Language acquisition

The development of domain-specificity

Luca Cilibrasi

Conceptual Foundations of Language Science

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Contents

While reading is a recent invention in the history of humanity, several studies demonstrate that our brain contains a region that specializes in the processing of scripts. This finding is surprising because while we can exclude that the area evolved in connection to reading and writing (due to the recency of the invention of writing systems), the existence of domain-specific circuitry is often associated with skills that have a biological foundation. One proposal argues that the area evolved for other reasons, for instance, by accidentally mastering the processing of shapes, and that due to its properties it naturally develops into a “reading area” any time a child is trained to read during development. In this volume, I argue that an analogous process may take place for language as a whole. The biological foundation of language has been the object of an intense debate for more than five decades, and yet scholars disagree as to whether language should be considered a modular skill with a biological foundation or not. By providing converging evidence from language acquisition and cognitive neuroscience, I argue that language is a skill that partly relies on domain-specific circuitry, but that this circuitry did not necessarily emerge at the time language emerged and is not specialized for language at birth. Similarly to what happens for reading, thanks to their connectivity and their inherent properties, certain areas naturally develop into language areas when they are stimulated by language during early childhood, and quickly become domain-specific or develop a “preference” for language, a preference that will persist then throughout the life of the individual.

1 Two ideas on what language is

One of the main debates in psycholinguistics regards the biological foundations of language. According to one group of linguists, language is a modular skill that has a specific independent brain implementation, and it is the result of evolution. According to another group, language is a cultural tool that does not depend on domain-specific cognition, and that did not emerge through evolution. The first half of the introduction presents the main features of both positions, offering a short historical outline of the debate. In the second half of the introduction, the rationale for a cross-domain assessment of the two positions is presented. In short, the idea is that these two positions lead to different experimental predictions affecting various levels of linguistic analysis, and these predictions also go beyond language and are relevant for domains of cognition that are adjacent and connected. This chapter presents a list of the subdomains that are discussed in this book and how these can help evaluate the two opposing accounts of language. Finally, the groundwork for a conciliating position is presented.

1.1 Foundations of the debate

The year 2017 marked 50 years from the publication of "Biological foundations of language", one of the most important volumes in the field of psycholinguistics (Lenneberg 1967, Fitch 2017). The author, Eric Lenneberg, was a neurologist and a linguist, and through an extensive review of both linguistic and neurological literature he developed a theory of language that would be compatible with our knowledge of the brain. According to this view, language is a modular system (an idea further developed by Jerry Fodor 1983), meaning that it is an independent faculty of our cognition that works "in concert" with other independent faculties. Lenneberg noticed that the implementation of language in the brain follows specific patterns, and humans have substantially consistent brain areas for language, regardless of the language they are using. He also noticed that language development follows consistent stages across the world's population, making language similar to other cognitive skills with a clearer biological foundation (such as vision – for a discussion see Lee 1980). This position has elicited the sympathy of many linguists across the world, and particularly those working in the so-called "generative tradition" (Fitch 2017). Generative linguists argue in fact for the existence of an independent linguistic competence in our cognition; in particular, they argue for the existence of independent linguistic subskills: syntax, morphology, semantics, phonology, pragmatics (Washburn 1994, Schell et al. 2017). Fifty years of research in psycholinguistics have partly corroborated these claims, but they have also fueled an intense debate as to whether different interpretations of the data are possible (Ploux & Déprez 2018). The invention of neuroimaging techniques (that spread in the 1990s) indeed confirmed that certain areas of the brain are specifically used for linguistic sub-skills (Schell et al. 2017). However, several studies show that these areas are to some extent also involved in other tasks that do not require language (Fedorenko & Blank 2020). An opposing account to the biological foundation of language proposes thus that language is not an independent domain-specific cognitive system, but rather that language is an emergent skill relying on a substratum that is domain-general. This is the so-called "emergentist view" (MacWhinney 2001). Evidence from cross-language consistency in language acquisition is also described as evidence for the consistency of these domain-general skills in the world's population, rather than evidence for the biological foundation of language (MacWhinney 2001, Elman 2005).

Somewhat surprisingly, fifty years of research have exacerbated the debate between these two positions, rather than leading to a conciliating approach[1]. Often evidence can be interpreted by both sides, at least at first glance, since it is complex to design experiments that clearly tease apart one model from the other (MacWhinney 2006, Adani et al. 2017).[2]

Scientists have adopted a number of terms referring to various features of each account, and it is important to define some of them here. The generative

[1]Even though some eminent conciliating proposals do exist, see for instance the proposal of Karmiloff-Smith (1992), and its more recent version in Karmiloff-Smith (2009), known as "neuroconstructivism", which builds particularly on analyses of autism and William's syndrome. While the current volume does not discuss these conditions, the conclusions we reach by analyzing different topics are comparable: domain-specific brain specialization may be in most cases the combination of innate biases and developmental trajectories related to experience. Notice that in this view, innate biases are not domain-specific, but brain areas may become domain-specific through development.

[2]The contrast between generative and emergentist views is carried throughout the volume, but it should be cautioned that I rarely use these terms. Over the decades the clash has taken "corporativist" traits, where scholars tend to identify with one position or the other and defend it strenuously. I am attempting an agnostic analysis of the problem, and for this reason I decided to avoid describing evidence as belonging to one faction or the other. Instead, the volume attempts to include evidence from both positions in a rather mixed fashion and it tries to find an account that can smoothly put together these contrasting pieces of evidence.

tradition has insisted on the idea that the biological foundations of language must be domain-specific, meaning that the cognitive substrate that language relies upon is uniquely used for language (Zaccarella & Friederici 2015). Some go further and make the same statement about the neurological implementation of these skills. The dichotomy between mind and brain is however a complex issue (Marr & Hildreth 1980, Pennington 2005, Rutherford 2018): one may be tempted to simply claim that a domain-specific cognitive system must correspond to domain-specific circuitry in the brain, but linguists in the generative tradition have disagreed on this necessity, and some claim (even Chomsky 2000), that a domain-specific implementation is not a necessity for a domain-specific cognitive skill. Researchers in the emergentist tradition have been obviously criticizing the notion of domain-specificity itself (Elman 2005). In the emergentist tradition, several domain-general skills are seen as the foundation of language. Among them, the ability to recognize patterns (Aslin et al. 1998), the ability to socialize (Tomasello 2009) and the ability to combine elements (Elman 2005).

One crucial issue the two factions have been dealing with regards the initial stages of language development, one favorite topic for research and debate. The rationale for this focus on acquisition is the following: while it is difficult to establish the biological foundation of a skill in a specimen who has been alive for a long period of time (i.e. in adults), if we can observe linguistic skills in young children we may conclude that these are part of their biological endowment (Lacerda et al. 2001). Researchers in the generative tradition have returned to the term “innate” to refer to a number of skills observed in children. This term is charged with ambiguity, since it is used in papers with a number of different meanings. In the literature, there are at least three uses of the term:

1. Some features of language are already expressed at birth in the child (Gómez et al. 2014).

2. Language is not expressed at birth, but the system is written in our genes and will express with maturation given a standard environment (Samuels 1998).

3. The ability to learn is innate, and this is unrelated to language (Elman 2005).

On the one hand, aspects of language which are innate in the sense of (2) have been mostly argued for syntax (Hauser et al. 2002, Coolidge et al. 2011) and syntax has indeed occupied a pivotal role in the discussion of the biological foundations of language. To reflect this prominent role, the second half of this volume is devoted uniquely to syntax[3]. On the other hand, definition (3) certainly applies to all domains of cognition, but it is not clear whether it applies in an exclusive fashion (only the ability to learn is innate, language is not) or whether it applies together with (1) and/or (2) (the ability to learn is innate, and so is language). The emergentist view normally supports the former definition of (3), with innatism referring to general skills only (Elman 2005), though it should be stressed that the term "innate" is in any case not popular in emergentist papers. Definition (1) is the most stringent among the three definitions of the term, and it is used only in reference to research on phonology, since the only linguistic skill that might potentially be innate in the sense of (1) is phonology. Before proceeding to the next section, it should be pointed out that the innatism claim "simply" states that some aspects of language acquisition are innate and domain-specific, not that language as a whole is innate. In other words, the environment is not irrelevant for the acquisition of language (Chomsky 1975). Linguists in the generative tradition do not claim that children are born with language, and they do stress that tuning to L1 depends on the environment, but they claim that some linguistic skills and/or predispositions are there at birth and are independent from the environment (Chomsky 1975). Gervain & Mehler 2010, for example, argue that speech perception in early infancy is influenced by language specific innate abilities, combined with skills attaining to general cognition and environmental factors. This type of nuanced explanation is incompatible with the emergentist approach, since even the existence of one language specific innate skill is incompatible with their claim.

1.2 The current proposal

The two positions (generative and emergentist) presented make different predictions across subdomains of language and also across adjacent domains of cognition. This book presents and discusses scientific evidence from a list of domains and tries to refine the theory of the biological foundation of language taking into

[3]The chapter on language and the brain introduces research on the implementation of linguistic syntax, the chapters on music and mathematics discuss syntax in other domains. This should not be interpretated as an implicit claim that syntax in music and mathematics relies on the same processing system. This claim is in fact what is debated in those chapters. The chapter on language and evolution focuses again on linguistic syntax, and particularly on the adaptive role this could have had in the phylogenesis of human beings. Once again, the idea is contrasted with opposing accounts that criticize the idea of syntax being adaptive *tout court*.

account recent research. It is fundamental to conduct an analysis that crosses subdomains of language and cognition, since a theory of language that aims at being psychologically valid must take into account the bigger picture: whether or not language is a module, it does operate together with the rest of our cognition (Fodor 1983), and it does have a crucial role in the shaping of our species as a whole (Bickerton 1990).

This book may be seen as divided in two parts: The first part deals with language acquisition and language pathology[4], two topics that always received attention in psycholinguistic research for the reasons outlined above. The second part deals with syntax (the so-called computational core), and after trying to define its basic principles it attempts at describing its role in other domains of cognition (music and mathematics), as well as its role in the evolution of the species. Despite this division in two parts, all sections are connected to each other and all deal with the same question: Are the biological foundations of language domain-specific or domain-general? In all the topics I cover, the two theories (generative and emergentist) make different predictions, and often provide different interpretations of the data available.

A modular account of language, for example, would focus on the fact that acquisition follows regular steps across languages (Lenneberg 1967), that brain injuries lead to dissociated language disorders (Caramazza 1984), or that modern neuroimaging techniques show fine-grained brain specialization (Zaccarella & Friederici 2015, Friederici 2020). A domain-general account, on the other side, would focus on the fact that general features of cognition can explain acquisition without the need of a language-specific module (Behrens 2009), on the fact that dissociated language pathology is very rare (Siegel et al. 2016), or on the fact that modern neuroimaging techniques show that brain areas can often be used for a number of cross-domain tasks (Fadiga et al. 2009, Kunert et al. 2015, Koelsch 2006, Fedorenko et al. 2012). The volume attempts to look neutrally at this debate, in order to present both positions fairly. This neutrality is the main instrument used to propose a conciliating view of language acquisition that is gradually defined throughout the book and developed in the general discussion.

It may be worth introducing this conciliating view here, in order to explain how the whole book ties together. The proposal I make in this volume is that

[4] The section on language pathology is a prompt for presenting studies on the implementation of language in the brain. Historically, the first language areas were discovered by looking at the brain of patients with a language pathology, thus it seemed reasonable to start the description of language implementation with language pathology. However, it should be stressed that the chapter also presents evidence from studies investigating language areas in healthy individuals using neuroimaging techniques.

domain-specificity for language is not innate, but it emerges (quickly) during child development. The book tackles two issues at the same time. The first one is whether domain-specific circuitry for language exists at all. By reviewing a large number of studies, working on the edge of linguistics and cognitive neuroscience, I conclude that some of these circuits do exist, though they are probably considerably less spread than previously believed. The second issue is whether these circuits are part of our biological endowment or not. I will try to explain in multiple parts of the book why the two issues are separated, and a skill might have a domain-specific implementation and yet not be part of a biological endowment. The most convincing example of such a case is reading, a skill that I will discuss at length in the chapter on brain and language. My conclusion is that while there is some evidence to claim the existence of language- specific circuitry in the brain, there is not sufficient evidence to conclude that this is not the effect of development. This may appear as a contradiction, as it was already noticed by Lenneberg 50 years ago: if specialization happens during development, why do all children use the same regions of the brain for language? One hasty conclusion would be to claim that since during development all children grow to use the same areas for language, this specialization must be written in our biology. In other words, why don't we all develop differently if specialization follows experience? Contrary to previous work on this topic, I suggest that an alternative explanation may be possible, recurring to the notion of neuronal recycling. Neuronal recycling is an idea introduced by Stanislas Dehaene, a researcher at the University of Paris-Sud, to explain brain specialization for reading. A number of studies across different populations show that the processing of written language (scripts) happens in a specific section of the occipital lobe (posterior part of the fusiform gyrus, that spreads across temporal and occipital lobe), now known as the Visual Word Form Area (Dehaene & Cohen 2007). The VWFA is one of the most studied regions of the brain. This area, part of the visual stream, appears to respond specifically to written text, and not to shapes that do not form written text. This finding is clearly interesting per se, but there are a number of other features that make this area particularly important for the current discussion. The location of the Visual Word Form Area may be observed in Figure 1.1.

One first interesting feature of the VWFA is that it responds to different kinds of scripts, whether they are transparent, opaque or intermediate (Liu et al. 2008). This finding suggests a specialization for the function, rather than for the mechanical procedure of character recognition. In other words, the area seems to embed a cognitive skill, not the mere transformation of visual information. A second interesting feature of the VWFA is its connectivity: it is part of the visual stream, it is heavily connected with language areas, and it develops in a

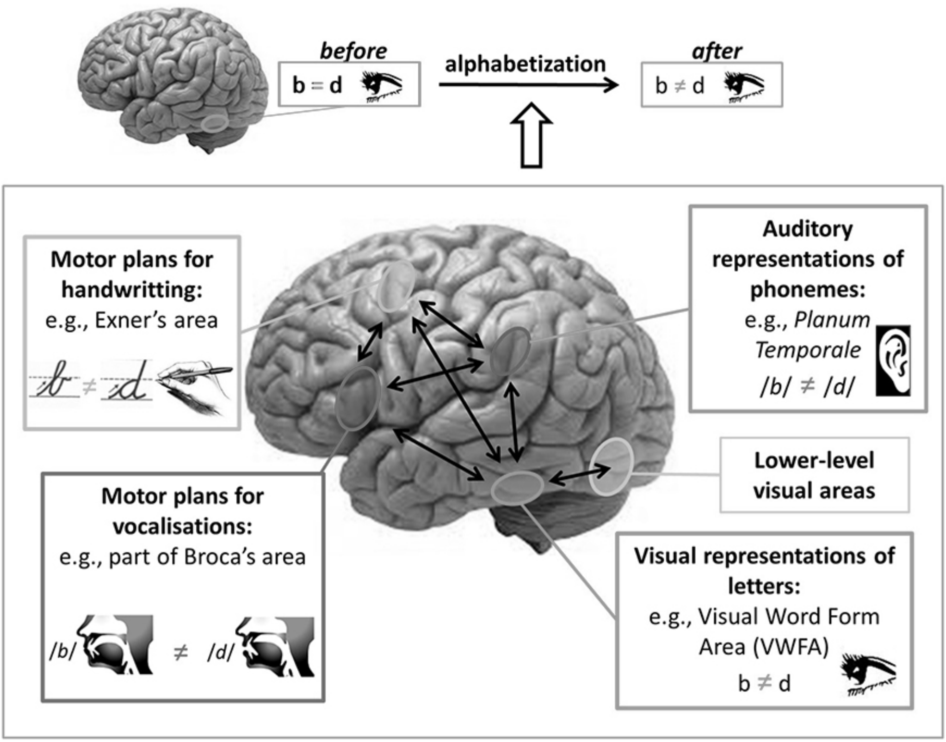

Figure 1.1: Brain pathways in literacy acquisition. (CC BY 3.0 Pegado et al. 2014. Original source: doi: 10.3389/fpsyg.2014.00703)

strategic position between the primary visual cortex and the language circuitry of the temporal lobe (Chen et al. 2019). Recent interpretations of the topography of this area suggest that its connectivity is the main reason for its existence. The processing of this function (reading) happens in that area not because our genes contain information for that area to develop there, but rather because the connectivity of surrounding regions (in the initial stage described by our genes) makes the VWFA appropriate for that function. In other words, the area takes the job because it can. This hypothesis is consistent with two apparently contradictory pieces of information. On the one side the fact that all humans use the same area of the brain to read. On the other side the fact that reading is a recent invention in human's history.

The argument (or, maybe better, the leitmotiv) of this volume is that something similar may be true for language as a whole. The psychological study of language has been characterized by an intense debate because there are two apparently contradictory pieces of information to conciliate. On the one hand, all humans use the same areas of the brain for language. On the other hand, these areas do not appear to be (completely) language-specific, and domain-general cognition may (according to some analyses) explain acquisition on its own. These two contradictory pieces of information are conciliated if we think of language areas as specialized thanks to their connectivity and/or thanks to their inherent properties. These areas are the seat of language because they can take the job, and anytime a child is exposed to language, they develop a preference for that kind of information because they can make sense of it. If we look at the problem with this approach, some findings that are surprising for one or the other account are not surprising anymore. For example, the fact that language areas show some involvement in the processing of other aspects of our cognition, like music or mathematics, is not surprising. These areas have the ability to find structure, and while they may show a strong preference for the structure of language, they may also show sensitivity to other kinds of structures[5]. Similarly, the fact that some subregions show a unique preference for linguistic stimuli (i.e. domain-specificity) is not surprising either, since it may be the case that those areas are the most qualified to take that specific job. This may be due to their connectivity and their inherent properties, without the need for those areas to be written in our genes as domain-specific for language[6].

To sum up the structure of the book and the relevance of each chapter for the general discussion: **Chapter 1** deals with language acquisition, and it focuses on the early stages of development, when children tune to the phonology of their environment. In this chapter I discuss the evidence for early linguistic skills, and their role in a theory on the biological foundation of language. The chapter then explores bilingual acquisition, presenting the important role of age of onset for the acquisition of phonology, and thus the notion of critical (or sensitive) period. Finally, the chapter presents evidence from polyglots with exceptional language skills, to discuss the concept of modularity of language, and particularly the idea of the separation of language skills from other cognitive skills. **Chapter 2** deals with language and the brain. The chapter opens with a discussion of language pathology, and how brain traumas can affect language. The chapter then

[5] As I will discuss in detail in the chapter on music and mathematics, these skills bear important similarities with language, particularly when it comes to the basic operation needed to combine units. For this reason, some have argued that language, music, and mathematics share the so-called computational core, a basic system that allows the combination of two units to form another unit.

[6] The location and function of this area is described in detail in the chapter on language and the brain. For the moment, it may be worth mentioning that this area appears to be a small subsection of what was normally considered the main language area of the brain.

discusses the implementation of language in the brain referring to neuroimaging studies. In this chapter, I discuss at length the dissociation of some linguistic skills in the brain, and I present recent evidence suggesting the presence of some, small, domain-specific subsections of the brain. In the last section of the chapter, the notion of neuronal recycling is introduced, a crucial idea for this book, since it explains the separation between the concept of brain specialization and the concept of biological endowment. **Chapter 3** deals with syntax outside of language, focusing on music and mathematics. Similarities and differences between language and these skills are described, and evidence for their neurological overlap and separation are presented. In the first part of the chapter, I focus on music, where I show that the concept of rhythm applies to both language and music. Then, I show that both language and music operate a formatting of a perceptual continuum, though with important differences. Finally, I show that even though both music and language rely on a form of syntax (in the broad sense of a meaningful combination of units), the systems appear different. In the second part of the chapter, I show that while syntax in music and mathematics are characterized by some similarities, they are different in crucial aspects. **Chapter 4** deals with language and evolution, presenting the two main theories of the evolution of language: one theory defines language as an adaptive skill, and the other one defines language as a skill emerging from other competences of our cognition. The chapter shows how the two accounts make very different predictions on how humans evolved, and which role language had during evolution. In the first case, the proposal is that a group of humans accidentally developed a computational core, and this proved to be adaptive when applied to language. In the second case, the proposal is that human accidentally (and possibly incrementally) developed some other skills, such as social skills, and these gradually allowed for the development of language. The chapter finally outlines the evolutionary consequences if the proposal of this book is correct. In short, if the ontogeny of language in children is a form of neuronal recycling, it may be argued that, evolutionarily speaking, the skills that proved to be adaptive are not language specific; nonetheless, children are exposed to language from their first days of their life (in fact, some information is processed already in the womb), and these domain-general skills are efficient in making sense of speech and thus "take this job" in any individual exposed to language[7]. The proposal thus argues for the

[7]This idea is in line with a neuro-constructivist approach to child development (Karmiloff-Smith 2009). The idea is that brain specialization (and domain-specificity in language areas) are the consequence of innate wiring of the brain and experience: Certain circuits of the brain are naturally qualified for certain tasks, and they take charge of these tasks, during development, when a relevant stimulation is faced by the individual.

potentially adaptive value of a domain-general computational core.

