anthropod Species. More or less? *Science*, v. 329, p. 41-42, 2010.
- MCCARTY, Christopher; KILLWORTH, Peter D.; BERNARD, H.Russell; JOHSEN, Eugene C.; SHELLEY, Gene A. Comparing Two Methods for Estimating Network Size. *Human Organization*, v. 60, n. 1, p. 28-39, 2001.
- MINAI, Utako; GUSTAFSON, Kathleen; FIORENTINO, Robert; JONGMAN, Allard; SERENO, Joan. Fetal rhythm-based language discrimination: a biomagnetometry study. *NeuroReport*, v. 28, n. 10, p. 561-564, 2017.
- MIYAGAWA, Shigeru; BERWICK, Robert C.; OKANOYA, Kazuo. The emergence of hierarchical structure in human language. *Frontiers in Psychology*, v. 4, p. 71, 2013.
- MIYAGAWA, Shigeru; BERWICK, Robert C.; OKANOYA, Kazuo. The integration hypothesis of human language evolution and the nature of contemporary languages, *Frontiers in Psychology*, v. 5, p. 564, 2014.
- MORA, Camilo; TITTENSER, Derek P.; ADL, Sina; SIMPSON, Alastair G.B.; WORM, Boris. How Many Species are there on Earth and in the Ocean? *PLoS Biology*, v. 9, n. 8, 2011.
- MUENSSINGER, Jana; MATUZ, Tamara; SCHELEGER, Franziska; KIEFER-SCHIMIDT, Isabelle; GOELZ, Rangmar; WACKER-GUSSMANN, Annette; BIRBAUMER, Niels; PREISSEL, Hubert Auditory habituation in the fetus neonate: an fMEG study. *Developmental Science*, v. 16, p. 287-295, 2013.
- NUÑEZ, Cassandra M. V.; ASA, Cheryl; RUBENSTEIN, Daniel I. Zebra Reproduction: plains zebra (*Equus Burchelli*), mountain zebra (*Equus Zebra*), and Grevy’s zebra (*Equus Grevyi*). In: McKinnon, A. O. et al. (eds.). *Equine Reproduction*. United Kingdom: Wiley-Blackwell, 2009.
- OLIVEIRA, Luiz Alberto. *Imagens do Tempo*. In: DOCTORS, Marcio (org.). *Tempo dos Tempos*. Rio de Janeiro: Jorge Zahar Editora, 2003.
- PAUS, Tomáš; ZIJDENBOS, Alex; WORSLEY, Keith; COLLINS, D. Louis; BLUMENTHAL, Jonathan; GIEDD, Jay N.; RAPOPORT, Judith; EVANS, Alan C. Structural Maturation of Neural Pathways in Children and Adolescents: In Vivo Study. *Science*, v. 283, n. 5409, p. 1908–1911, 1999.
- PAPADIMITRIOU, Christos H.; VEMPALA, Santosh S. Random projection in the brain and computation with assemblies of neurons. In: BLUM, A. (Ed.). *Leibniz International Proceedings in Informatics*, v. 57, p. 1-19, 2019.