2 Domain-specificity in acquisition

One of the fundamental debates concerning the biological foundations of language regards language development. According to one view, children are endowed at birth with some basic linguistic skills that are used to bootstrap into acquisition, while according to the opposing view, children are only endowed with some domain-general skills that are used to make generalizations on the linguistic input they are surrounded by. The first part of this chapter reviews these two positions, underlying their strengths and weaknesses. The second part discusses the biological foundation of bilingualism and the cognitive and neurological phenomena associated with the use of two languages. The chapter finally presents evidence from polyglots, data that has been used for and against the proposal of a domain-specific system for language. The two positions are discussed in detail.

2.1 Language acquisition: basic concepts

Are children born with language? At first glance this question is nonsensical. There is no need to involve linguistic analysis to know that newborns do not speak. As soon as babies are born, they do nothing but cry and sleep[1]. In addition, even if they hypothetically attempted to talk, their tongue is too large and it does not allow them to articulate and control the sounds produced (Anisfeld 1996). Children's first words arrive during the first, sometimes the second year of age (Ambridge & Lieven 2011). Generally, these are very simple words, like mommy, daddy, or yummy. These words can be revealing of babies' internal processing. In fact, there are aspects of the first real words like daddy or mommy or of the childlike words such as yummy that show the extent to which children's knowledge of their language is already advanced in the first year of life. One first crucial aspect to consider is that, at this age, children already produce words that respect the phonological rules of their mother tongue. Mommy, daddy, but also

[1]Even though cries vary across linguistic environments (Mampe et al. 2009). In this study, the researchers investigated the prosodic contour of cries produced by newborns in France and in Germany, and they showed that these contours partly reflect the melodies of these two languages.

the child-word yummy respect the phonological rules of English (Vitevitch & Luce 2004). This means that at about 12 months children have already extracted the phonological rules of their mother tongue from the surrounding environment (Tomasello 2009). This result is astonishing in itself. To understand why it is astonishing, it is necessary to reflect on the phonological variability of human languages. Human languages vary considerably in relation to the sequences of sounds that are allowed within words (Jusczyk et al. 1994). For example, German uses consonants that are not allowed in Italian or English (Wiese 2000). The phoneme that concludes the word Ich in Ich bin (I am) is a phoneme that does not exist in Italian or English. This phoneme is a non-sonorous palatal consonant and is represented with this symbol: /ç/. If one observes the words that children who grow up in Italy or the UK (whatever their origin) use during the early stages of their life, one will notice that the phonemes used do not include the /ç/, or other foreign sounds, but include only phonemes of their environment (De Boysson-Bardies & Vihman 1991). In fact, this pattern is already observable at the age of eight months (Kuhl et al. 2006). At that stage, children do not produce words yet, but produce syllables, at first glance in a random fashion (so-called *babbling*, see Guasti 2017). The sounds produced during babbling from the age of about eight months are sounds allowed in the language of the environment. The ability to produce the sounds of the environment is completely disconnected from the parents' DNA (Kuhl 2000). For this reason, the children of immigrants begin to speak with a local accent, indistinguishable from that of their peers with local parents (unless they are exposed during the first months of life only to the language of their foreign parents). Children also have very precise control on the sequences of sounds that are allowed in their native language (Majorano & D'Odorico 2011). Across the world, children learn to call their mum and dad in the initial stages of word production: in Slovak, for example, the child-word for dad is *ocko*, which is pronounced /ɔzko/. The sequence of sounds /zk/ is not allowed in Italian or Japanese, but it is allowed in Slovak. At first, Slovak children tend to operate a phonological simplification, and pronounce the word with the sequence of sounds /ɔzo/ (or /ɔzi/). The /ɔzi/ sequence respects the phonological rules of Slovak, but at the same time it does not contain sequences of two or more consonants (so-called phonological clusters), and it is therefore easier to articulate. Within a year or so, children switch to the articulation of the word /ɔcko/ in its entirety. Slovak children show, at the age of about two years, to have knowledge of the phonemic rules of their language, including complex rules that manage the sequence of consonants (Scherer et al. 2013). The sequence of sounds they produce are allowed in their language, but not in Italian or English. No Italian child at the age of two produces the /zk/ sequence, while all Slovak children who are following a typical development do so naturally (Scherer et al. 2013).

Noticing that these abilities are already mature at the age of one or two, researchers have investigated how the child can set their own linguistic system to that of the environment in such a short time. To answer this question, psycholinguists have begun to conduct experiments on even younger children to understand what kind of linguistic skills they could have. Newborn studies are normally conducted using two techniques that measure attention. One is called the high amplitude sucking paradigm, and the other visual habituation procedure (Floccia et al. 1997, Colombo & Mitchell 2009). Studies using the high amplitude sucking paradigm rely on the fact that babies tend to suck their pacifiers more insistently when they are in contact with situations that stimulate their attention and interest (Gervain & Mehler 2010). The studies with the visual habituation procedure are based on a similar principle, namely the fact that children tend to shift their gaze to stimuli that they find interesting and tend to gradually look away when a stimulus becomes boring (Colombo & Mitchell 2009). Using these two techniques associated with very ingenious experiments it was possible to understand what kinds of language skills very young children have. Many studies, conducted in various parts of the world, have shown that infants are able to discriminate sounds of languages that do not belong to the language of their environment, during the very first months of their lives (Gervain & Mehler 2010, Cheour et al. 2002). Patricia Kuhl (Kuhl 2004), a researcher at the University of Washington, has shown that this ability is found in children up to the age of six to eight months. After that, this competence disappears. In the next section I will try to explain exactly what this competence consists of, and how and why it is absent in adults and children older than 8 months.

I will start with an example: in English we can find both the sound /r/, as in race, and the sound /l/, as in lace (Roach 2009)[2]. From the articulatory point of view, these sounds are very similar to each other. In fact, both sounds are called lateral sounds, because in both cases the phoneme is produced by making the air flow on both sides of the tongue (Roach 2009). The two phonemes are so similar that in some languages they are not even distinguished. In Japanese, for example, speakers use a sound very similar to the English /r/ as a prototypical sound, and in an interchangeable and random way they can use the sound /l/ or variations of it, without this implying a variation in the meaning of the word pronounced

[2]The sound /r/ is actually pronounced in different ways depending on the English variety, but I am not going to discuss about this variability. For a reference to this issue, see Hosseinzadeh et al. (2015).

(Labrune 2012, Kawahara 2015). Because of this type of phonological formatting, Japanese speakers who decide to learn English experience many difficulties learning the distinction between /l/ and /r/ (Bada 2001). As far as they can discern, those two sounds are identical (Strange & Dittmann 1984). When we ask them to produce the two sounds distinctly the task becomes even more challenging (Flege et al. 1995). The task is extremely complex. These kinds of problems are indeed pervasive and affect speakers of all languages when they are presented with languages that use different phonological systems. However, despite these gross mistakes made by adults, children younger than six to eight months seem to have no problem with all this linguistic variation (Tsushima et al. 1994). For example, Japanese infants, unlike their parents, have no problem distinguishing the sound /r/ from the sound /l/. Studies presenting babies in Japan, even at the age of a few weeks, with the syllables /ra/ e /la/, show that when the speaker switches from one syllable to the other, the baby starts to suck the pacifier more intensely. By measuring the rate of suction per minute with special pacifiers connected to a computer, we can measure the level of attention of the children (Kuhl 2004). The results clearly show that Japanese babies, up to the age of six to eight months, are perfectly capable of perceiving the distinction between the two phonemes. After that age, however, they lose this ability, and perceive the sounds with a phonological formatting proper of Japanese (therefore, they no longer perceive the difference between them, and they do not show any increase when the experimenter switches from one syllable to the other, Kuhl et al. 2006)[3].This pattern has been shown consistently in many languages and in many countries of the world. In Israel, for example, it has been shown that Arabic and Israeli infants are both sensitive to the distinction between /ba/ e /pa/, although this distinction is peculiar to Hebrew but not to Arabic (Segal et al. 2016). American infants are sensitive to Hindi contrasts that are not present in English (Werker & Lalonde 1988), German infants are sensitive to English contrasts (Polka & Bohn 1996), and so on. The point of this discussion may be clear. What is observed is that children can discriminate, as infants, most of the contrasts of human languages (Kuhl et al. 2006). This skill is quickly lost, as a result of the fact that newborns, within six to eight months, organize their phonological system in relation to the environment that surrounds them (Kuhl et al. 2006). This is one of the fundamental points of linguistic research on newborns, and one of the most important discoveries in this field of research. Children are able, at birth, to discriminate the vast majority of phonemes, but within six to eight months they become at-

[3]This description applies to consonants. See, for instance, Mugitani et al. (2009) for a reference to vowels.

tuned to the phonological system of the environment, and they stop being able to discriminate phonemes from the other languages (Werker & Tees 2005).

But there is more, as some linguistic skills are shown to appear even earlier, at just a few days of age[4]. Infants can in fact discriminate one language from another from the earliest days of their life (Guasti 2017). More precisely, studies on newborns show that infants, from their early days, manage to discriminate between languages that belong to different rhythmic classes (Nazzi et al. 1998, Ramus 2002). For example, newborns growing up in Italy can discriminate Russian and German without difficulty. Research shows that this skill is due to a more fundamental skill which is the ability to distinguish vowels from consonants (Nishibayashi & Nazzi 2016). The distinction between vowels and consonants is perceptually very basic: while consonants require some friction of air in the oral cavity, vowels are produced by flowing the air through the oral cavity in a gentle way and without disruption (Ladefoged & Disner 2005)[5]. The main features of the vocal tract may be seen in Figure 2.1.

Languages differ when looking at the distribution of vowels and consonant. Some languages allow long sequences of consonants, while other languages do not allow them. Slavic languages, such as Czech or Russian, allow the combination of many consonants one after the other; languages such as Italian allow smaller clusters of consonants (Davidson 2011, McCrary et al. 2002). Some languages, like Japanese or Korean, allow only a small number of clusters and normally have syllables that are composed of a sequence of a consonant and a vowel (Bada 2001). These distributions are used to differentiate languages by infants. The claim that it is exactly the distribution of vowels and consonants to allow the discrimination of languages in infancy is corroborated by the fact that newborns cannot discriminate languages that belong to the same rhythmic class (Ramus et al. 1999). For example, when newborns hear Dutch and English, they cannot distinguish one from the other, and this likely is because the distribution of consonants and vowels is very similar in these two languages (Christophe & Morton 1998). For English children, several months are necessary for English to be distinguished from Dutch. Similarly, for Italian children it takes several months for them to be able to distinguish Italian from French or Spanish. For Czech children

[4]Some skills are even observed in the womb. For example, by measuring variation in heart rate, Kisilevsky et al. (2009) demonstrated that fetuses can recognize their mother's voice.

[5]More on this distinction will be presented in the chapter on music. The ability to distinguish vowels and consonants may in fact be at the basis of the rhythmic properties of language, and these properties may have a parallel in music. The chapter will discuss in detail the relationship between linguistic and musical rhythms, and how the ability to perceive linguistic rhythms may be an index of (some) linguistic skills.

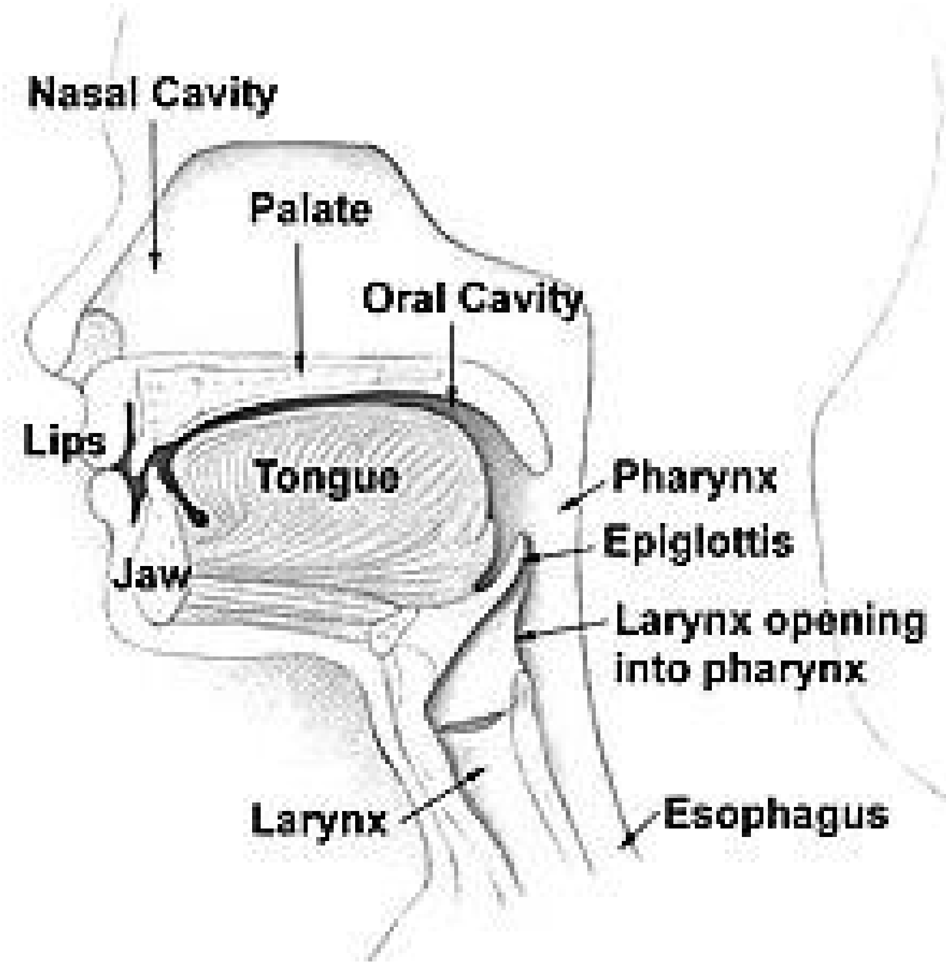

Figure 2.1: The vocal tract. (CC BY-SA 4.0 Wikimedia Commons, Original source: https://commons.wikimedia.org/w/index.php?title=File:Tracto_-vocal.png& oldid=963106414)

it takes several months for them to be able to distinguish Czech from Slovak or from Croatian.

Despite the fact that these experiments have been replicated several times and with very different languages, there is a clash among researchers as to what the implications of these scientific results are. According to a first group of linguists, these data show that children are equipped, at birth, with a biological predisposition for language (Locke 1988). This account capitalizes on the fact that babies need to be able to discriminate between vowels and consonants from day one in order to discriminate languages. If anything, one may argue that babies need to have, at birth, this simple phonetic distinction. According to a second group of linguists, these data only show that human beings have excellent general cognitive skills, and that they can use them to perform a range of tasks, including discriminating exotic sounds and distributions of sounds (Behrens 2009). Vowels are different from consonants in major acoustic traits. As such, one may not need phonological categories of any sort to perform language discrimination, but only acoustic and statistical skills.

The importance of this debate may be clear: if the first group were right, it would mean that children display a specific predisposition for language, a fact that would be in line with the idea that language is a biological system not dissimilar to vision, for example (a modular biological cognitive system). If the second group were right, however, language would be nothing but a property that emerges from other skills, and that does not have a special status in itself (Tomasello 2009).

The parallelism between language and vision was proposed, for example, by the American linguist Ray Jackendoff (see for instance Jackendoff 2011). Several of its traits make evident that vision is a biological system. In the first place, vision is possible because we are endowed with a set of physical structures that make it possible (McIlwain 1996). For a start, the eye, and in particular the retina, are specialized organs essential for vision (Masland 2001). The light that pervades the world passes through the lens at the center of our iris and collides with the retina at the back of our eye socket. There, a set of specialized cells transforms light waves into an electrical signal through an electrochemical phenomenon (Grossniklaus et al. 2015). This electrical signal can then be processed by the brain, in the form of nerve impulses. Some brain circuits (note, the same in all human beings) organize the information coming from the eyes in increasingly complex architectures. For example, while the cells of the retina "perceive" dots, the cells at the back of the brain perceive lines with different orientations (Lamme 1995). The combination of these lines in turn allows us to see objects as we see them with our consciousness (Tong 2003). Finally, the visual system is a system that needs to be stimulated in order to function "fully", and this must happen within a certain period of time (Morishita & Hensch 2008). Experiments on mice have shown that if both eyes are covered for a certain period of time shortly after birth, the animal will never develop a visual system (Morishita & Hensch 2008).

Human language is similar to the visual system in many of the aspects just described. First of all, a system of specialized organs transforms sound waves into electrical signals: the ear, and a transduction system present in it, transforms the pressure exerted by the air that carries auditory messages (and in general all sounds and noises within a certain spectrum of frequencies) in sequences of brain synapses (Corey 2003). In the brain, then, this information is organized and processed, through circuits that seem to be specialized, or at least have a preference, for linguistic stimuli (Galaburda & Sanides 1980, Vigneau et al. 2006). Areas specialized for language are located in the same position of the brain in all the speakers, regardless of what their mother tongue is. For the production of language, similar considerations apply: Specialized areas activate when we produce a sentence, and the electrical impulses are transformed into an air wave with our organs of sound articulation (oral cavity, teeth, tongue, vocal folds) with very fine-grained movements (Masapollo & Guenther 2019). As for vision, the circuits of language need to be stimulated within a certain window of time so that they work properly (Hurford 1991). We have already seen, for example, that the phonological system of language is established in the first few months of life, within about six to eight months (Kuhl 2004). Some studies of children raised in isolation show that if the linguistic system is not stimulated at all (or very little) in the period from birth to puberty, then that person will never be able to develop a complete and functional language (Curtiss et al. 1974). Considering these facts, it appears legitimate to see language as a biological faculty similar to vision, and many linguists defend this idea (Smith & Kirby 2008). According to the second group of scientists, however, the data presented above can be explained in other ways. According to these scientists, language is nothing but an emerging faculty within a very advanced general cognitive system (Kelly & Martin 1994). In other words, human beings have particular cognitive abilities, which are of general-domain, and through these abilities they have developed language (Tomasello 2009). For example, human beings are animals with great social skills (Herrmann et al. 2007), who are able to work together to achieve common results (West et al. 2011), who have the ability to imagine the mind and thoughts of the other specimens they encounter (Brüne & Brüne-Cohrs 2006), and are skilled at finding patterns in the input (Saffran 2003). According to this group of researchers, language is only the product of other faculties, not an independent faculty (Tomasello 2009). This notion can be exemplified looking at the infants' ability to recognize linguistic contrasts. From a logical point of view, is it really necessary to presuppose a biological and specialized linguistic faculty to perform the discrimination of phonemes? Infants may be able to discriminate phonemes just because these are acoustically different (Scott et al. 2007), and they could do so using faculties that are not strictly linguistic (Rakison & Yermolayeva 2011). For example, with the same general system they could distinguish the sound of a horn from that of an elevator, without this requiring any kind of linguistic competence. According to this group of linguists, children use general skills to perform linguistic acts such as phoneme discrimination (Scott et al. 2007). How do we explain, then, that discrimination follows a certain time window? Why can children at the age of 4 months discriminate the sounds of most human languages, while at 9 months they discriminate only the sounds of their language? Even this phenomenon can have a non-linguistic explanation. This narrowing could just be a way to organize our cognitive (domain-general) resources. Once the phonological system of the mother tongue has been acquired, cognitive resources can be used for other tasks and therefore one is no longer able to discriminate contrasts of other languages (Rakison & Yermolayeva 2011). This kind of explanation applies well to different types of linguistic skills, and, in many cases, it becomes difficult to establish with certainty whether the type of skills used is specific to human language or whether it is a domain-general competence.

Note that I am delineating in these lines one of the most open clashes in current linguistic research: are we born with a biological predisposition for language, or not? Is the ability to acquire a language and speak a property described in our DNA and then realized in the brain from birth, or is it the consequence of particular brain structures of general domain? Current knowledge allows us to design increasingly refined experiments that will slowly succeed in giving a final answer to this question, but a precise answer is not yet available. The distinction outlined in these lines will recur throughout the book, since it matters not only for language acquisition, but for the nature of language itself. The next section will instead deepen our discussion of phoneme discrimination in infants and what it might say about innate linguistic skills.

The discrimination of phonemes is a crucial ability, since it can offer important insights into the (potentially) innate abilities of infants. As mentioned, it is well acknowledged that at the age of 6-8 months, babies can discriminate phonemes that are present in their linguistic environment. Using the high amplitude sucking paradigm, we can observe that in 8-months-old, the sucking rate increases when babies listen to a change between phonemes and these phonemes belong to the child's language of exposure. This finding, though interesting, is not relevant for a discussion on innatism because, in principle, this skill may simply be an acquired competence, based on what infants experienced during the first months of life. Our attention needs to be turned instead to the perception of unfamiliar contrasts. As discussed, during the first 6 months of life, babies can discriminate contrasts that are not present in their language. In this section I will present several studies showing the cross-linguistic pervasiveness of this skill. I will present these studies in chronological order, just to show how these findings have been consistent over time.

In pioneering work, Trehub 1976 showed that English children as young as 5 weeks are able to discriminate distant non-native contrasts, specifically pa-pã and za-řa, while adults fail in the same task. In 1981, Werker and colleagues tested English speaking children with Hindi contrasts that are not present in English (Werker et al. 1981) and showed that the contrasts were successfully discriminated by the children. In this case, the stimuli used were multiple natural tokens (a larger number compared to Trehub 1976). Best et al. 1995 showed that at 6 months English newborns can discriminate non-native contrasts belonging to Zulu, specifically Non-Assimilable Clicks and Single Category Ejectives. The stimuli used were multiple natural tokens, selected according to their similarity to prototypical forms. Polka & Werker 1994 showed that English speaking children can discriminate German vowels at 6 months, but rapidly lose this ability. In this experiment, children were presented with several naturally created exemplars. Along similar lines, Polka et al. 2001 showed that both French and English newborn discriminate the contrast /d/, /ð/, even though the contrast is only relevant in English. Also in this case, the test was conducted using a set of naturally created stimuli. Tsao et al. 2006 showed that English and Chinese newborns can discriminate the affricate-fricative contrast that is only present in Chinese at 6 months, and that this ability is gradually lost by English infants. The stimuli used were artificially created stimuli varying acoustically (but not systematically on a continuum). Finally, Segal et al. 2016 showed that at four months, both Arabic and Hebrew monolingual children discriminate /pa/ and /ba/, but the contrast is only relevant in Hebrew. The experiment was conducted using a large number of naturally created items.

The evidence for the perception of unfamiliar contrasts in newborns is thus quite solid. At birth, babies are able to perceive a large number of phonological contrasts that are not present in the language of their environment or in the language of their parents. The consonants that are not used in the first eight months of life are then "forgotten" by children. This does not undermine the fact that, before this narrowing takes place, babies are able to perceive any contrast between the phonemes of unfamiliar languages. It remains unclear at this point whether this perception is based on auditory mechanisms alone or whether it is indeed a phonological perception that leads to these results. In other words, it is unclear whether the perception of these contrasts follows categorical patterns[6] – an indication that phonological categories are innately present – or whether infants start out with an ability to discriminate any speech sound regardless of whether in adult speech this would straddle a phonological boundary or not.

I will explain in further detail the concept of categorical perception. As Harnad 2003 puts succinctly, there are two types of perception in human cognition, one that is gradual and quantitative and one that is more abrupt and qualitative. The first type of perception is what we experience, for example, when we perceive different shades of the same color, while the second type of perception is what we experience when we perceive two different colors. The first type of perception is called continuous while the second one is called categorical.

There is substantial evidence showing that adults perceive linguistic contrasts in a categorical fashion. The phenomenon was first documented by Liberman et al. 1957 and Liberman et al. 1961. In order to explain their experiment and their findings, a few concepts on the acoustic nature of consonants need to be introduced. Each phoneme can be described with a specific, limited set of features, corresponding to the articulatory features needed to utter that sound (Jakobson et al. 1951). A change in one feature can lead to a different phoneme. For instance, the difference between /t/ and /p/ is solely one of place of articulation: the former is a voiceless alveolar plosive, while the latter is a voiceless bilabial plosive. Another feature that can turn one phoneme into another is voicing. When vocal folds vibrate, a consonant is called voiced, otherwise it is called voiceless. This is the difference that occurs, for instance, between /b/ and /p/ respectively. The distance, in time, between air release (burst) and the vibration of vocal folds is called Voice Onset Time (VOT). In voiceless consonants this value is large, since vibration only starts towards the end of the production. In contrast, in voiced consonants, this value is very small, if not negative, since fold vibration starts very early in comparison to the burst. Figure 2.2 shows differences in VOT in prototypical /pa/ and /ba/. VOT can be modified artificially using computers, and an infinite number of consonants in between prototypical voiced and devoiced consonants (such as /p/ and /b/) can be created. The number of possible intermediate sounds between /p/ and /b/ is infinite, but, despite this, speakers divide

[6]The notion of categorical perception will be mentioned again in the chapter on music, where it is shown that while the acoustic continuum is perceived categorically when analyzing speech sounds, the same cannot be said on the acoustic continuum within a musical octave. This difference occurs despite the fact that both linguistic and musical continua are divided in "slices" to obtain their units (phonemes and notes).

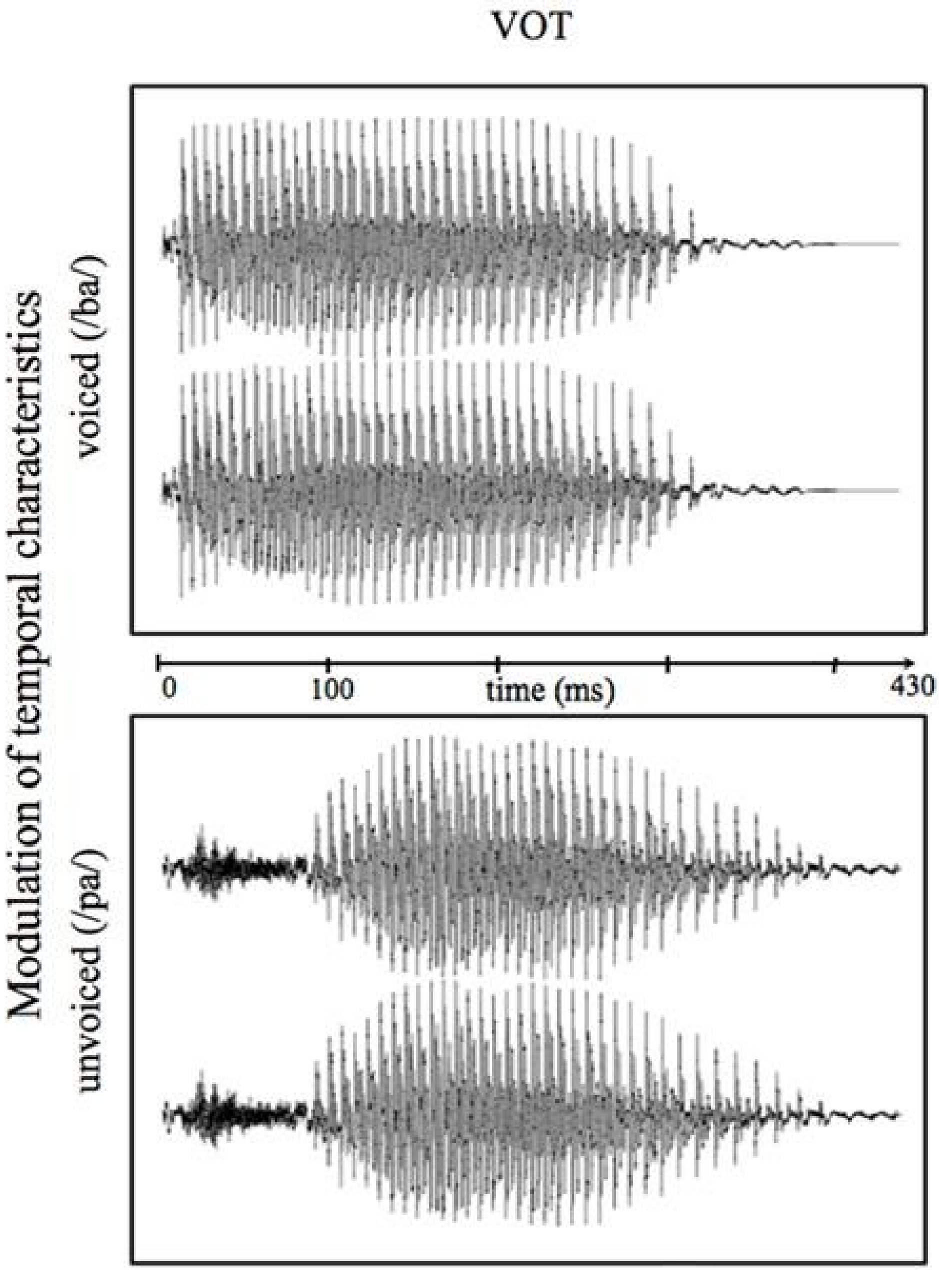

Figure 2.2: Voice onset time for the syllables /ba/ and /pa/. (CC-BY 4.0. Ott et al. 2011. Original source: https://aclanthology.org/P11-1032/)

that perceptual space into precise islands (Harnad 2003). In Italian, English, and many other languages familiar to us, for example, the perceptual continuum will be divided in two prototypical sounds: /p/ and /b/. Other languages divide the perceptual space in 3 parts instead of 2, and others divide it in 2, but with a slightly different boundary (for example, Spanish, as explained in Flege & Eefting 1987, or French, as explained by Hoonhorst et al. 2009). The crucial finding of Liberman et al.'s 1957 study is that human beings do not perceive these intermediate forms as intermediate forms, but show a sharply changing categorical perception of either /p/ or /b/. Up to a certain boundary, all modified versions of a phoneme are perceived as /p/; after that boundary, all modified versions are perceived as /b/. Additionally, if two items which are on the same side of the perception boundary are played, they are perceived as identical. In contrast, if the two consonants belong to different sides of the perception boundary, they are perceived as different. It is noteworthy that categorical perception is not related to the actual acoustic difference between the two sounds, i.e. it is not predicted by the amount of variation in VOT between the two sounds, but only by boundary crossing. Following this pioneering work by Liberman et al. 1957, a number of studies on categorical perception assessed the precise nature of the boundary and the extension of categorical perception to other domains, such as facial expressions, but maintained the general features identified in its first definition (Hoonhorst et al. 2011, Goldstone & Hendrickson 2010). It should be noted that while experiments on the categorical perception of consonants have been replicated across different languages and age groups, vowels and tones seem to be more difficult to categorize (Abramson 1978; Pisoni 1973; Crowder & Repp 1984). Thus, the rest of the discussion will focus on consonants only.

The presence of categorical discrimination in adults is interesting but it is not relevant to make any claims about innatism of phonological categories. In fact, it may be the case that children start with a graded perception of linguistic sounds, which are later organized into categories when they tune in to their L1. In this type of account, the success of newborns with unfamiliar contrasts would not be due to innate phonological formatting, but rather to a general ability to discriminate sounds that differ acoustically. Thus, the perception would be based on auditory parameters only, instead of phonological categories.

The studies presented in the previous section just happened to test phonological contrasts, but the data reported above do not entail that the child is perceiving these contrasts in a categorical fashion, or, in other words, phonologically. In such an explanation, innatism would not have any role; in principle, innate phonological categories are not needed to discriminate phonological contrasts.

The next step is thus answering the question of whether infants display categorical perception or not.

Seminal work from Eimas et al. 1971 shows that children as young as one month perform categorical perception in the same way as adults when presented with the language of their environment. Using the high amplitude sucking paradigm, in which the baby's sucking rate is measured electronically and used as an index of attention, the authors showed that 1-month-old babies are able to discriminate phonemes of the language they are familiar with. Using artificially created stimuli varying in the continuum between two minimally different phonemes, Eimas et al. 1971 showed that children are not sensitive to the difference between intra-boundary exemplars, but they are sensitive to inter-boundary differences, thus mirroring adult perception. In other words, newborns perceive the phonemes of their L1 categorically already at 1 month of age.

Can we then conclude that infants possess phonological categories at birth? This question cannot be answered looking at L1 contrasts, since categorical perception to L1 contrasts may have developed in the first weeks of life, or even within the womb. Some studies suggest that children also perceive non-familiar contrasts in a categorical fashion, but the studies addressing this problem are few and far in between, and since most of them were not designed to answer this specific question, they present some methodological limitations. I will present here a list of these studies:

Werker & Tees 2002 showed that English newborns can perceive unfamiliar contrasts of Salish (a Native Indian language) at 6 months, such as /k̀i/ vs /q̀i/. In their task, the authors used several intra-boundary items, but they were not assessing categorical perception, thus the intra-boundary exemplars are not varied on a continuum. Variation on a continuum is however a fundamental property of the materials used in categorical perception studies. Consequently, the work by Werker and Tees is not unequivocally informative regarding categorical perception. A similar problem occurs in Tsushima et al. 1994 who showed that Japanese infants at 6 months similarly perceive both the contrasts between /r/ and /l/, which are not distinctive in Japanese, and the contrasts between the glides /w/ and /y/, which are distinctive in Japanese. Infants were tested using an artificially created continuum, but unfortunately only the first and second stimulus in the continuum were used to provide intra-boundary variability, a level of variability that is not sufficient to make any strong claim about categorical perception. Work more relevant for our discussion was conducted by Lasky et al. 1975 and Streeter 1976. Lasky et al. 1975 tested the categorical perception of the VOT continuum in four- to six--month-old infants growing up in a Spanish environment. It should be noted that categorical perception of the VOT continuum is different in Spanish and English adults, since the two languages have different boundaries (Benkí 2005). This experiment, thus, offers a clear ground for the observation of whether prototypical or baseline innate boundaries exist at all. The results of this study show that children perceived all contrasts categorically, and they did so at the boundary of VOT used by English adults. Crucially, the newborns in this study did not show any sensitivity to the boundary of Spanish, even though Spanish was the only language they had heard from birth. As the authors explain, this finding suggests that "experience has little effect in determining bilabial stop phonetic categories in 4-6.5 month-old infants" (Lasky et al. 1975, page 215). This type of result is thus compatible with the idea that there are prototypical or baseline phonetic boundaries which are independent from the language of the environment and that are encoded in the biology of the child. This may not necessarily be of representational nature, but may simply be a strategic formatting of the acoustic space. Streeter 1976 investigated the perception of the /pa/ /ba/ continuum in two- month-old newborns exposed to Kikuyu, a Bantu language that does not distinguish between /pa/ and /ba/. The author's results show that children do indeed categorically perceive the distinction between sounds with different values of VOT, but they seem to divide the VOT spectrum in three parts rather than two (they have, in other words, two boundaries rather than one), a result that is in contrast with the result of Lasky et al. 1975. The results of Eimas et al. 1971, Lasky et al. 1975 and Streeter 1976 therefore suggest the existence of baseline prototypical boundaries, although it is quite complex from their data to establish the exact VOT values for them.

Conversely, some studies provide evidence of intra-boundary discrimination in newborns. Miller & Eimas 1996 conducted a study in which infants of three to four months of age growing up in the United States were tested with prototypical and non-prototypical forms of plosive consonants in English, and found that consonants were judged to be more similar when the prototypical form was used as standard. The authors claim that this result implies the existence of structured phonological categories for consonants in newborns. In the meantime, their data show that children were able, to a certain extent, to differentiate contrasts belonging to the same side of the boundary, suggesting that phonological categories may be to some extent blurred. McMurray & Aslin 2005 showed that eight-month-old infants can show intra-boundary sensitivity in their L1. In this experiment, infants were presented with tokens of /p/ and /b/ with varying degrees of VOT, but in this task the phonemes were presented as part of real words (see Beckman & Edwards 2000 for a discussion of this choice). Results demonstrate that infants were sensitive to both inter- and intra-boundary variation. This evidence may be equivocally interpreted as incompatible with innate phonological formatting. However, importantly, this study shows that infants are differently sensitive to intra- and inter-boundary variation. As the authors explain: "infants' early phonetic categories may reside in dimensional "islands", with gaps near category boundaries (and possibly at extreme values along a dimension as well) where no category is strongly activated." (McMurray & Aslin 2005: 24). In fact, in McMurray & Aslin 2005 infants were shown to be sensitive to differences between /b/, and a consonant in between /b/ and /p/, represented with /b*/, and also to differences between /b/ and /p/. However, they failed to differentiate between /b*/ and /p/. As the authors state, this could be explained in 2 possible ways:

A. Children may have an innate categorical boundary in which /b*/ and /p/ are together on the same side (unlikely option if we look at previous studies and at the VOT of /b*/). B. Children may rely on what the authors call "dimensional islands": /b*/ is far enough from /b/ to be differentiated from it, but it may be too close to the boundary to be identified as different from /p/. According to this proposal, even if newborns can perceive differences occurring within a boundary, they may still organize their perceptual space in islands (proto-categories) that will then be useful to map future phonological categories. The concept is re-proposed by Galle & McMurray 2014 in a review of the literature, where it is noticed that while newborns show a certain sensitivity to intra-boundary differences, their perception seems to operate in combination with categorical boundaries.

Interestingly, a study by Maye et al. 2002 shows that exposure to a continuum can de-activate an infant's ability to discriminate a contrast. In this experiment, American six-month-old infants were tested in their ability to discriminate the contrast /ta/ /da/. Subjects were divided in two groups: one group experienced a habituation phase where VOT distances were distributed binomially (i.e. limited intermediate sounds), while the other group experienced a habituation where phonemes were in a continuum between /ta/ and /da/. In the testing phase, only the first group was able to discriminate prototypical /ta/ /da/ syllables.

In summary, while infants do not display innate phonological formatting in a strict sense, they do display some level of categorical formatting of the perceptual continuum (Kuhl 2004). Whether this should be considered a kind of innate linguistic knowledge, and how it affects the overall topic of domain-specificity, remains an object of discussion (and it will be discussed in the final chapter of this volume). Similar reflections may be applied to other basic acoustic skills that babies display from birth, such as the ability to interpret intonation or the preference for speech over other kinds of sounds[7].

[7]Many animals display, right after birth, an instinctive preference for the sounds produced by

2.2 Bilingualism and multilingualism

These are years of great migration, and Europe is becoming an increasingly bilingual continent. According to the Euro-barometer measurements, in fact, there are more people in Europe today using at least two languages in their everyday life than those that only use one language (55% of Europeans speak at least two languages in their everyday life, as of 2018). For a long time, bilingualism was viewed with stigma and considered a disadvantage for children (Pujolar 2007). In the last 20 years, however, scientific research has shown that speaking two languages brings many advantages, both from a social point of view and from a cognitive point of view (Ramírez-Esparza et al. 2020, Filippi et al. 2015, Bialystok 2010). This historical dualism has created a clash of opinions between the traditional view of bilingualism and the modern one. The next section presents experimental studies conducted on this topic that will help explain the concept of cognitive advantage in bilingualism and the debate associated with it[8]. Furthermore, the section will present data from polyglots, showing how these subjects can be used to make claims about domain-specificity in language and how this notion may be critiqued.

Many studies show that there is a cognitive advantage in some non-linguistic tasks for children and adults who speak more than one language (Costa et al. 2009, Guasti 2017, Filippi et al. 2015, among many others). The studies of Ellen Bialystok, at the York University of Toronto clearly show these effects and were among the first to show these patterns consistently. In her studies, we can see how bilingual children and bilingual adults display better performances than monolinguals in non- linguistic tasks of various kinds (see, for instance, Bialystok 2010).

their own species over other sounds. While this certainly appears to be a natural capacity, its presence across different animals suggests that it cannot explain what makes human communication different from that of other species, nor can it resolve the question of whether language is innate.

[8]The literature on child bilingualism has grown exponentially in the last decades, and this section will thus be necessarily a selection of studies, rather than a comprehensive review of this topic. The articles are selected as to exemplify a number of important aspects of bilingual acquisition. First, the fact that bilingual acquisition is normal, and possibly associated with a cognitive advantage. Second, the fact that age of onset matters in bilingual acquisition, and certain phenomena appear to be dependent on the age at which children are exposed to the second language more than others. Finally, the chapter wants to stress that even though bilingualism is often associated to improved general cognitive skills, there are cases of multilingual subjects with reduced cognitive skills. Those examples show that the advanced cognitive skills observed in bilinguals do not undermine claims about the domain-specificity of language (one might potentially display multilingual skills and reduced cognitive skills as well).

An example of these tasks, and the most studied one, is the Simon Task. In this experiment, participants are placed in front of a screen and are asked to press the button to their right when they see a red square, and the one to their left when they see a blue square. Notoriously, when the squares are presented on the screen in a congruent position with that of the buttons, the subjects are faster. When the squares are presented in a non-congruent way, the subjects are slower. For example, if the red square is presented on the left, it becomes complex for the subject to press the button on the right (which is the correct one), because there will be a natural tendency to press the button on the left. The subject must ignore this temptation and press the button to the right, but the effect of the interference is strong and slows down the performance (Simon & Berbaum 1990). These patterns can be observed in Figure 2.3, below.