- POWELL, Joanne; LEWIS Penelope A.; ROBERTS, Neil; GARCÍA-FIÑANA, Marta; DUNBAR, Robin. Orbital prefrontal cortex volume predicts social network size: an imaging study of individual differences in humans. *Proceedings of the Royal Society - Biological Sciences (Series B)*, v. 279, p.2157–2162, 2012.
- PIERCE, Benjamin A.; SMITH, Hobart M. Neoteny or Paedogenesis? *Journal of Herpetology*, v. 13, n. 1, p. 119, 1979.
- PENFIELD, Wilder; ROBERTS, Lamar. *Speech and brain-mechanisms*. Princeton, NJ: Princeton University Press, 1959.
- PINKER, Steven. *The language instinct: the new science of language and mind*. London: Allen Lane, the Penguin Press, 1994.
- PRADHAN, Gauri R.; TENNIE, Claudio; VAN SCHAİK, Carel P. Social organization and the evolution of cumulative technology in apes and hominins. *Journal of Human Evolution*, v.63, p.180-190, 2012.
- PRUETZ, Jill; BERTOLANI, Paco; BOYER-ONTL, Kelly M.; LINDSHIELD, Stacy; SHELLEY, Mack; WESSLING, Erin G. New evidence on the tool-assisted hunting exhibited by chimpanzees (*Pan troglodytes verus*) in a savannah habitat at Fongoli, Sénégal. *Royal Society Open Science*, v. 2, n. 4, p. 140507, 2015.
- PUJOL, Jesus; SORIANO-MAS, Carles; ORTIZ, Hector; SEBASTIAN GALLES, Nuria; LOSILLA, Josep M.; DEUS, Joan. Myelination of language-related areas in the developing brain. *Neurology*, v. 66, 2006.
- PYLKKÄNEN, Liina; MCELREE, Brian. An MEG Study of Silent Meaning. *Journal of Cognitive Neuroscience*, v. 19, p. 1905-1921, 2007.
- REED, Umbertina Conti. Desenvolvimento normal do sistema nervoso central. In: NITRINI, Ricardo; BACHESCHI, Luiz Alberto. *A neurologia que todo médico deve saber*. 2. ed. São Paulo: Atheneu, p. 395-400, 2005.
- RICE, Sean H. The role of heterochrony in primate brain evolution. In: MINUGH-PURVIS, N.; MCNAMARA, K. J. (eds.). *Human evolution through developmental change*. Baltimore, MD: Johns Hopkins University Press, p. 154-170, 2001.
- ROSENBERG, Karen R.; TREVATHAN, Wenda R. Birth, obstetrics and human evolution. *BJOG: An International Journal of Obstetrics & Gynaecology*, v. 109, n. 11, p. 1199-1206, 2002.
- ROSENBERG, Karen R.; DESILVA, Jeremy M. The evolution of Human Pelvis. *The Anatomical Record*, v. 300, p. 789-797, 2017.
- RUBEN, Robert J. A time frame of critical/sensitive periods of language development. *Acta Otolaryngologica*, v. 117, n. 2, p. 202–205, 1997.
- RUFF, Christopher B. Mechanical constraints on the hominin pelvis and the Obstetric Dilemma. *The Anatomical Record*, v. 300, p. 946-955, 2017.
- SCHLINGLOFF, Laura; MOORE, Richard. Do chimpanzees conform to social norms? In: ANDREWS, Kristin; BECK, Jacob (org.). *The Routledge handbook of philosophy of animal minds*. Routledge, p. 381-389, 2018.
- SCOVEL, Thomas. *A Time to Speak: A Psycholinguistic Inquiry into the Critical Period for Human Language*. Rowley, MA: Newbury House, 1988.
- SAKAI, Tomoko; MIKAMI, Akichika; TOMONAGA, Masaki; MATSUI, Mie; SUZUKI, Juri; HAMADA, Yuzuru; TANAKA, Masayuki; MIYABE-NISHIWAKI, Takako; MAKISHIMA, Haruyuki; NAKATSUKASA, Masato; MATSUZAWA, Tetsuro. Differential prefrontal white matter development in chimpanzees and humans. *Current Biology*, v. 21, n. 16, p. 1397-1402, 2011.

SAKAI, Tomoko; HIRATA, Satoshi; FUWA, Kohki; SUGAMA, Keiko; KUSUNOKI, Kiyoko; MAKISHIMA, Haruyuki; EGUCHI, Tatsuya; YAMADA, Shigehito; OGIHARA, Naomichi; TAKESHITA, Hideko. Fetal brain development in chimpanzees versus humans. *Current Biology*, v. 22, n. 18, p. 791-792, 2012.

TAU, Gregory Z.; PETERSON, Bradley S. Normal development of brain circuits, *Neuropsychopharmacology*, v. 30, n. 1, p. 147-168, 2010.

TOBIAS, Phillip V. Brain-size, grey matter and race - fact or fiction? *American Journal of Physical Anthropology*, v. 32, p. 3-26, 1970.

VAN SCHAIK Carel P.; ISLER, Karin; BURKART, Judith M. Explaining brain size variation: from social to cultural brain. *Trends in Cognitive Sciences*, v.16, p.277-284, 2012.

WASHBURN, Sherwood L. Tools and human evolution. *Scientific American*, v. 203, p. 63-75, 1960.

WERKER, Janet F.; HENSCH, Takao K. Critical periods in speech perception: new directions, *Annual Reviews in Psychology*, v.66, n.3, p. 173-196, 2015.

YANG, Charles. Ontogeny and phylogeny of language. *Proceedings of the National Academy of Sciences (USA)*, p. 110-116, 2013.

ZACARELLA, Emiliano; FRIEDERICI, Angela D. Merge in the human brain: a sub-region based functional investigation in the seft pars opercularis. *Frontiers in Psychology*, v. 6, p. 1818, 2015.

ZUCKERMAN, S. Age-changes in the chimpanzee, with special reference to growth of brain, eruption of teeth, and estimation of age; with a note on the Taung ape. *Proceedings of the general meeting for scientific business of the zoological society of London*, v. 1, p. 1-42, 1928.

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