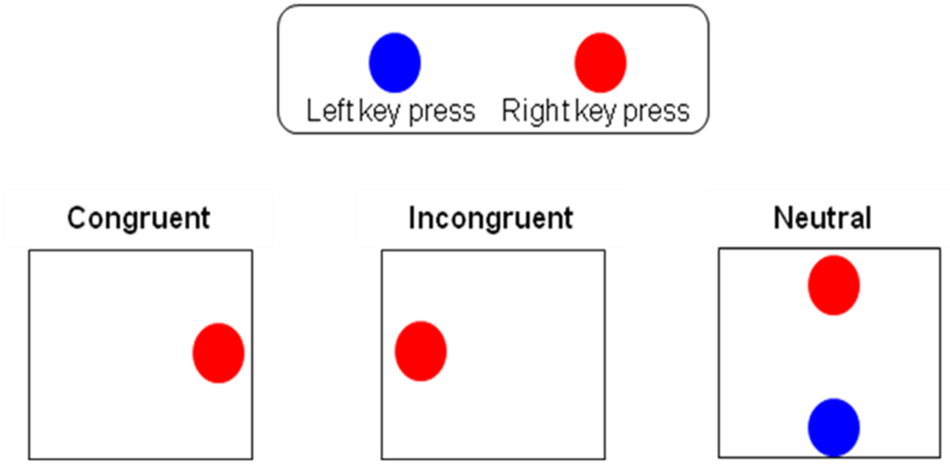

Figure 2.3: The Simon task. The square on top indicates the instructions received by the subject. The squares at the bottom indicate a number of scenarios in the task. The first one is a congruent scenario: the lighter dot is on the right, so it is simple for the subject to press the appropriate button (on the right). The second one is incongruent: the lighter dot is on the left, so it is difficult for the subject to press the appropriate button (on the left). The third scenario is neutral, with dots in the center. (CC BY 4.0, Aisenberg et al. 2015. Original source: doi: 10.1371/journal.pone.0117151)

Bilingual speakers, however, are less subject to the interference given by the position of the square when compared to monolingual speakers and have good performance even when the square is not positioned congruently with the button (Bialystok et al. 2004). The fact that bilingual speakers have better performance in such experiments suggests that bilingual speakers have greater ability to inhibit irrelevant stimuli, or, in other words, greater ability to concentrate on relevant stimuli (Bialystok 2010, Bialystok et al. 2004). In fact, in order to complete this type of task participants need to inhibit the information that interferes with the information necessary to solve it. If one thinks of what bilingual speakers are constantly doing in their mind (inhibiting one of the two languages), one can perhaps understand the origin of such a capacity (Bialystok 2010).[9]

Speaking two or more languages is natural for human beings. However, learning a second language as a child or learning it as an adult can be very different processes, and even learning at different stages during childhood can be substantially different processes (Kovelman et al. 2008, Tsimpli 2014). The result, too, can be substantially different and this could erroneously lead us to think that learning a second language is positive for our brains only up to a certain age. In reality, neuroscientific studies suggest that the positive effects of bilingualism occur both in children and adults (Grundy 2020). The bilingual advantage is reflected in both structural and functional differences in the brain of bilinguals.

The human brain is composed of two types of matter: gray matter (the body of neurons) and white matter (supporting cells and myelin, a substance that makes the flow of information very fast). Anatomical studies have shown that in bilingual speakers there is a greater amount of both gray matter and white matter, when we compare their brains to that of people who speak only one language (Pliatsikas et al. 2015, Olsen et al. 2015). Moreover, functional studies of the brain (that is, of the brain in action, not of its anatomy) have shown that in bilingual speakers there is a greater use of the Broadman area 44, an area of the brain associated with linguistic processing (Fabbro 2013).

But if bilingualism is positive for our brains, where did the stigma associated with it come from? Why doesn't everybody have a positive opinion about bilingualism, and why are some people still very reluctant to raise their children in a bilingual environment? The answers to these questions should be looked for in a series of performance patterns that are observed in bilingual children, patterns that scare and discourage parents: Bilingual children often start talking later compared to their monolingual peers, they learn words more slowly and often have more limited vocabularies than their peers if measured at the same age (Petitto & Holowka 2002). For example, a study by Bialystok and colleagues showed that both young and old bilinguals are less skilled than their monolingual peers in

[9]Note that the fact that the use of two languages is often associated with an increase in executive functions does not exclude that these could be dissociated from linguistic skills. The use of two languages may require (or cause) an increase in a cognitive function like inhibition, but this may still be modular. The second part of this chapter discusses the case of individuals with exceptional multilingualism who however display limitations in their cognitive skills.

tasks that measure access to the lexicon (Bialystok et al. 2008). Now, these limitations are indeed discouraging, but there are at least two issues to consider when analyzing these data:

- Having a more limited lexicon in a given language may not be the most logical way of making the comparison. If a 5-year-old bilingual knows fewer words than a 5-year-old monolingual in a given language, this is because on the whole he/she knows many more words (almost double), if we consider both the languages he/she speaks (Petitto & Holowka 2002).

- The differences observed during pre-school age and sometimes during school age tend to get smaller over the years. Young bilingual adults normally do not show substantial differences in the use of linguistic structures, and even differences in the lexicon are noticeable only with specific tests but are not reflected in the way they speak in everyday life (Sorace 2003).

The differences observed between adults who are fluent in two languages and monolingual adults are often very subtle, and in many cases these differences consist of linguistic or grammatical choices that are unusual but not forbidden by the grammar of the language. For example, a study conducted by Adriana Belletti, Elisa Bennati and Antonella Sorace, between the University of Siena and Edinburgh, shows that native English speakers with a high proficiency in Italian tend to use an explicit subject in their productions more often than Italian monolinguals do (Belletti et al. 2007). This choice does not violate the rules of Italian, but it is not the option favored by native speakers. Likely, this phenomenon indicates an impact (albeit subtle) of English grammar, which necessarily requires the subject, on Italian grammar. Notice that the bilingual speakers of this study did not produce explicit subjects in all the sentences, but rather tended to almost exclusively produce sentences with a null subject, as is customary in Italian. Simply, the number of explicit subject sentences created by these speakers was slightly higher than the number of explicit subject sentences created by monolingual speakers. These data suggests that bilingual speakers had appropriately acquired the grammatical “parameter” that establishes the use of the subject in Italian, but also suggests that there is an influence of the English version of the same parameter - which has a different ”value” - on the production in Italian.

The negative gap observed with monolinguals is therefore limited, and within a few years it becomes very subtle. Nonetheless, differences in development between bilingual and monolingual children are observed from the very early stages of language acquisition, and these changes are not necessarily negative or positive. I will present here three interesting patterns (found in three different experiments) that we observe in infants and toddlers growing up in a multilingual environment:

The first study regards infants that are only a few days old and their preferences for languages at birth. The effects of bilingualism are already observed a few days after birth, and this is likely thanks to the input the child receives while in the womb. It is well attested that newborns of a few days prefer to listen to the language that was spoken by their mother during pregnancy. The phenomenon was first demonstrated by Christine Moon, Robin Cooper and William Fifer in the early nineties with an ingenious experiment conducted at Columbia University (Moon et al. 1993). In this study, the authors found a system for infants a few days old to take control of the stimuli presented during testing. They idea is simple but very effective: connected to an electric pacifier, children could reinforce or turn-off the stimuli coming from the speaker. If their sucking rate was high, the speakers kept presenting the stimulus, while if the sucking rate got lower, the speakers would turn off, and then switch to a different stimulus. The study clearly showed that when presented with a familiar versus a non-familiar language, children had a preference for the familiar language, despite the fact that the only stimulation they ever received in that language was while being in the womb[10]. A study conducted by Krista Byers-Heinlein and colleagues, at the University of British Columbia, showed how this pattern varies in bilingual children (Byers-Heinlein et al. 2010). The babies chosen consisted of infants whose mothers were bilingual and were speaking both Tagalog and English during pregnancy. First, the results of the English monolingual control group confirmed previous findings: when presented with English and Tagalog the infants who were only exposed to English while in the womb preferred listening to English. The experimental group, instead, showed to behave differently: when tested a few days after birth, "bilingual" infants showed no preference for one language over the other (Byers-Heinlein et al. 2010). Notice that all children could discriminate between the two languages (see the discussion of rhythmic discrimination in the first part of chapter one), but their preferences were different depending on the type of exposure during pregnancy. "Bilingual" infants were not confused, they could discriminate as successfully as the "monolingual" infants, but they did not show a preference for one of the two languages (Byers-Heinlein et al. 2010).

As a second example of the differences observed in monolingual and bilingual acquisition, I present a study conducted by Sebastian-Galles and colleagues

[10]Note: children do like unusual stimuli (Stahl & Feigenson 2015), but here the study is rather measuring how quickly they get bored of a stimulus, and this study shows that maternal language was slower in getting them bored (Moon et al. 1993)

at the University of Barcelona Pompeu-Fabra (Sebastián-Gallés et al. 2012) that deals with the use of visual features to discriminate languages at eight months. The study was conducted with eight-month-old infants in Spain and showed that bilingual infants at this age have greater "visuo-linguistic skills" than monolingual children. In this study the newborns were placed in front of a screen on which a person was talking while the audio was turned off. At first all children, both monolingual and bilingual, showed attention for what was happening on the screen and carefully observed the face of the person who was speaking (despite the fact that there was no sound coming from the screen). Since the person was talking but the audio was off, the interest of the children was in the movement of the lips of the person's face and more generally in their facial expressions. After a few minutes all the children, monolingual and bilingual, were bored of watching this person and began to look away and take an interest in other objects in the room. The person who was talking on the screen was bilingual, and after a while she started talking in her second language. Children obviously could not hear any difference because the sound was off, but the lip movement of people is slightly different when they speak one language or the other. Bilingual children noticed the variation of the language and therefore they started to be interested again in the person. Their gaze was focused again on the screen for a few minutes. Monolingual children, on the contrary, did not show any interest in the person and did not notice that there had been a change of language and therefore a change in the person's lip movement[11]. Perhaps the most extraordinary and interesting aspect of this discovery is that the effect can be observed both when the person's spoken languages on the screen are known to the newborn, and also when the languages are new (Sebastián-Gallés et al. 2012). The effect is present even when the input consists of languages to which the child has never been exposed. It is not entirely clear what the reasons that lead bilingual children to have these abilities are. It is possible that the ability to distinguish languages through the use of lip movements can be an advantage for a child who grows up in an environment where caregivers often switch from one language to another. The lip could be a sort of anchor or flag that tells the child in which language the conversation is taking place. These findings are very much consistent with the idea that language is multimodal in its essence (Enfield 2009, Levinson & Holler 2014). Even though linguistic and psycholinguistic research has focused on speech for most of its history, a more comprehensive account of language should stress that our communication takes places multimodally. The visual as-

[11]Studies on monolingual younger children show that these do display this ability for a short time in the first months, but they lose it very quickly (Sebastián-Gallés et al. 2012).

pect of language (facial expressions and gestures, in particular) is tightly intertwined with what we say through speech. As Enfield 2009 explains, communication is made of "composite utterances", where the visual and the speech aspect are typically both present. Video analyses of conversations show that when delivering or deciphering composite utterances, we are highly dependent on both visual and speech cues. Conversating using speech, without these visual cues, is tiring and unnatural. As I will discuss in the chapter on evolution, there are also good reasons to think that gestures were the foundation of our communication system for our ancestors during earlier stages of human evolution, stressing once again the tight relationship existing between auditory and visual information during communication.

The last competence I want to present does not strictly concern language, but rather the social skills of bilingual children. The study presented was conducted by Zoe Liberman and her colleagues at the University of Chicago (Liberman et al. 2017). In this study, 16-month-old children were placed near a researcher and had a number of puppet games and other objects in front of them. Some objects were visible to both the researcher and the child, while other objects were located in a position that was visible only to the child. Some objects were present in the scene more than once. For example, in one of the trials there were two cows in the scene, one visible to both to the researcher and the child, and one which was only visible to the child because it was hidden by an opaque barrier. In the experimental apparatus the researcher asked the child the following sentence: "can you pass me the cow"? Crucially, monolingual children and children exposed to multiple languages responded differently to the researcher's request. While monolingual children decided whether to give to the researcher one cow or the other in a random way, without having a precise system, bilinguals consistently decided to give to the researcher the cow that was in the visual space that was shared between the child and the researcher. This type of finding suggests that the communication and social skills of bilingual children are somewhat more advanced than those of monolingual children at the age of 16 months. These skills may be the consequence of the greater stimulation that bilingual children receive. In fact, while the amount of input that children receive in two languages is comparable to the amount of input for monolingual children in their language, the amount of information and structures that bilingual children receive during the first months of life is different, and this challenge may enhance the communicative skills of bilingual infants (Cilibrasi & Tsimpli 2020b).

Apart from these different developmental trajectories, there is also another major reason for confusion in the analysis of bilingualism, which often leads to a stigmatization of the phenomenon: the relationship with socio-economic status (Meir & Armon-Lotem 2017). In Western countries, bilinguals often have a lower socio-economic status (SES) than monolinguals (Hoff 2013). This is true for the United States, where most bilinguals are economic migrants from Mexico or Latin America (Espinosa 2015), and for Europe, where most bilinguals are economic or war migrants from Africa or the middle East. They are often the children of immigrants, or immigrants themselves. Sometimes (not always) the children of immigrants have more difficulties at school and have lower results than their monolingual peers (Entorf & Minoiu 2005). However, regression analyses show that there is no causal link between these school results and bilingualism. First, studies show that it is the SES, rather than the presence of a second language, to be a variable that can predict school performance, with bilingualism even reducing the disparities caused by SES (Engel De Abreu et al. 2012). It is not the status as such that determines the performance of the boys and girls at school. Rather, it is what the status entails to play a role in student learning. Students with a higher SES have access to more learning opportunities: For example, they can afford rehearsals when needed; at home they often have more books and more stimuli for their learning (Constantino 2005); they are followed more closely by their parents; they do not normally need to work after school (and so on). All of these factors cause boys and girls with a lower SES to have a lower yield at school (Lacour & Tissington 2011). A first look at the problem could include bilingualism among the problems of these children, but several scientific studies suggest that bilingualism has no direct role. For example, a study from Dosi et al. 2016 investigated the issue on Albanian immigrants who moved to Greece. The study showed that, although the SES of this group of people was evidently lower than that of the control group of Greek speakers, measures in cognitive performance displayed an advantage for bilingual speakers. Interestingly, the study revealed that literacy played an important role in modulating performance. The bilingual advantage was strong in biliterate children, and weaker in monoliterate bilingual children. In one task, in fact, monoliterate bilingual children were outperformed by the monolingual children, who were however outperformed in all of the other tasks. The picture is thus quite complex, and education, literacy in particular, plays a role in boosting the effects of bilingualism.

In addition, it is interesting to notice that despite the common pattern observed in most Western countries, where bilinguals tend to have a lower SES than monolinguals, the notion of bilingual advantage has been criticized because, it appears, many of the studies published on bilingual advantage included bilinguals with a high SES (much research has been published in Canada, where bilingualism instead often corresponds to a high SES, contrary to most of the other Western countries). As a consequence, several studies have rediscussed the bilingual advantage as a socio- economic effect *tout court*. A prominent publication in this regard is the one by Morton & Harper 2007, who showed that the bilingual advantage in inhibitory tasks disappears when groups are controlled for SES. Furthermore, SES does affect performance in executive functions tasks, with bilinguals from high SES displaying better performance than bilinguals from low SES. A recent article by Naeem et al. 2018 contributed to these claims and refined some of their features. In this study, the authors compared low and high SES monolingual and bilingual children directly, trying to clarify the independent role of these two variables (bilingualism and SES). Interestingly, the study did display a bilingual advantage in inhibition, but it appears that this advantage was significantly more important in the low SES subgroup. In addition, when children were assessed on a different subdomain of cognition (executive planning), the authors recorded a bilingual disadvantage. In summary, these results do indicate that there may be some cognitive advantages associated to bilingualism, but they also indicate that these advantages may not appear across all executive functions, and they may indeed be affected by other external variables, such as SES.

I have discussed how the human mind/brain is predisposed to acquiring more than one language, and how bilingualism is more common than monolingualism in most countries in the world. But it is evident that there are limits to the number of languages that each person can speak. A country with a particularly high rate of multilingualism is India (Pattanayak 1990). In India, the vast majority of speakers know three languages fluently: the lingua franca of the peninsula, Hindi, the residual language of the colonial past, English, and the language of the state, which varies from region to region (Pattanayak 1990). Three languages do not seem to be a problem and are acquired naturally by children. In Europe, trilingualism is less frequent, but many trilingual speakers are still found. Many immigrants from African countries, for example, come from bilingual countries, and add to the two languages of origin the third language of the host country, once they arrive. For example, immigrants from Morocco and residing in Italy, the third largest group of foreigners by number of residents in Italy, is composed mostly of people who speak fluent French, Arabic and Italian (Di Lucca et al. 2008). Another large group of bilinguals in Europe is that of the children of European mixed couples. According to estimates of the European Union, about one million children were born as consequences of couples formed during the Erasmus project. These children most often speak the language of the two parents, and a third lingua franca that the parents use to talk to each other (for example the language of the country of residence). Another context of high levels of trilingualism is that of countries where bilingualism is frequent, and speakers additionally are relatively fluent in English. In Prague, there is a very large community of Slovaks for example: most of these speakers are fluent in Slovak, Czech and English (Blommaert 2011, Kużelewska 2016). We can imagine that a number of these people know a fourth language, and maybe even a fifth, for example for personal reasons or for simple interest. But intuition seems to suggest that there should be a limit to the number of languages that can be learned by an individual to the point of fluency. First, as mentioned before, bilingual people tend to have slightly reduced lexica compared to monolinguals. If the languages to be learned are many, this effect will be greater, even if not *drastically* greater. Just as when two languages are spoken our lexicon will not be divided in half, when a third and fourth language are added, the decrease in space will be limited and gradual.

The analyses on polyglots that speak more than 6-7 languages are mostly anecdotal, because these speakers are in quite a small number. The Guinness World Record for the number of languages spoken fluently by one person is 42, and the person in question is a man named Powell Janulus, a Canadian with Polish mother and Lithuanian father (McWhirter 1985). His skills were tested by the Guinness experts, who submitted him to a two-hour conversation with native speakers of the 42 languages. As often happens with the Guinness World Record, after the performance of Powell Janulus there were no other people who have managed to come close to this record in any way, and all the other famous polyglots speak a considerably smaller number of languages. People who know more than 6-7 languages are rare, and those who succeed in this intent have special predispositions or experience particular circumstances that make them appear out of the norm (Papagno & Vallar 1995). In other words, the acquisition of such a large number of languages is not commonly observed in human beings (unlike bi-, tri- and even quadri-lingualism) but rather reflects the presence of mental conditions and/or environmental conditions altogether special (McNaughton et al. 1996, Papagno & Vallar 1995). One of these cases received particular scientific attention and was studied using the scientific methods of psycholinguistics (unlike Powell Janulus). It is a person named Christopher, of English nationality, who speaks, with various levels of fluency, about 20 languages.

Christopher's study started at the beginning of the 1990s, at the hands of a group of researchers at UCL - University College London. The project was directed by Ianthi Tsimpli, now the chair of English and Applied Linguistics in Cambridge, and Neil Smith, now emeritus at UCL. The first researchers' report mentioned a subject with "abnormal" linguistic skills, and these abilities were associated with an inverse cognitive profile. In other words, while Christopher showed exceptional talent for languages, he also proved very limited in other aspects of cognition (Smith & Tsimpli 1995). Faced with this very particular situation, the researchers first decided to analyze Christopher's development, and described thus his path from the prenatal period to adulthood. Reports of his mother's pregnancy in 1961 were not entirely clear: In the early months of pregnancy, the mother had contracted measles, although the doctors were sure that it was too early for it to affect the fetus. In addition, during the last period of the pregnancy, the mother had a bad fall, even if, again, there seemed to be no evidence that this had had an effect on the fetus. The advanced age of the mother during pregnancy - 45 years - may or may not have affected the development of the newborn, but at birth the doctors did not notice anything unusual. During the first few weeks of life, Christopher was not inclined to eat. Following this constant resistance, at the sixth week, he was taken to the hospital by his mother, where doctors diagnosed brain damage. In addition to his refusal of food, the child produced strange sounds during the night, and for this reason the doctors prescribed barbiturate medication, a medication that continued to be administered to the child until the age of 6. At the age of 7, the child was diagnosed with mental retardation, and he had evident difficulty in movement; at the age of 10 he was admitted to a school for children with special needs. At the age of 14, Christopher showed a test performance of fluid intelligence equal to that of 8-year-old children. However, to the great surprise of the psychologists, when presented with tests of linguistic comprehension, he had the ability to communicate in an extraordinary number of languages, specifically: Danish, Dutch, Finnish, French, German, Greek, Hindi, Italian, Norwegian, Polish, Portuguese, Russian, Spanish, Swedish, Turkish and Welsh. It was indeed a profile that had never been described in the medical literature. Over the years, his language learning has not stopped, and today Christopher knows more than twenty languages, including British sign language (Smith et al. 2010). This impressive dissociation between linguistic skills and non-linguistic skills has led Neil Smith and Ianthi Tsimpli to reflect upon the relationship between language and cognition and it brought them to the suggestion that also in typical subjects there is a dissociation between cognition and language. In typically developing people, both domains develop within certain limits considered standard. In Christopher one of the domains, the domain of cognition, has shown extreme limitations (of a pathological nature), while the other domain has developed beyond the norm. Magnetic resonance analysis of the brain of Christopher shows a brain not compatible with the traits of autism. There are no large malformations on the cortex that can justify neither the difficulties nor the exceptional capacities of Christopher. The cerebellum shows some abnormalities, but these do not seem to justify the cognitive patterns of the subject, but rather the difficulties of Christopher with movement, which he had shown in the early years of his life. Christopher's history still remains exceptional, and his profile continues to be a window in the understanding of language and the relationship between language and other aspects of cognition. Over the years, Tsimpli and Smith have investigated the acquisition of different kinds of languages in the talented Christopher. In one of their most interesting studies, the authors taught Christopher an artificial grammar that contained structures and rules that do not appear in any actual existing language (Smith et al. 1993).

First, the authors familiarized both Christopher and a control group with a series of rules that respected the general principles of grammar and are attested in other languages, such as the SVO order and the use of bound morphemes. When presented with these rules, both Christopher and the control group showed an ability to learn without particular problems (as it is the case when learning a second language). Now, apart from these standard structures, the artificial language contained some rules that are not attested in any natural language. For example, this invented language contained an element that was positioned according to arithmetic rather than structural principles: this element was an emphatic word, *nog,* that was always positioned as suffix of the third word in each sentence; if a sentence contained less than 3 words, the word would appear in isolation at the end of the sentence. Christopher, similar to the control group in the study, did not manage to learn this rule, despite it being presented to him multiple times. This result sheds light on two different aspects of human cognition. On the one hand, it shows that human beings tend to have expectations of the structures that are to be found in languages. Not every possible structure is equally welcome in the input, and there seem to be some constraints on the type of structures that are possible in languages[12] . On the other hand, this finding shows that Christopher's acquisition is not completely different from that of the typical population, suggesting that there must be an overlap between the processes involved in the acquisition of a polyglot like him and people that only speak 2 or 3 languages.

In the meantime, data from a second linguistic phenomenon adds nuances to these statements. This is because, once presented with the second impossible rule, Christopher managed to learn it, where the control group failed. The rule in question regards the agreement of complex subjects (in which two pronouns

[12]Recent work from Martin et al. (2024) shows that speakers from languages with unusual word orders still prefer more frequent word orders when trained with new artificial languages. This very intriguing result is taken to indicate a Universal Cognitive Bias for word order. As the authors explain, the nature of this bias is still unclear, as "it may be innate, it may reflect conceptual knowledge about the world or about which linguistic categories are more informative about each other" page 309.

were combined) with their verb. Normally, the combination of two singular pronouns as a subject requires agreement with a plural verb, as in: Marie and I *work* in the shop [not: Marie and I works in the shop]. This type of rule is consistent across languages, reflecting the application of a logical principle (two people make a plurality). In the artificial language used in this experiment, the verb was instead inflected with the singular feminine bound morpheme when referring to a complex subject that contained two singular pronouns. This structure was not mastered by the control group, but it was mastered by Christopher, hinting to the fact that his acquisition skills are, to some extent, atypical and exceptional.

The study of Christopher fueled an important and wider debate regarding the faculty of language. According to Tsimpli and colleagues, the fact that language skills can manifest an extreme development in a subject with limited cognitive skills, reflects a substantial separation of language from other areas of cognition. Language was defined, following the terminology of the cognitive psychologist Jerry Fodor, as a module (Fodor 1983): a cognitive system connected but independent from the others, in which domain-general cognition plays a supportive role, but where general cognition neither defines it nor is a crucial component of it. Other researchers, such as Michael Tomasello, from the Max Planck Institute for Evolutionary Anthropology of Leipzig, have strongly criticized this interpretation of the skills of polyglots like Christopher (Tomasello 2009). Tomasello stresses that, while being considerably lower than expected for his age, Christopher's cognitive skills when he started being tested were not absent: they were in fact comparable to those of children of the age of eight. According to Tomasello, since children master very complex structures at the age of five, before attending primary school, Christopher's linguistic skills may depend on his cognitive skills much more than what is proposed by Tsimpli and colleagues. This argument was, naturally, criticized by Tsimpli and colleagues: if these poor cognitive skills are allowing Christopher to learn so many languages, why aren't all children learning to speak multiple languages to the impressive extent of Christopher? According to Tsimpli and colleagues it is necessary to include the concept of language modularity to explain this peculiar performance. The language module can be intact, or even enhanced, separately from the rest of cognition. The debate on the modularity of language is still ongoing, and while positions are more and more refined over the years, the fundamental question still stands: is language an independent module in our cognition or not? In the discussion, findings from polyglots like Christopher will be presented in the wider context, and a conciliating view will be proposed.

3 Domain-specificity in the brain

Traumas in the brain can result in dissociated language pathologies. For example, a trauma in Broca's area typically results in a syntactic deficit, while a trauma in Wernicke's area typically results in a semantic deficit. This fact is often used as evidence for the claim that linguistic subdomains have a biological foundation in the brain. However, opposing views - and neuroimaging data - show that these areas are not necessarily language specific, that some aspects of linguistic processing require the use of the entire brain and also that dissociations are rare. These two accounts reflect the ongoing debate on the domain-specificity of "language" areas, and evidence for both positions is reviewed in detail. In the second part of the chapter, I focus instead on reading, since this skill can be used to explain the notion of neuronal recycling. While there is debate as to whether language is a domain-specific system bound to evolution, no linguist argues the same for reading (being a recent invention in evolutionary terms, it cannot have a biological foundation). Nonetheless, reading seems to be relying on specific circuitry of the brain. This fact complicates claims on the biological foundation of language, since it shows that cerebral specialization is not per se evidence for the biological foundation of a skill. According to one hypothesis, reading might have recycled circuits of the brain that evolved with "different purposes", and if this was the case, the cerebral implementation of reading would offer interesting insights about the implementation of language as a whole. These ideas are presented in detail, along with a thorough discussion of reading impairments and reading neurodiversity.

3.1 Language and the brain

The brain may be the most important organ of our body. It is no coincidence that evolution has provided us with an extremely resistant skull, which wraps it completely and protects it from traumas of all kinds (Yoganandan et al. 1995). Unfortunately, despite the existence of the skull, sometimes parts of the brain can remain compromised following strokes or other damage. While I was doing my PhD, I encountered a patient named Mike. Mike suffered a stroke that affected a portion of the right hemisphere of his brain. It was easy to understand that this unfortunate event had serious consequences on this person. First of all, Mike could no longer move the left side of his body: the leg and the left arm, in particular, were still, which forced him to use a wheelchair in the last years of his life. In addition, some aspects of his cognition seemed to have deteriorated. He could easily forget things that had been said to him a few minutes earlier, despite remembering the position of the books in his bookshelves, which were located on the first floor of his home and that he had not visited since the day of the stroke (note that Mike was the curator of the university library, before retiring, so such a memory for the placement of books is not entirely surprising). Despite these serious changes, some aspects of his knowledge seemed in excellent condition. For example, Mike had no problem completing crossword puzzles and other language games even after the stroke. He had no problem talking: his sentences were well articulated, complex, and his pronunciation was impeccable. What explains such a curious pattern?

The answer lies in the organization of the brain. The main cells of the brain are neurons (Palay & Palade 1955). The main function of neurons is to transmit information (Stevens & Zador 1995). Specifically, it is said that neurons transmit signals of all-or-nothing type: given a moment “x”, each neuron can be in two possible states: in the state of transmitting information, or in the state of not transmitting (Perkel & Nicoll 1993). Neurons, in other words, cannot transmit blurred messages. In practice, they are like traffic lights, with the difference that they only have two lights: green and red. One might wonder how a complex organ such as the brain can function through cells that have such a limited spectrum of activity. The answer to this question lies in the nature of the connections between neurons (Posner et al. 1997). I will explain this phenomenon with a metaphor. If we were told that we can only use two signals, say a green light and a red light, to write a book, or to explain to someone how to use a bicycle, we might at first think that this is an impossible task. However, the first distance communications were done this way, and the messages conveyed could be very complex. For example, the Morse code works with binary signaling (Petzold 2000). Morse code is a very ingenious example of how a binary system can transmit complex information. In Morse code there are only two types of signals: dot and line. If one wants to transmit a danger signal, one uses the specific sequence of the two signals:

- … — …

The brightness of this system lies in having a letter of the alphabet associated with each sequence of 3 symbols. In the case just quoted, S, O and again S. Using different combinations of points and lines one can create all the letters of the alphabet, and consequently all the words of the vocabulary and all the possible sentences of human language. Starting from a very simple binary system, any type of information can be transmitted. What counts is the sequence of signals, not the number of signals available. Now, the human brain contains about 86 million neurons (Herculano-Houzel 2009), organized into hyperconnected networks that largely outnumber the neurons. Despite a binary signal at the level of the neuron, with networks of this type an extraordinary amount of information can be created and transmitted (Posner et al. 1997). Human cognitive abilities, such as language and vision, but also the emotions we experience, are emerging systems that are based on the transmission of this binary information (Berntson & Cacioppo 2004). Our brain networks are organized so that certain areas are more active in completing certain activities, while other areas "prefer" other functions (Frackowiak et al. 2004). For example, the region near our nape, known as the occipital region, specializes in processing visual information (Hubel 1982). Some regions are specialized in language processing (Binder et al. 1997).

Historically, two key brain areas for language processing are identified: the Broca's area and the Wernicke's area (Dronkers & Baldo 2009). The names of these two areas originate from the names of the two neurologists who discovered them. The two areas were discovered in the nineteenth century, when modern neuroimaging techniques had not yet been invented (see Figure 3.1 for a left side view of the brain). At the time, the study of the localization of cognitive functions in the brain was based on the study of clinical cases (Lenneberg 1967). Specifically, the best tool that scientists had to understand the localization of brain function was autopsy. When a scientist found a patient with particular cognitive patterns, they followed them until their death and then studied their brain with an autopsy (MacCarthy & Warrington 2013). Using this technique, the French neurologist Paul Broca identified an area of the left temporal lobe which, when disrupted by a stroke or a different trauma, generated a linguistic impairment (Broca 1861).

The type of pathology associated with an injury to Broca's area is now known as Broca's aphasia. Patients with Broca's aphasia usually display very fragmented speech and cannot create complete sentences. On the contrary, they tend to speak using single words, and their productions lack nearly entirely the so-called "function words", the words that are necessary to have a grammar: articles, prepositions, pronouns, verbal and noun inflections, conjunctions and so on (Caramazza et al. 1981). One of the most frustrating aspects of Broca's aphasia is that patients are often aware of the condition in which they are living and realize that they are using fragmentary language. However, no matter how hard they try, it is impossible for them to find the words necessary to construct

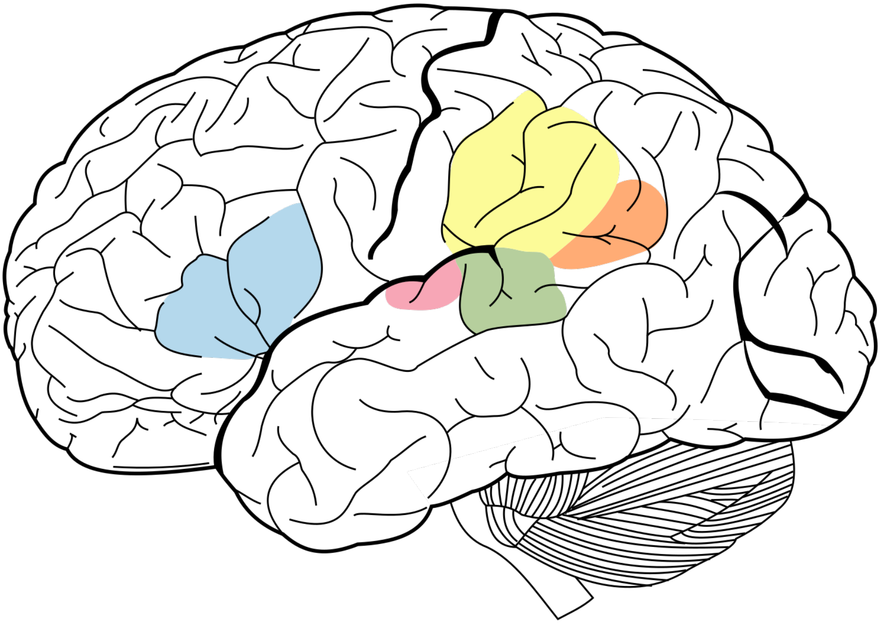

Figure 3.1: Left side view of the brain, main language areas in gray shades. (CC BY-SA 4.0, Wikimedia Commons original source: https://commons.wikimedia.org/w/index.php?title=File:Brain_Surface_Gyri.SVG& oldid=936053141)

sentences, and it is impossible for them to use grammar (Berndt & Caramazza 1980).

Wernicke's aphasia, discovered with similar methods by the German neurologist Carl Wernicke, presents itself with very different patterns (Wernicke 1881). Patients with Wernicke's aphasia are often called fluent aphasics because their speech is very fluid and fast (Danly et al. 1983). Wernicke's aphasics construct very long sentences, often rich in grammatical features such as verbal inflections, conjunctions, prepositions, and so on. However, the words used to construct sentences seem to be chosen at random or have rather weak semantic links to the topic of the discussion. In particular, the names and verbs used, the so-called content words, are not always semantically appropriate for the context (Blank et al. 2002). Below is an excerpt from the conversation of a fluent aphasic with his speech and language therapist (Sutton 2015):

Megan: Hi Byron, how are you?

Byron: I'm happy. Are you pretty? You look good.

Megan: What are you doing today?

Byron: We stayed with the water over here at the moment and talk with the people for them over there. They're diving for them at the moment, but they'll save in the moment held water very soon, for him, with luck, for him.

Megan: So we're on a cruise and we're about to get to…

Byron: We will sort right here and they'll save their hands right there for them.

Megan: And what were we just doing with the iPad?

Byron: Uhh… right at the moment they don't show a darn thing (laughs).

Megan: With the iPad, what were we doing? Like, here?

Byron: I'd like my change for me and change hands for me. It would be happy. I would talk with Donna sometimes. We're out with them. Other people are working with them and them. I'm very happy with them. This girl was very good, and happy. And I play golf and hit up trees. We play out with the hands. We save a lot of hands, on hold for peoples, for us. Other hands. I don't know what you get, but I talk with a lot of hands for him. Sometime. Am I talk of anymore to saying.

Megan: Alright, thank you very much!

Byron: Thank you very much, I appreciate it, and I hope the world lasts for you.

Megan: Thank you, it's been a pleasure. Bye bye!

Byron: Have a good day!

In the '90s of the last century, the development of imaging technologies, such as functional magnetic resonance imaging, allowed the study of the cerebral areas used in language in people with typical development (Price 2010). Neuroimaging studies in the healthy population have confirmed and refined our understanding of the relationship between language and the brain. The classic view proposes that the areas of Broca and Wernicke have fundamental roles respectively in the processing of syntax and in the processing of semantics (Tremblay & Dick 2016). However, it is becoming increasingly clear that many other brain regions are used for linguistic purposes (Stowe et al. 2005). Importantly, a recent study by a team of researchers at the University of California shows how the whole brain is actually activated when we look for the meaning of a word (Huth et al. 2016). As already mentioned, we know that each area tends to have a specialization of some kind: the occipital area is specialized for vision, the posterior part of the frontal area is specialized for movement (Sanes & Donoghue 2000). The limbic system, below the cortex, deals with emotions and long-term memory (Isaacson 1982). Now, the activation of words seems not only to draw on areas with linguistic specialization, such as the areas of Broca and Wernicke, but also on other specialized areas, such as motor, visual and emotion areas (Pulvermüller et al.

2005). This phenomenon suggests that the meaning of words is in fact a system distributed throughout the brain (Huth et al. 2016). For example, the phrase ”I love that t-shirt with stripes” will activate the areas of Broca and Wernicke, but also the occipital area, specialized in processing lines, and potentially also specialized areas in the processing of emotions, such as the amygdala, if the shirt is associated with some kind of memory, or in general with a feeling of pleasure. Meaning therefore does not appear as a system encapsulated in a specific area of the brain, but rather as a distributed system (Huth et al. 2016).

Similar conclusions can be drawn from electrophysiological studies. One of the cheapest and most effective ways to study cerebral activation consists in measuring the electrical activity that crosses the scalp. To measure this activity, researchers use a machine called electroencephalogram (EEG). In essence, the idea is to present subjects with linguistic stimuli and observe what happens in the electrophysiological components that are generated after the presentation of the stimuli. A system that has proved very effective over the years in getting large components is to present the subjects with sentences that contain violations. Sentences can contain violations of a phonological, syntactic, morphological, or semantic type. If we compare the components that are obtained with these different types of violations, we find that results are consistent with those obtained by studying aphasic patients and also with the results obtained with the functional magnetic resonance: The electroencephalogram has an excellent temporal resolution but not an excellent space resolution. We may thus start with talking about the temporal features of these components. Take the following sentences with violations:

- house the is on fire
- the children eats pudding
- the child drinks the chair

If we measure brain activity by anchoring the recording to the moment in which the violation is presented, what we get is that these three types of violations generate brain components with different timelines: The peak of the component obtained with the first sentence comes very quickly, within about 200 milliseconds; the peaks of the components obtained with the second and third sentences, come after a longer time, 300 to 500 milliseconds. This is already an interesting fact, because it shows that syntactic violations are noticed by our brain in a shorter time than the morphological and semantic ones. Phonological violations are even faster, and are noticed by our brain in around 100 milliseconds.

As I mentioned, the electroencephalogram does not have a good spatial resolution. However, it can still give us an indication about the lateralization of brain activity. While it cannot tell exactly where components are generated, it can tell if they are generated in the left hemisphere or in the right hemisphere, and even if they are anterior or posterior. The syntactic violations and morphological violations generate a component that is located in the left frontal region. Semantic violations generate a component that appears more distributed, and can affect frontal and occipital regions, as well as both hemispheres. As you will notice, these results are in line with those obtained with magnetic resonance imaging and with the study of aphasic patients: while grammar, that is, syntax and morphology, seems to be localized in the left hemisphere, semantics seem to have a more distributed nature.

It is interesting to note that, despite this distribution of meaning, other aspects of language seem to be relatively localized (Zaccarella & Friederici 2015, Friederici 2020). Injuries in Broca's area show *dissociated* deficits of the syntactic system (see Caramazza et al. 1981, for a classic analysis, and Pracar et al. 2025, for a state-of-the-art discussion). Patients with injuries in Broca's area are able to choose semantically appropriate words for the context and are able to articulate them. However, they are not able to combine words to form sentences and display severe deficits in the use of grammar (Caramazza et al. 1981). These patients have deficits limited to syntax, while the other linguistic domains - semantics, pragmatics and phonology - appear intact. In other words, it is becoming clear that while some aspects of language are distributed in different parts of the brain, for example the meaning of words, other appear more localized, for example core grammatical rules (Zurif et al. 1993). One crucial contribution to the debate on the domain-specificity of brain circuitry is provided by a study of Zaccarella & Friederici 2015. In this experiment, participants were presented with minimal sequences of two words while being scanned in an fMRI machine. The pairs of words could be of three kinds: two words that cannot form a unit, such as for example two nouns (dog grass); two words where one is replaced by noise or by a nonsense sequence of sounds (the xxx); two words that can form a unit (yellow bricks). The results showed that while all stimuli activated at large circuitry that is related to language processing, only the third kind activated one specific small subsection of this circuitry. The authors suggest that this cluster of neurons might be specialized for the processing of the so-called "merge" operation, the combination of two linguistic units into a larger unit. The authors suggest that this cluster of neurons is an example of a section of the brain that is domain-specific for language.

Clearly, these findings are not a common outcome in the study of brain areas. While brain areas have "a preference" for certain tasks, they are rarely strictly domain-specific for a certain task. "Language" areas are no exception, and their involvement is demonstrated to occur also in the processing of nonlinguistic stimuli.[1] Given these considerations, one can expect some cascaded effects on language even when traumas regard areas that are not necessarily specialized for language. Mike, the patient I mentioned at the beginning of the chapter, had a trauma that mainly affected the motor area of the right hemisphere. His language appeared intact, but, in all likelihood, if we had tested his ability to understand movement verbs, we would have observed delays or errors if his performance had been compared to that of people of his age but that had not suffered a brain injury. A study conducted between Cambridge, Stockholm and Helsinki, for example, has shown that the processing of motion verbs can be influenced when stimulating the motor cortex using transcranial magnetic stimulation, a technique that interferes with normal brain functioning (Pulvermüller et al. 2005). In patients who have suffered a trauma, however, there may be compensating strategies that make the phenomenon weaker.

As emergentist scientists notice, it should be stressed that the two main kinds of aphasia reported are umbrella terms, and that traumas are unlikely to affect in a purely dissociated manner a specialized circuit, despite the fact that specialized circuits exist (Kean 1977)[2]. Traumas more often spread in different areas, and affect various aspects of cognition, and various aspects of language as well (Blennow et al. 2016). In other words, despite the classic distinction between Broca's and Wernicke's aphasia, patients often present with peculiar symptoms that seem to either encompass both definitions, or that seem to deviate from these definitions. For example, a few years ago Dr Vitor Zimmerer, from UCL, reported a curious clinical case of a patient who could understand passive voice sentences but could not understand active voice sentences (Zimmerer et al. 2014). This pattern is surprising, because it is well known that passive voice sentences are more

[1] This idea will be developed in the chapter on music and mathematics, where I will present studies that address directly the question of whether these skills rely on a cognitive substratum that is shared with language or not. The analysis will regard both the levels of representations (more abstract) and the level of implementation in the brain.

[2] This is true for language neurodiversity, but it is also true for neurodiversity that affects other aspects of cognition. As it will be discussed in the chapter on mathematics and music, there is substantial evidence showing that several circuits are shared between different cognitive skills, possibly even in their core properties. As such, a stroke affecting an area that is primarily devoted to language may affect the processing of music and mathematics as well. It is not surprising, in this sense, that the prevalence of co-morbidity of issues in language and mathematics is quite high.

complex than active sentences, and extensive evidence shows that patients with Broca's aphasia struggle with passive sentences[3]. In preliminary testing, the patient was presented with pairs of pictures of the kind below (Figure 3.2) and was then presented with active and passive sentences relating to the picture (Zimmerer et al. 2014).

Examples of stimuli pictures for these stimuli could be:

A. The doctor paints the soldier

B. The soldier is painted by the doctor

In both cases the correct picture to indicate is the second picture, but it is well attested that patients with Broca's aphasia present considerably bigger difficulties in choosing the picture when they are presented with sentence B. More specifically, while they can quickly point to the right picture when presented with sentence A, they answer more randomly when presented with sentence B. Similar results are obtained with typically developing young children (Sinclair et al. 1971, Armon-Lotem et al. 2016), and even typically developing adults are shown to be slightly slower in condition B when compared to condition A, despite being accurate in both conditions. Clearly, condition B is syntactically more complex than condition A, since the order of words in passives is non-canonical.

The patient described by Zimmerer, contrary to what is normally found in aphasics (Garraffa & Grillo 2008), performed exactly in the opposite way, answering correctly when presented with sentences such as B, and answering randomly when presented with sentences such as A. The pattern was indeed very surprising. The explanation for this unusual pattern arrived once the researchers developed a new version of the task, in which a third element was included (Zimmerer et al. 2014).

In the second experiment the researchers created pictures as the one presented above and then created sentences of various kinds (Figure 3.3). The crucial kind of sentence they included this time is the active sentence presented at the letter below:

C. The woman washes the car by the man

The correct picture to choose when hearing sentence C is clearly the one on top, where the woman is the agent of the action of washing, and the car is in the

[3]The patient studied by Zimmerer was diagnosed with primary progressive aphasia, a pathology caused by a general ageing of the brain, that manifests in patterns overlapping with Broca's aphasia when the decay affects Broca's area (Gorno-Tempini et al. 2011).

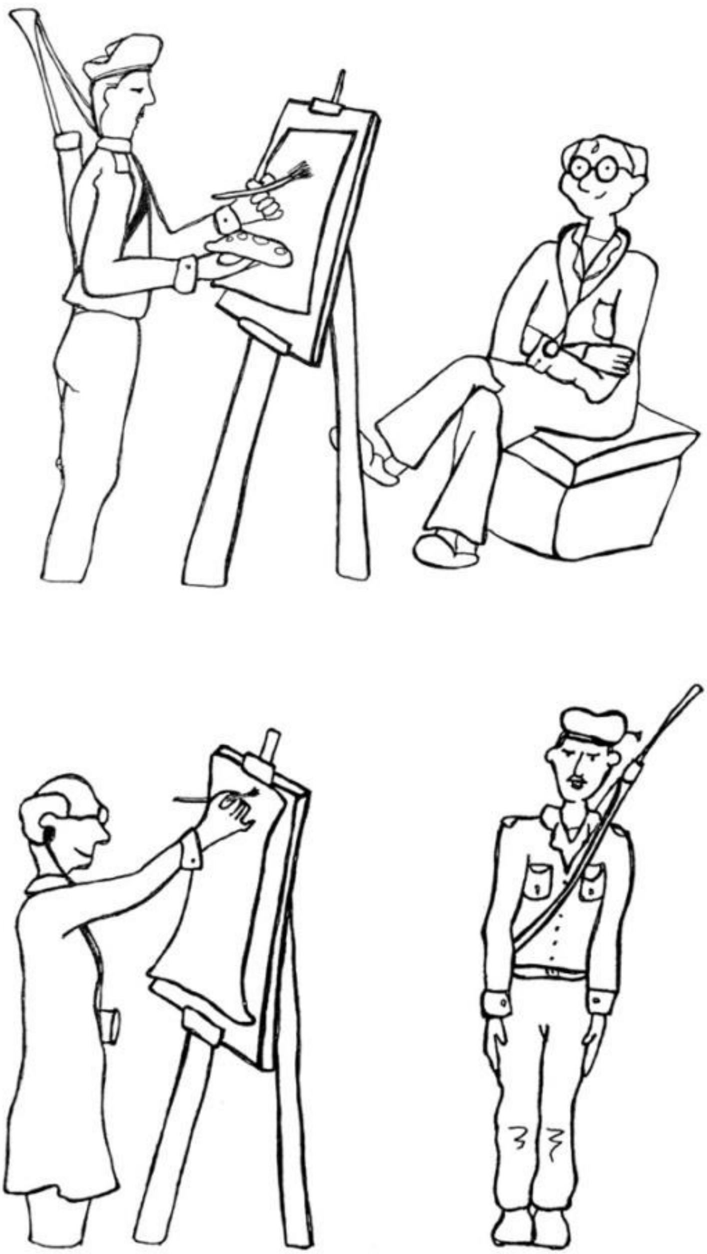

Figure 3.2: Pictures with reversed theta roles for syntactic testing. Picture from the BAMBI test.(copyright: Friedmann, N., & Novogrodsky, R. 2002. BAMBI: Battery for assessment of syntactic abilities in children. Tel Aviv: Tel Aviv University)

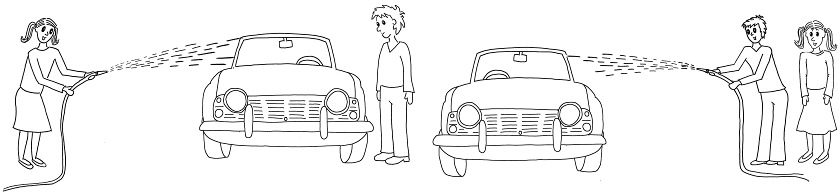

Figure 3.3: Pictures for by-phrase testing. (Picture owned by Prof. Vitor Zimmerer, permission to use granted by the owner in written form).

proximity of the man. When presented with a sentence such as C, the patient was shown instead to consistently choose the wrong answer, which is the picture at the bottom (Zimmerer et al. 2014). This pattern was different from the previous one with the doctor and the soldier, where the patient would choose *randomly* when presented with an active sentence. In this second task, the choice of the patient was not random: the choice was consistently wrong. Why was the patient choosing the picture at the bottom? The answer lies in his interpretation of the particle *by*, which is ambiguous in English: in English, the particle *by* may in fact indicate the agent of a passive verb, or the physical proximity of a noun (Manzini 2017). The patient was interpreting *by* as a flag of the agent and was thus always assuming that whatever was following the particle *by* was the individual carrying out the action (Zimmerer et al. 2014). This is also the reason why the subject was successful in passive sentences but not in active sentences in the previous example (with the doctor and the soldier): He was not building the syntactic structure of any of the sentences, but he was instead interpreting the thematic roles with a flat rule: "whatever is next to *by* is the agent". The rest of the structure was unfortunately lost, and so the meaning of active sentences, despite relying on simpler syntax, was a mystery to him, while the comprehension of passives was spared. Studies on patients with aphasia are a window into linguistic processing and have occupied a crucial role in the discussion on the domain-specificity of language (Bates 1993). Findings such as those presented here have led some researchers to assume that linear structure is more important than usually believed when processing language (Varley & Siegal 2000), and some researchers have actively explored this possibility:

Analyzing the frequency of sentences (rather than words) in large collections of human speech, researchers have discovered that we very often tend to use sentences that are quite similar to each other (Wood 2015). This fact leads to a question: What if those frequent sentences were stored in our memory? And what if most of what we said was nothing but a subtle variation on these stored entries? Some studies with EEG and fMRI point in this direction: Bhattasali et al. 2019 used fMRI while participants read *The Little Prince*, and they found that highly likely word sequences (so-called collocations) triggered less activation in the left hemisphere than less likely word sequences, suggesting that the brain retrieves familiar sequences from memory rather than actively building a syntactic structure for them. Molinaro & Carreiras 2010 used EEG to measure brain responses to varying degrees of semantic predictability. They found that the less likely a sequence, the larger the N400 component (the component typically obtained with semantic violations), indicating increased processing effort for unexpected combinations. Lau et al. 2016 also used EEG in a priming task and showed that likely word pairs (e.g., "salt and pepper") led to weaker N400 responses, particularly in the left hemisphere, compared to unlikely pairs (e.g., "fuel and pepper"), reinforcing the idea that expected word sequences are processed more efficiently.

The idea that word sequences may be stored (see Wood 2015, among others) intrigues some researchers and baffles others. On the one hand, researchers that see language as a system emerging from general cognitive skills – shaped uniquely by input (for example, proponents of the usage-based grammar) – see ideas like this one fairly compatible with their explanation of language in both patients and the typical population (Zimmerer et al. 2016). On the other hand, researchers that see language as system emerging from domain-specific skills, and more precisely a system that depends on a combinatorial skill that lies at the foundation of syntax (most linguists in the generative tradition) discard this idea and find the pattern observed by patients such as the one described by Zimmerer et al. 2014 simply as cases lacking this combinatorial skill, with no damage for the overall theory of language being grounded in syntax (Grillo 2008). In other words, many linguists see the ability to combine words as the main property of language and find perplexing the idea of syntax being a storage of sentences rather than a system of rules devised to put words together (Chomsky 2014, Jackendoff 2002). Whether or not the data from patients such as the one described by Zimmerer et al. 2014 should be considered evidence for flat processing of language, it remains important (and fascinating) to see how linguistic behavior can vary when different parts of the brain are impaired.

In conclusion, traumas in the brain can have important effects on our ability to produce and understand language. Due to its very physical nature, malfunctioning of the brain is unlikely to affect isolated circuitry, and so disorders often span across different domains of language and also across different domains of cognition (Siegel et al. 2016, Blennow et al. 2016). Nonetheless, the existence of dissociated clinical cases confirms the existence of relative dissociated implementations (Caramazza et al. 1981), and many recurring patterns can be expected in patients with strokes. As Fedorenko et al. (2012, page 2059) explain:

> "In 1861, Paul Broca stood up before the Anthropological Society of Paris and announced that the left frontal lobe was the seat of speech. Ever since, Broca's eponymous brain region has served as a primary battleground for one of the central debates in the science of the mind and brain: Is human cognition produced by highly specialized brain regions, each conducting a specific mental process, or instead by more general-purpose brain mechanisms, each broadly engaged in a wide range of cognitive tasks?"

After one-hundred and fifty years the answer to this question is still evasive, to some extent. Certainly, a great amount of linguistic processing is performed through general cognition (Tomasello 2009). Pattern recognition (Chou & Juang 2003), memory (Ellis 2001, Gathercole & Baddeley 1993), acoustic processing (Obrig et al. 2010) all play a role in language. While all scientists agree that domain-general skills are necessary for language (Saffran & Thiessen 2007), they disagree as to whether this is all that is needed (Ambridge & Lieven 2011, Tomasello 2009). Studies on patients are still illuminating in this sense. Double dissociations, the methodological foundation of cognitive neuroscience (Caramazza 1990), are still found, observed, and discussed, and they still offer a window into our mind. While studies of patients and of the brain in action in healthy individuals do not support domain-specificity of semantics nor pragmatics (Huth et al. 2016), syntactic dissociations are observed in both patients and health individuals, and this suggests that there are networks that may be domain-specific for syntax (Caramazza et al. 1981, Zaccarella & Friederici 2015). The relevant issue for the topic of this book is whether there are networks in the brain that respond solely to linguistic syntax, thus showing domain-specific processing. This quote from Campbell and Tyler (2018, page 132), historically critical of the concept of syntactic dissociation, gives a sense of where recent evidence seems to point:

> While we have long argued that syntactic processing does not occur in isolation but is processed in parallel with semantics and pragmatics — functions of the wider language system — our recent work makes a strong case for the domain-specificity of the frontotemporal syntax system and its autonomy from domain-general networks.

Reviewing a large body of literature, the authors conclude that (linguistic) syntax does rely on a circuit of the brain that is domain-specific, since it activates significantly more in tasks that tap specifically into syntax, and it does not respond to any other kind of stimulus (Campbell & Tyler 2018). This area roughly corresponds to Broca's area, though the authors insist that we should abandon a topographic approach to the brain, but rather look at networks (on many occasions, a network spans into different areas, and several networks can occur within the same area). They also demonstrate that domain-general skills are constantly used when processing language, and that semantics and pragmatics do not rely on domain-specific skills. Domain-specific activation for syntax is obtained when using stimuli that isolate syntax, that is, when tasks do not require participants to perform semantic or pragmatic judgments of the stimuli.

As I will discuss in the next half of the book, for this and other reasons, syntax appears as a crucial component of language, and the idea that syntax is the computational core of language will be put under scrutiny. The facts that aphasia can affect syntax in a dissociated manner and that some evidence points to domain-specificity of some circuitry does not lead to an automatic description of syntax as a biologically founded skill, though it does suggest that domain-specific circuitry devoted to syntax may exist[4].

3.2 Reading as a window into neuronal recycling

Reading difficulties (dyslexias) are one of the most common issues during language development, affecting more than five per cent of the population (Snowling 1987, Hulme & Snowling 2013)[5]. Several studies show that reading impairments are not a monolithic concept, and subdomains of reading can be affected

[4]Here I am touching upon one of the core ideas of the book. The fact that certain parts of the brain display domain- specific behavior for language does not imply that those areas are biologically endowed for language (they might be, but the "simple" existence of these areas is not a proof of it). This claim is counterintuitive because we naturally see language as an adaptive skill, and one of the fundamental competences of our species. In the next section of this chapter, when talking about reading, I explain how a phenomenon known as neuronal recycling can lead to the illusion of a biological foundation of a skill. In the chapter on music and mathematics I will discuss the potential domain- general foundation of syntax, and in the chapter on evolution I will present theories that see syntax as an adaptive skill and theories that only see it as a consequence of other adaptive skills.

[5]According to some studies a similar prevalence is also reached by Developmental Language Disorder (previously known as Specific Language Impairment). DLD is a disorder affecting language development that cannot be explained by any (obvious) deficit external to language. The profiles of children with dyslexia and children with DLD are shown to overlap to some extent, with some studies reporting that half children in each group meet the criteria for a

in different ways. While this approach to reading difficulties traces back to the sixties (Myklebust 1965), one of the most refined views on these subdomains is offered today by the work of Naama Friedmann (Friedmann & Coltheart 2018). One of Friedmann's major contributions is having better understood the many different ways dyslexia can manifest itself. More precisely, Friedmann's studies have shown that different types of dyslexia can manifest themselves *dissociated* in different children. This means that while a child may have problems with certain types of words or structures, another child may have problems with very different words or structures, even though both fall into the diagnostic criteria of dyslexia (Friedmann & Coltheart 2018). To understand the nature of some of these types of dyslexia it is necessary to make a small digression on how reading works.

Reading is a process that presents differences in relation to the spelling of the language used (Dehaene 2010, Vellutino et al. 2004). Some languages have a spelling system that is termed *shallow*, or transparent, others have systems that are termed *opaque* and others have intermediate systems (Dehaene et al. 2005). Italian, Spanish, Czech and German are examples of transparent systems (Serrano & Defior 2008, Cilibrasi & Tsimpli 2020a). In transparent systems the sounds of words can be accurately predicted by the sequence of graphic symbols that define them. Firstly, transparent systems tend to have a very regular relationship between a single symbol and a single sound. For example, in Italian the p symbol is pronounced roughly the same way, independently of the word in which it is found. Some symbols are more irregular, but their sound can still be predicted with rules. The symbol c is an example. The c symbol is pronounced differently depending on the symbols that come after. The most concise way of representing this rule is as follows: c is pronounced /tʃ/ when it is immediately followed by "i" or "e"; is pronounced /k/ in all other cases. Different rules apply if c is preceded by s. So, ciao is pronounced /tʃao/, while Coca Cola is pronounced /kɔkakɔla/. English, in some ways, is not very different from Italian. The k symbol, for example, is always pronounced in (pretty much) the same way. The symbol c, as in Italian, can be pronounced /k/ o /tʃ/. However, there is an important difference between

diagnosis in the other disorder (McArthur et al. 2000). While this chapter mainly focuses on the reading difficulties of children with dyslexia, it is important to mention that several studies have shown that children with dyslexia may also experience difficulties with syntactic and morphosyntactic (spoken) comprehension (Cantiani et al. 2013, Delage & Durrleman 2018). While this kind of neurodiversity is extremely important in the study of child development, I decided to focus on dyslexia in this book because the proposal I make about the ontogeny of domain-specific cognition is tied to the hypothesis of neuronal recycling made for reading. As such, it seemed important for me to offer a thorough description of reading neurodiversity.

English and Italian. In English, the sound of the symbol c cannot be predicted by the symbols surrounding it. Take the following example:

- "The choir doesn't like anchovies"

which translates into the international phonetic alphabet to:

- / ðə kwaɪə dʌznt laɪk æntʃəviz /

As one can notice, the string of symbols cho is pronounced differently in the word choir and in the word anchovies. The symbol c has two distinct sounds in the two words: choir, is pronounced /kwaɪə/, and anchovies, is pronounced /æntʃəviz/. In this case, unlike Italian, it is impossible to make a prediction about the pronunciation of the words if one does not know these specific words. The only way for children (and adults) to read these words is to memorize them. English speakers are thus forced to memorize the string of graphemes (letters) and the whole string of sound associated with them. This bilateral connection is then associated with a meaning in the semantic system of the mind. Languages such as English are partially opaque and display a semi-regular mapping between graphemes and phonemes (Cao et al. 2015). While the sound of words can be predicted in many cases with precise rules, in many other cases the only way to read a word is to have it recorded in long-term declarative memory.

Some languages, of which the most widespread example is Mandarin Chinese, have an orthography that is almost completely opaque (Chen et al. 1995). Chinese ideograms are a writing system that represents the meaning of words, but not their sound (and in the few cases in which sound is represented, inconsistencies abound). Thus, the only way that Chinese children (and adults) can learn to read is to memorize the symbols, their meaning and the sound associated with the graphic and semantic bundle. The existence of these different spelling systems is useful for us to introduce a very famous model that describes how humans read. The model was developed by an Australian psycholinguist called Max Coltheart and his collaborators (Coltheart et al. 2001). The model, in short, proposes the existence of two ways of decoding graphic signs, two paths that are parallel and complementary. The first path is defined as the grapheme-phoneme conversion route. This part of the system simply transforms the graphic symbols – or short sequences of them, like /k/, /t/, /s/ etc – into sounds. Languages such as Italian or Czech make heavy use of this route, because in principle all words (except for loans from other languages, such as chauffeur) can be read using this system (Proverbio et al. 2004). The second path is defined as the lexical-semantic route

(Humphreys & Evett 1985). In this route the sound of whole words is recorded, together with the sequence of symbols that are necessary to write the words and its meaning. Languages like Chinese make massive use of this route, because this is the only way to represent words – though sub-lexical units do exist and provide some cues about pronunciation (Bi et al. 2007). Languages like English are in between the two extremes, so in these languages it is usually necessary to use both routes (Coltheart et al. 2001). Although, in principle, languages such as Italian or Czech do not require the use of the lexical-semantic route, there is good evidence to argue that even speakers of Italian and Czech make some use of this route when they read in their language (Humphreys & Evett 1985). For example, frequent words are read faster, whatever the speaker's language is. This means that, for those words, decoding does not take place grapheme by grapheme, but a bundle of sounds, symbols and meaning is being drawn from the long-term declarative memory (Hanley et al. 2002).

The reading system can be compromised, and children (but also adults) may have reading difficulties of various types. Through a number of studies, researchers have shown how both routes can be compromised (Ziegler et al. 2008). Data shows that the pathways can be compromised in a *dissociated* or *associated* manner (Zoccolotti & Friedmann 2010). This means that some children may show signs of a problem with only one of the two routes, while other children may show signs of a problem in both routes (Zoccolotti & Friedmann 2010). A deficit of one of the two routes can have very different effects depending on the language of the child and the type of spelling that the child must use (Landerl et al. 1997). For a Chinese child, for example, an issue with the lexical-semantic route can have detrimental effects on their ability to read (Weekes & Chen 1999, Ho et al. 2007). At the same time, an issue with the grapheme-phoneme conversion route could go relatively undetected throughout their life (Ho et al. 2007). The opposite is true for an Italian or a Czech child. An issue with the grapheme-phoneme conversion route leads to an obvious delay in the acquisition of reading skills, and it will be necessary to implement strategies so that the child can use the other route to learn to read. An issue dissociated to the semantic-lexical path, however, could remain silent until the child begins to read fluently. At that point, an issue with the lexical route will lead the child to read more slowly than their peers, because they will always need to decode the graphemes and phonemes with the other route (Tilanus et al. 2013).

An issue with the lexical pathway is at the foundation of what is called surface dyslexia (Frith 2017, Friedmann & Coltheart 2018); an issue with the grapheme-phoneme conversion route is, instead, at the foundation of what is called phonological dyslexia (Lyon et al. 2003, Cantiani et al. 2013). In English children, both types of dyslexia can have a very large impact on reading skills, and this makes the situation in English speaking countries quite complex. These two kinds of dyslexia cover the majority of individuals with reading difficulties (Wybrow & Hanley 2015). However, these linguistic-based explanations are complemented by explanations that are less domain-specific and manage to better describe a subgroup of children with reading difficulties that do not necessarily show a linguistic deficit (Ramus 2003). For example, Prof. Stein and his collaborators, at the University of Oxford, have demonstrated that some children with dyslexia have difficulties in reading because of an impairment in their visual (rather than linguistic) processing, the so-called magnocellular path (Stein 2001). For these children, non-linguistic remediation approaches may be the key. The team of Prof. Facoetti, at the University of Padua, is developing action videogames that are shown to improve the reading skills of children with this kind of dyslexia by increasing their spatial attention abilities (Franceschini et al. 2012, Franceschini et al. 2013).

In addition, many children with dyslexia display difficulties in other linguistic subdomains, particularly with syntactic and morphological processing (Cantiani et al. 2013, Friedmann & Coltheart 2018. While early accounts have discussed how (morpho)syntactic problems can arise from phonological problems (Kelly 1992), recent experimental work conducted on children with dyslexia suggests that some morpho(syntactic) difficulties may be independent. An interesting property of French can help disambiguate phonological from (morpho)syntactic difficulties: In a study conducted between France and Switzerland (Delage & Durrleman 2018), primary school children with dyslexia were shown to display difficulties with object clitics but not with homophonous determiners, with results that are comparable to those of children with DLD. In this experiment, children were presented with scenarios where either clitics or determiners were elicited. For instance, in the clitic condition children were presented with the picture of a man washing his car, and they were then asked the following question: "what does the man do to his car". In French, the answer to this question requires the use of an object clitic (underlined in the example): "Il la lave" (he is washing it). While French is an SVO language, in this specific context objects appear before the verb, making object clitics a rather challenging type of structure from the syntactic point of view. This study showed that children with dyslexia experience difficulties with this kind of clitics, but they do not experience difficulties with determiners, even when the determiners elicited are phonologically identical. For instance, when presented with a similar picture, if they are asked the question "what is the man washing?", children answer "la voiture" ("the car"), without struggling with the determiner "la". This finding indicates that dyslexic children's difficulties cannot be explained recurring to phonology alone (phonologically speaking these targets are identical), but they must be explained recurring to syntax.

As mentioned, neuroimaging studies show that all human beings use the same region of the brain to read, independently of the script used (Dehaene & Dehaene-Lambertz 2016). This region has been named the Visual Word Form Area, since it responds selectively to written words. The existence of such an area is useful to extend our discussion of domain specificity, and it offers us a chance to discuss brain implementation and some aspects related to evolution[6]. First, it appears that this area is specialized for written words, suggesting that some circuitry of our brain is domain-specific for reading. This finding is surprising for a number of reasons. First of all, reading is not a defining trait of our species. The first scripts were invented approximately 5000 years ago, in the Middle East. 5000 years is a short time in evolutionary terms, and no one can argue that there is any biological foundation "for" reading. Simply, the time is too short to make such a claim. The natural prediction given the fact that reading is a relatively recent invention, is to expect reading to rely uniquely on domain-general components of our cognition. The fact that a region of the brain is specialized for reading scripts goes against this intuition and requires an explanation.

Dehaene 2010 attempted to give one: the VWFA is a region of the brain that developed, during evolition, with a different purpose. For instance, it may be the case that the a certain circuitry accidentally emerged in some individuals and revealed a capability of recognizing abstract shapes, a skill that became adaptive among our ancestors. Such circuitry would then become prevalent through the typical steps of natural selection. When scripts were invented, then, it proved useful for the task, and, naturally, our brain ended up using it to read. When children are exposed to scripts during development, this area naturally takes the job of decoding those symbols, because it is capable of doing so. Receiving inputs from the visual cortex and from language areas, the VWFA is topographically in an excellent location to perform a task such as reading.

This phenomenon of reuse has been described with the term neuronal recycling (Hernandez et al. 2019). If this theory is correct, it is worth trying to refine what the role of the area was before it was allocated to reading. This question can

[6]Here I use reading and the visual word form area to explain the concept of neuronal recycling, and to explain how a skill can have a domain-specific brain implementation and yet not be the consequence of natural selection during evolution. For a discussion on the evolution of language, and how the current reflection applies to language as a whole, see the chapter on language and evolution.

be addressed by investigating our evolutionary cousins, the other primates. Studies on macaques (Popovkina et al. 2019) show that this area does exist in other primates and is used to recognize abstract shapes (like triangles, squares, circles and combinations of them). Interestingly, the area seems to respond differently when the shapes are filled and when only the contour is provided (Popovkina et al. 2019). To give a sense of the phylogenetic timing of these developments, if we assume that the substrate for what we now call the visual word form area existed at least with the beginning of Homo sapiens, we can say that the area existed for at least 200000 years, while scripts were invented only 5000 years ago. However, since a homologue of this area is observed also in other primates, there is a very good chance that this area has existed in our brains at least before the split from the other old-world monkeys (baboons, macaques and vervets). In Figure 3.4, below, one may see that this split happened approximately 30 million years ago[7].

The existence of an area such the VWFA, that now appears specialized for reading (and not for shapes in general) has implications regarding our discussion on the domain-specificity of language. First, the existence of such an area shows that the domain-specificity of a brain network does not entail that that the behavioral skill relying on it has a biological foundation or an evolutionary foundation. Reading relies on a domain-specific network, though it certainly did not evolve because of natural selection, and it does not have a biological foundation.

One additional piece of evidence we can look for regards the use of this area in children that have not learned to read yet. A study by Saygin et al. 2016 investigated this issue using a longitudinal design. In the first step of this project, a group of 5-year-old children with no training in reading where tested and measured using functional and diffusion imaging. In the experimental session, while in the scanner, children were presented with faces, fonts and artificial (non-existing) pseudo-fonts. The experiment showed that at age 5 children's Visual Word Form Area did not distinguish between these stimuli, and similar activation was obtained in all conditions. Children were then tested again at age 8, once they had learned to read. At that time, the visual word form area did differentiate between conditions, showing a stronger activation for English letters (as observed in English adults). These findings are consistent with the so-called connectivity hypothesis: the VWFA specializes for reading because of its properties, particularly in terms of connectivity. It is in a particular location that makes it

[7] On the other hand, the common ancestor we share with chimpanzees lived much more recently, at a time estimated around 7 million years ago. The few fossil remains of this animal are object of a scientific debate, and the species is known with the rather unimaginative name of Chimpanzee-Human Last Common Ancestor (McGrew 2010).

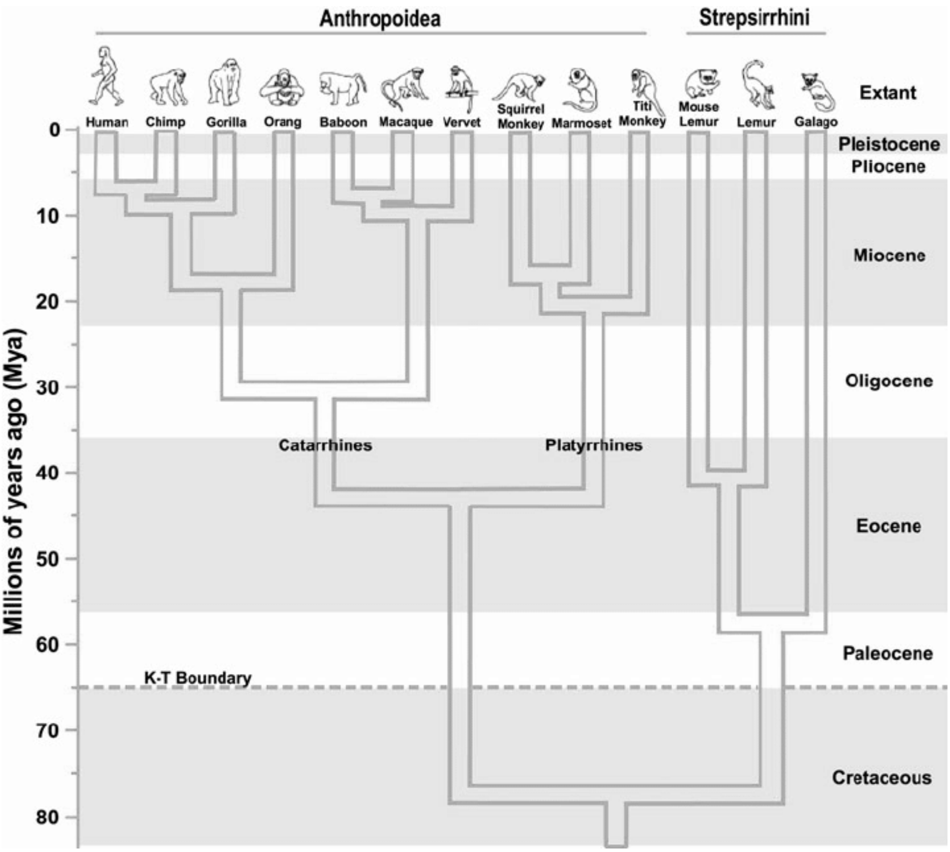

Figure 3.4: Phylogenesis of the major primate groups. (CC BY Steiper & Young 2006, original source: https://doi.org/10.1016/j.ympev.2006.05.021)

"qualified" for that specific job, once the reading stimuli (scripts) are presented and the system used to decode these stimuli is being learned.

The studies focusing on the VWFA in non-human primates and in children that have not yet learned to read bear very important implications for the debate on the domain-specificity of language. These results demonstrate that, even if we proved that language relies on domain-specific circuitry of the brain, this would not entail that language has a biological foundation, nor that it evolved through natural selection. Reading relies on domain-specific circuitry of the brain, but it does not have a biological foundation, and it did not evolve through natural selection.

Similar reflections may be applied to spoken language. Children produce the first words around twelve months (Guasti 2017, Ambridge & Lieven 2011, Tomasello 2009), and they start producing the first multi-word utterances around twenty-four months (Guasti 2017, Ambridge & Lieven 2011, Tomasello 2009). According to the biolinguistic view, this regular timeline observed across cultures indicates that syntax is innate and biologically determined, in the sense that it develops "naturally" if the child is exposed to a standard environment (Samuels 1998). The fact that some areas of the brain appear to be domain-specific for syntax has been used as evidence for the claim that brain specialization for syntax occurs because of a biological endowment (Hauser et al. 2002). This notion can, however, be criticized, because it assumes a one-to-one relationship between brain specialization and biological endowment (Karmiloff-Smith 1992). As I have shown in this chapter, the brain may display local specialization also for skills that are not bound to evolution, just because a certain subregion is built in a way and in a position that naturally can take that role (McCandliss et al. 2003, Karmiloff-Smith 2009). This idea is complex because it requires the combination of notions from reading, evolution, syntax and child development, and it will be presented in detail in the final discussion. For the moment, suffice it to say that the evidence for domain-specificity for syntax in sub-regions of Broca's area does not entail a biological endowment for syntax, nor does it entail that syntax per se is a consequence of evolution. [8]

[8] Similarly, the fact that neurodiversity can affect a domain of cognition in a dissociated fashion does not entail that that domain has a biological foundation nor that it evolved through the pressure of natural selection. A dissociated deficit of reading cannot be used to make this claim about reading as a skill, for example. This notion was analyzed in depth in the previous chapter, where I discussed acquired language pathology.

4 Computational core in other domains

The generative tradition has always given a privileged role to syntax, suggesting that the computational core of language consists in the ability to combine words following rules. This chapter reviews this idea and presents data suggesting that the computational properties at the foundation of language may also be found in the domains of music and mathematics. Music shares with language some fundamental properties: It is a rhythmic system, it uses hierarchical structures, and it partly relies on the same circuitry of the brain. Similar considerations apply to mathematics: Both language and mathematics are combinatorial, both rely on symbolism, and they appear to deploy similar regions of the brain. These facts are used to criticize the notion of a biological domain-specific foundation of language, since they suggest that these three skills (language, music and mathematics) rely on the same domain-general cognitive skills. Nonetheless, some properties of these skills seem to be isolated, and, as a consequence, some linguists argue against the existence of a "fully" shared system for language, music and mathematics. The strengths and weaknesses of both positions are presented, together with the impact that this debate has on the notions of domain-specificity and biological foundations of language.

4.1 Music

As it is widely known, the sounds of human languages are divided into two macro-categories: vowels and consonants (Ladefoged & Disner 2005). The main difference between vowels and consonants concerns articulation. In vowels, such as /a/, /o/ and /i/, there is no friction in the flow of air coming out of the mouth. The air flows without constraints; and the position of the lips and the tongue allow us to create different sounds, but the air is not blocked in its path. On the other hand, when we produce consonants, such as /t/, /f/ or /s/, the air is obstructed with various articulatory elements (Ladefoged & Disner 2005). The distribution of vowels and consonants in a given language is important. Certain languages have a relatively regular distribution of vowels and consonants, with vowels separated by a (relatively) consistent number of consonants in every occurrence of speech. These languages are called syllabic languages, since the relative consistency of the distance between vowels is due to the fact that syllables tend to have the same length, and thus what gives rhythm to the language is the regularity of its syllables (normally, the nucleus of a syllable is its vowel). Examples of this kind of languages are Italian, Spanish, Turkish or Korean. Other languages display larger variability in their syllable length, and thus syllabic structure does not offer a rhythm to that language (rhythm intended as the regular occurrence of an event over time). Most of these non-syllabic languages, however, are regular in a different regard[1]. In some of these languages, the distance between the stressed segments in a given occurrence of speech tends to be constant. Thus, while syllable length varies, the prosodic contour is rhythmic because stress peaks at a (relatively) regular rate. Examples of stress-timed languages are English, Thai or Russian.[2]. The distribution of consonants and vowels gives the languages different rhythmic properties. In English, sequences of fairly complex consonants are permitted (Roach 2009), sequences that do not appear in languages such as Italian or Spanish (McCrary et al. 2002, Tagliapietra et al. 2009). For example, in English this sentence is allowed:

- I asked for him already

This sentence contains a sequence of sounds that is quite difficult to articulate. We shall focus on the sequence of words asked + for, which is pronounced /asktfor/: here, the consonants s, k, t and f are pronounced in sequence. In Italian or Spanish, this type of sequences is not allowed (McCrary et al. 2002). The fact that there are many vowels to divide consonants in languages such as Spanish and Italian, is what may be giving them a musical feeling. Some languages, such as Czech or Russian, allow even more complex consonant sequences than English. According to some researchers, for example Guasti et al. (2018) and Thomson & Goswami 2008, the rhythmic properties, such as the distribution of consonants and vowels, as well as the stress within words, could have a parallel with the

[1]An interesting article of the Guardian published in 2014 by Matthew Jenkin discusses what makes languages more or less attractive to native English speakers. Some languages are often perceived as harsh (for example German), some are often perceived as melodic (Spanish and Italian, see Reiterer et al. 2020), some are often perceived as odd and unexpected (Chinese, see Deutscher 2010). What do these perceptions derive from? One element that seems to matter massively is the phonology of the language, its rhythmic properties, and particularly the distribution of vowels and consonants.

[2]It is worth stressing that “regular” has different meanings when talking about language and music. In music, a rhythm is regular when the beats are at exactly the same distance in time. In language, a rhythm is regular when the peaks (typically vowels or stress, depending on the type of language) occur at approximately the same distance in time.

rhythm that is observed in music. According to these researchers, there may be a relationship between the ability to understand musical rhythm and linguistic skills, and this may be especially true for reading skills (Guasti et al. 2018). Several studies suggest that children with the highest performance in rhythm tasks are also children who show better language and reading skills (Hallam 2010). The next section will review this evidence.

In a study by Huss et al. 2011, it was shown that there is a relation between the ability to perceive metrical structure (that is, rhythm, and particularly rise times in rhythm beats), phonological awareness and reading. According to the authors, this may be due to the fact that the acquisition of phonology may rely to some extent on basic auditory skills, which are also the foundation for the development of musical skills (Huss et al. 2011). Particularly, the authors suggest that a major role in this relationship may be played by the ability to perceive "rise time", the time that a beat takes to become sharp. The ability to identify this time accurately may be necessary to develop both a sense of rhythm in music and a refined sense of phonological categories. Interestingly, all children with reading difficulties in this study performed more poorly than the control group in the acoustic rhythm tasks, in line with the interpretation proposed.

In a different study, Guasti et al. (2018) showed that adults with dyslexia have difficulty completing a task in which they are asked to predict the beat of a certain regular rhythm. In this experiment the subjects listen to a sequence of sounds placed at a constant distance from each other, as in a sort of metronome. We can represent the sequence with this series of lines, placed at a constant distance from each other:

- _ _ _ ad libitum

Occasionally, and unpredictably, two sounds in the sequence – one after the other – have a different, higher pitch, as in the representation below. Note that the temporal distance of these sounds is still the same compared to the previous sounds.

- _ _ _ - - _ _ ad libitum

The first different sound acts as a signal. The subjects do not have to do anything, as they are instructed to click on the mouse at the second high sound. When participants hear the first high sound, they must therefore prepare to press the mouse, so that they can press it at the second high sound. While subjects with good reading skills do not have problems with this task, subjects with dyslexia struggle in clicking the mouse at the right time (Pagliarini 2016, Guasti et al. 2018). This finding suggests that the ability to predict impending stimuli, a fundamental feature in the perception of rhythm, could also be at the basis of reading skills. In a study with similar methods, Guasti decided to test subjects without dyslexia, but who had musical experience, to see if these would show particular patterns. When completing this task with musicians, the authors found that not everyone behaves in the same way: the type of music that participants play affects their ability to predict the beat of a certain regular rhythm (Guasti 2017). While classical musicians are quite accurate and click exactly at the beat, jazz musicians tend to press early. This suggests similar prediction skills in the two groups, but weaker inhibitory effects in jazz musicians: in fact, completing this task does not only require understanding the rhythm and distance between one beat and another, but it is also requires inhibiting the "desire" to press early once we realize that it is time to press. This desire to click is a rather natural phenomenon when the task is understood, and classical musicians seem to be better at inhibiting it than jazz musicians. Musicians' performance can help us understand children's performance: The same task, conducted by children with and without dyslexia, shows that children with typical development behave like jazz musicians: they show to be catching the rhythm and constantly press the button slightly before the beat (thus showing to understand the rhythm but to "lose" against inhibition). Children with dyslexia, on the other hand, constantly press the button after the beat, showing that it is not an inhibition problem that they are dealing with, but rather a problem in understanding the rhythm (Guasti et al. 2018). In order to be able to press at the right moment, one needs to internalize the distance between the beats and make a prediction on the next beats. Subjects with dyslexia seem to have difficulty formulating these predictions and therefore predicting the arrival of the target beat in the sequence.

Studies on the relationship between rhythm, phonology and reading are still ongoing and the connection between these skills is gradually being understood more precisely, but it is becoming clear that there is some kind of relationship between them. However, the parallelism between music and language could go beyond the role of rhythm in the two systems. Once we reflect on the nature of the musical notes, we may notice that there is a parallel with the nature of linguistic sounds. As previously mentioned, each language uses a limited number of phonemes, and the chosen phonemes differ from one language to the other. English, for example, uses about 40 phonemes – the exact number varying with linguistic varieties (Brooks et al. 2021). The repertoire includes pairs of phonemes that are identical but for one trait. For example, /p/ vs /b/ are identical, except for the voicing trait (Liberman et al. 1967). In the chapter on the potentially innate properties of phonology, I discussed at length the categorical formatting that humans make when dealing with phonological continua.

Now, crucially for the current discussion, the same reasoning applies to musical notes. The notes used in the West are twelve, namely: C, C sharp, D, D sharp, E, F, F sharp, G, G sharp, A, A sharp, B – or Do, Do diesis, Re, Re diesis, Mi, Fa, Fa diesis, Sol, Sol diesis, La, La diesis, Si, in Romance notation (Figure 4.1).

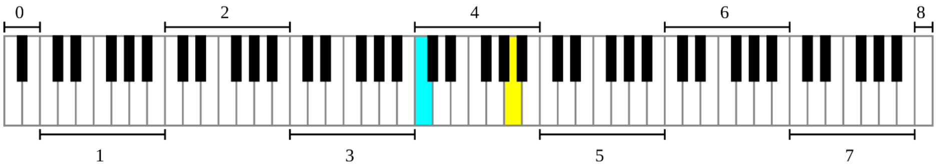

Figure 4.1: Section of a piano covering 3 octaves (12x3 notes). (CC BY-SA 3.0, Wikimedia Commons, original source: https://commons.wikimedia.org/w/index.php?title=File:Piano_Frequencies.svg& oldid=505597266)

After the B (Si), one encounters a C (Do) once again, this time higher than the previous one. But what makes us identify this new note as another instance of C, and not a completely different note? The answer lies in physics. From a physical standpoint, the two Cs have frequencies in a 2:1 ratio: one frequency is exactly two times the other (Johnston 2009). From a cognitive perspective, when we listen to them in sequence, we perceive them as the same note at two different heights: one lower, one higher. These notes are said to be an octave apart (Johnston 2009). If we listen to an entire melody played at two different octaves, we recognize it as the same melody, only transposed. This indicates that the internal organization of notes is replicated across octaves.

Within each octave, the space is typically divided into twelve equal parts, yielding the twelve notes of the chromatic scale. But why is the space of an octave divided into twelve slices? Why not 100, or 1000? After all, musical notes are nothing but frequencies (Levitin 1994; Johnston 2009), and in principle, we could create an infinite number of notes within an octave. Indeed, some musical techniques, like guitar string bending, involve gradually passing from one note to another, producing a continuous stream of pitches. Yet, in Western music, we consistently divide the octave into twelve equal parts, each representing a semitone (Johnston 2009). This structuring of a continuous acoustic space into discrete, repeatable units is reminiscent of what happens in spoken language. Although we could, in theory, produce an infinite number of speech sounds, we typically restrict ourselves to a finite inventory, a few dozen consonants and vowels per language (Bloomfield 1926). As in language, the way this perceptual space is sliced may appear arbitrary, yet cross-cultural similarities suggest that the division aligns with certain cognitive constraints. Importantly, however, there is one key difference between the structuring of sound in music and language: the musical system is not perceptually categorical in the same way: In language, non-canonical sounds are often normalized or go unnoticed, especially if the contrast is not relevant in a given language. In music, by contrast, we are acutely sensitive to deviations: a poorly tuned guitar or an unskilled singer are immediately perceived as unpleasant. This difference highlights how musical perception remains more closely tied to physical precision, while linguistic perception tends to be more abstract and flexible. In summary, both domains involve a formatting of a continuous perceptual and productive space (Harnad 2003). This formatting is not uniform across cultures: just as not all languages contrast /p/ and /b/, not all musical traditions divide the octave into semitones. For example, Indian classical music makes systematic use of quarter tones (Lentz 1961). Nonetheless, no known musical system dispenses with formatting entirely. The precise divisions may vary, but the principle of segmenting a continuum into meaningful units is universal (McPherson et al. 2020).

According to some scholars (for instance Jackendoff 2009) there is a third similarity between language and music, and it concerns structure. We have extensively discussed the theory according to which syntax may be the core property of language (Chomsky 2014)[3]. Now, according to some scholars, music makes use of the same property to create structure (Martins et al. 2017). In fact, the creation of melodies is based on the combination of notes, presented along a certain timeline. This process is not unlike the syntax we use to speak, in which sounds are combined to form words, and words are combined to form sentences (Chomsky 2014). A preliminary observation of the output suggests thus that the parallels between language and music go beyond phonology and also concern the creation of structure. A study by Maess et al. 2001 shows that musical syntax is also processed within regions of the brain "used" for language, a fact that would suggest a sharing of syntactic resources (Maess et al. 2001). In this study, a group of non-musician participants was presented with chord sequences in which one of them violates harmonic rules, and therefore sounds out of tune and unexpected (Tymoczko 2010). Conceptually, this type of violation corresponds to a syntactic violation in language (Maess et al. 2001), something that is obtained by concatenating sequences in which a word violates the rules of the syntax

[3]Importantly, we have also discussed its brain implementation. Particularly, we have discussed the brain implementation of the basic operation of merging in the chapter on language and the brain. This operation appears to have a domain-specific implementation, and, according to one view, this is the basic operation that is performed recursively to obtain syntax.

of the language used (Hahne & Friederici 1999). For example, take a sentence like: "House the is on fire". In this case, the article follows the noun, and therefore violates a fundamental rule of English. There is ample literature showing how these types of violations activate a left frontal region of the brain (Hahne & Friederici 1999, Steinhauer & Drury 2012), and generate a component known as ELAN[4] (Steinhauer & Drury 2012). The study conducted with musical violations has shown that these activate a very similar component (Maess et al. 2001), with the difference that this component is obtained both in the left hemisphere and in the right hemisphere. This finding has been replicated and further investigated in a study by Koelsch et al. 2013. As I mentioned, brain components elicited by long-distance dependency violations in syntax are seen as evidence for the use of syntactic hierarchies in language. In this ingenious study, Koelsch and colleagues modified known Bach pieces in order to produce long-distance musical violations. The components obtained in the tested subjects mirrored those obtained for linguistic violations, suggesting that a domain general network of the brain is (at least to some extent) responsible for both music and language.

In summary, music and language show numerous points of contact and similarities. In particular: (1) there seems to be a relationship between the understanding of rhythm and the ability to process written language and phonology; (2) both systems perform a formatting of the perceptual space (that is, create islands starting from a continuum) and (3) there seems to be a parallel in the combinatorial substrate of the two faculties. However, it is not clear whether these parallels are the consequence of the fact that both faculties depend on general cognitive systems, or whether the two faculties actually share a domain-specific substrate. In other words, it is not at all clear if the combinatorial property that seems to overlap in music and language is specific to these two skills, or if it is the consequence of a general skill of our cognitive system. There are actually 3 possible explanations of the combinatorial parallelism between music and language (Trainor 2008, Jackendoff 2009):

- There is a combinatorial system shared between language, music (and mathematics).
- There are 3 different separate combinatorial systems, one for music, one for language (and one for math).

[4]This component is discussed at length in the chapter on language and the brain. ELAN stands for Early Left Anterior Negativity, and it refers to the component obtained with major syntactic violations. This component appears to be spiking very rapidly, more quickly than components associated to morphosyntactic and semantic violations.

- There is no specialized system for combining symbols, but the ability to combine symbols results from the use of general properties of our cognitive system (such as memory and intelligence).

The second position is for example defended in recent work by Asaridou & McQueen 2013: Reviewing a large body of literature from neuroimaging and electrophysiological studies, the authors conclude that music and language must share some domain-general component of the brain. Linguistic and musical tasks activate similar regions of the brain, give rise to similar brain components, and training in one domain is shown to affect the other. A similar conclusion is reached by Koelsch et al. 2013. Nonetheless, studies focusing on the structures used in music and mathematics show that grammars across these domains can be rather different. Rohrmeier et al. 2015 analyzed structure building procedures across human syntax, music and animal vocalizations. Their conclusion is that, despite important similarities in the way units are combined (especially in music and language) important differences remain. For example, in human language, agreement is typically performed as a dependency among distant elements, and one element affects the other one with precise patterns. If I start a sentence with a singular noun, the verb attached to this noun will need to be inflected appropriately, whatever the distance between the two. For instance, see the following example: "The puffin, a kind of bird that lives across many islands of the Atlantic Ocean, is a beautiful animal.". The verb "is" must be used in its singular form, or the sentence would be ungrammatical. In music and animal communication we do not observe agreement of this kind. In music, a chord may entail the use of certain chords in the sequence that follows – for instance establishing the key to the piece – but this relationship is not comparable to the tight relationship between a subject and its verb.

We still do not know for sure which of these options is correct. Neuroscience may be the key to addressing this issue in the near future, and the spread of neuroimaging techniques may allow scientists to gradually answer this question. The actual picture may possibly conciliate assumptions that appear at first glance self-excluding. As Prof. Patel, from Tufts University, explains (Patel 2011: 24):

> There is growing evidence that either pitch-related or rhythm-related musical skills are related to phonemic abilities in language, such as the segmentation, categorization, or discrimination of phonemes. However, there is also evidence from neuropsychology that the auditory phonemic encoding of sounds can be selectively disrupted by brain damage, leaving the perception of musical sounds intact (i.e., in pure word deafness). Hence the

> relationship between musical and phonemic skills fits nicely into a resource-sharing framework, under the assumption that the end products of phonemic development are unique, but that some of the processes that give rise to these representations are shared by music and language.

In conclusion, music and language show numerous points of contact and similarities. In particular, there seems to be a relationship between the comprehension of rhythm and the ability to process written language, there is a parallel in the division of the perceptual space operated in both language and music, and there seems to be a parallel in the combinatorial systems of the two faculties. However, it is not clear whether these parallels are the consequence of the fact that both faculties depend on the same general cognitive systems, or whether the two faculties share a two-domain-specific substrate (Morley 2002). One possible explanation is that while the acquisition of music and language skills relies on shared circuitry in our brain, the end states reveal a substantial dissociation between the two abilities, with end skills appearing domain-specific. Nonetheless, research in these topics is ongoing; perhaps in the coming decades, a clearer answer to these questions will be found.

4.2 Mathematics

Mathematical structure is pervasive in nature. Plants, animals and rocks develop following mathematical principles, and the laws of physics can be described with mathematical formulas (Tegmark 2014). One elegant example of mathematical structure in nature is the Nautilus shell. If one looks at the section of the Nautilus shell, one can see that its growth follows a spiral shape (Landman & Cochran 2010). This spiral can be drawn following the trajectory outlined by the corners of a series of squares placed in continuous succession, one next to the other, with ever larger dimensions. The growth in size of these squares is not random but follows a precise trend, which can be predicted with a mathematical principle (Allen 2003). As one can see (Figure 4.2), if the first square has dimension one (regardless of what this value represents in millimeters) the second square will have a double dimension, or a dimension "two", and the third square will have a dimension "three". The fourth square, however, does not have a dimension four, but a dimension "five". Why is that the case?

The number five is obtained because the fourth square has as its side the sum of the sides of the previous squares, therefore the sum of 3 + 2; and in the same way the following square has, as side, the size of the two previous sides, or the

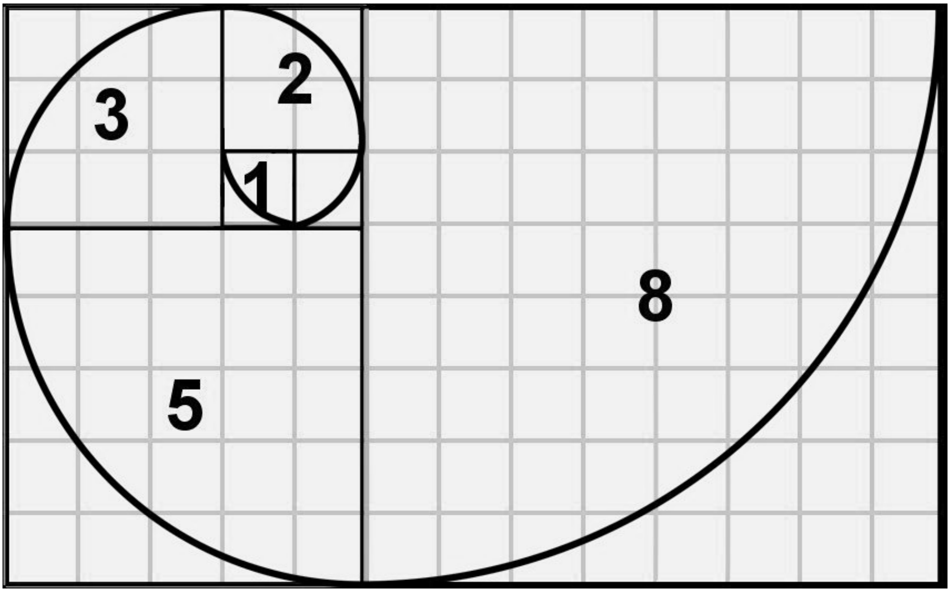

Figure 4.2: Fibonacci spiral. (CC BY-SA 4.0 Wikimedia Commons, original source: https://commons.wikimedia.org/w/index.php?title=File:Fibonacci_-Spiral.svg& oldid=776745260).

size "eight", being 8 the sum of the number 3 and the number 5. We then get to a square with a side 13, sum of 8 and 5, and then a square with a side 21, the sum of 13 and 8 (and so on). This sequence was first described by the Italian mathematician Fibonacci (Benavoli et al. 2009, Vorobiev 2012). Here is the initial part of the sequence:

- 1, 2, 3, 5, 8, 13, 21, 34, 55 ...

The interesting aspect of the Fibonacci sequence is that, in order to obtain it, a so-called *recursive rule* must be applied. By definition, a recursive rule is a rule that applies to the result of the application of the same rule (Lannin et al. 2006). I will explain this concept with a metaphor:

Some operations can be used on the result of their application. Take, for example, an operation like <put a book on top of the book>. This operation can initially be carried out over a single book. Thus, after only one occurrence of the operation, there will be a small pile of two books. Now, the interesting aspect of recursive operations is that they can be applied again on the result of their own application. In our case, the operation can be applied a second time, and a book is placed on top of the small pile of two books. We will thus have a stack of three books. The operation can be applied again, adding another book to the newly created pile of books. The process can go on indefinitely, in principle (Treves 2005). Of course, there are physical limitations, for example the Earth's atmosphere, but this does not change that *in principle* the tower could have an infinite height, obtained with a very simple recursive operation: <put a book on top of the book>. This type of procedure is used similarly in other scientific domains. For example, in computer science formulas of this type are often used:

- x = x + 1

Whenever the program encounters this formula, it adds 1 to the value of x in that particular cycle. Thus, x takes a new value, and when the operation is applied again, it will be applied on the result of the application of the same procedure operated previously. So, if x equals 1 at the beginning of the first cycle, it will become 2 at the end of it, 3 at the end of the second, and 4 at the end of the third.

- cycle I: if x = 1, x = x + 1, x = 2
- cycle II: x = 2, x = x + 1, x = 3
- cycle III: x = 3, x = x + 1, x = 4

The Fibonacci sequence is but one example of the application of a recursive rule in mathematics (there are many others, and new ones can be created anytime). Why does the Nautilus shell follow such a trend in its growth? One reason could lie in the fact that this trend is energetically cheap, because any addition that is made to the existing shell depends on what the shell already is. Now, it appears that both the use of recursive rules and the trend to economy that this use represents have parallels in language. According to a prominent view, in human syntax hierarchies are obtained, similarly, using a recursive operation (Chomsky 1975, Pinker 2003). In syntax, recursion is used when creating a sentence from a group of words. In this case, the operation is identified with the English word merge (Chomsky 2014). The noun phrase is obtained by combining two elements of the sentence, the article and the noun: (e.g. the + house). The verbal phrase is obtained by combining a verb and the complement (e.g. it is + beautiful). The sentence is obtained by combining the two previously produced phrases, or by applying the same union process on the result of the application of the same process (the house + is beautiful). In this case the noun phrase obtained previously is merged with the verb phrase obtained subsequently and a merge will be applied to these two merges. In other words, the same rule will apply once again to the result of the application of the rule (Haegeman 1997, Rizzi 2013, Chomsky 2014). As one can see, this procedure is not very different from what happens in the Fibonacci sequence. To be more precise, it is not different from what nature does with the Fibonacci sequence, guiding the formation of the Nautilus shell according to a precise mathematical principle. Since humans have both linguistic and mathematical abilities, am I therefore suggesting that at the basis of mathematics and at the basis of language there is the same cognitive competence? This is an intriguing idea that has crossed the minds of various cognitive scientists. The next section reviews experimental evidence addressing this question:

Stanislas Dehaene, professor at the University of South Paris (previously mentioned in regard to the Visual Word Form Area), has tried to investigate the problem with a series of ingenious experiments (for a general review see Dehaene 2011). In a study conducted with Marie Amalric, the brain activation of mathematics experts was investigated with functional magnetic resonance imaging while the subjects completed various mathematical problems. In this case, no activation of the language areas was observed, suggesting a division of the two systems (Amalric & Dehaene 2016). In a different study, Evelina Fedorenko and her colleagues at MIT in Boston, showed that the area that is considered specialized for syntax, Broca's area, also contains micro-regions with more generic functions, such as circuits used for the construction of hierarchical structures (Fedorenko et al. 2013). This fact would suggest the existence of basic circuits shared between language and other cognitive systems, and in particular mathematics, which presents hierarchical items of a similar nature, obtained through recursive rules. As the authors explain, however, the data also shows that there are some subregions that are specialized for linguistic hierarchy. The two regions lie side by side.

As far as mathematics is concerned, we have no doubt that it is a hierarchical system (Makuuchi et al. 2012). The parentheses used in mathematical formulas, for example, have the function of establishing that some operations must be carried out first, and subsequent operations must be performed on the result of the first ones (Makuuchi et al. 2012). But how can we be sure that, when talking about language, we are also actually dealing with hierarchies of a similar nature, and not with the simple "linear sum" of elements? A study by Pallier et al. 2011 answers this question. Take these three "word sequences", directly from their article:

- looking ahead important task who dies his dog few holes they write
- the mouse that eats our cheese two clients examine this nice couch

- I believe that you should accept the proposal of your new associate

From the point of view of the number of words, the three sequences are identical. In each of these cases the sequence contains 12-words. However, when reading them, we have a natural tendency to organize these sequences in different ways. In the first, the words are chosen so as to form units of two elements; in the second, the units are larger, and the sequence is divided into two sentences made up of six elements. In the last sequence, there is a single unit, made up of all twelve elements. The study investigated brain activation of participants when presented with sentences of this kind. The study shows that there is a region of the brain that is sensitive to these differences and shows an activation that is incremental and predictable based on the size of the hierarchical structure (Pallier et al. 2011). This circuit of the left hemisphere is activated based on the size of the constituents. In the third condition, it has an activation that corresponds to twice the activation obtained with the second condition. In the second condition it has an activation that corresponds to three times the activation obtained with the first condition. We can thus propose that our brain sees language as a series of mathematical formulas, in which words are organized into constituents (a bit like operations that follow the order of parentheses in mathematics). In other words, this study suggests quite convincingly that language is not a mere linear recognition of words, but rather a system looking for structure (Pallier et al. 2011).

Given this important similarity between language and mathematics, we can ask a further question: When we solve mathematical problems, do we use language as well? The answer to this question seems to be positive. A study by Olivier Houdé and Nathalie Tzourio-Mazoyer, at the University Paris-Descartes, shows how these two skills are linked and demonstrates that solving mathematical problems is easier when they are transformed into linguistic problems, a process that many of us do automatically in our mind. In this study, the researchers showed that children learn to solve mathematical problems differently and at different ages depending on the system used in their language to describe quantities and mathematical operations. If the language used by the child is more ambiguous when it comes to the description of mathematical concepts, the development of mathematical skills proceeds more slowly (Houdé & Tzourio-Mazoyer 2003).

To further investigate this issue, a group of French researchers led by Pierre Pica worked with speakers of Munduruku, an Indigenous language spoken in the Amazon region, which has been shown to display linguistic and numerical peculiarities relevant to this line of inquiry (Pica et al. 2004). One notable characteristic of Munduruku is that it includes lexical items for the numbers 1 through 5, but lacks exact number words beyond that range. The researchers explored how speakers approached mathematical tasks involving larger quantities. In one experiment, participants were initially shown an image containing between 6 and 10 dots. In a second phase of the task, some of the dots were removed from the screen, and participants were then asked to estimate how many dots remained. While the final quantities always fell within the range expressible in the language (five or fewer), solving the task required mental manipulation of larger numbers. Participants responded with approximate values that were consistently close to the correct answer, demonstrating an understanding of the task, though not providing exact results. These findings suggest that the availability of precise numerical terms in a language may be shaped by cultural practices: in communities where approximate quantification meets everyday needs, there may be less pressure for their language to include or use a system for precise arithmetic.

Some authors provide further evidence that the hierarchical features of linguistic syntax are shared with other domains and do appear to be used proficiently across domains. A study by Van De Cavey & Hartsuiker (2016), for example, shows that hierarchical structures from the domain of arithmetics can be used to prime hierarchical structures in language, and vice-versa. In this experiment, participants were presented with simple mathematical formulas and with ambiguous sentences that were prone to different attachment interpretations. The aim of the study was to understand whether unrelated mathematical formulas could act as primes for the attachment preferences in resolving the complex sentences. Consistently with predictions, results showed that low vs high attachment in sentence resolution was predicted by low vs high "attachment" in mathematical formulas (for instance, the formula $3 + (2 * (2 + 3))$ would lead to the last two elements of the associated sentence forming a phrase, while the formula $3 + ((2 * 2) + 3)$ would lead to the last element being attached separately). The authors conclude that their findings provide "clear evidence for a domain-general structural processing mechanism".

However, as Campbell & Tyler 2018 notice, no one is arguing against the existence of domain-general mechanisms for the processing of structure, shared and used by both language and mathematics. The point is rather that in addition to those domain-general mechanisms, there may also be some domain-specific mechanisms for these two domains. Neuroimaging studies seem to be convincing in this sense, to the extent that even researchers with a traditional resistance to this concept are now advocating for domain-specificity in syntax (Campbell & Tyler 2018). A team of researchers at the Max Planck Institute in Leipzig has been addressing this issue with a number of neuroimaging studies. For instance, as mentioned in the chapter on language and the brain, a study by Zaccarella et al.

(2015) shows that a subregion of the Broadman area 44 (Broca's area), responds specifically to minimal structures like phrases – thus units of very few elements (often only two), smaller than sentences – and does not respond when the same words are presented in an order that does not allow structure building. These results are consistent with those of Fedorenko et al. 2013 mentioned earlier, where it is shown that while Broca's area contains networks that are domain-general and can be used also to process non-linguistic hierarchy (such as mathematical hierarchy), there is at least one subregion that seems to be domain-specific. As Zaccarella & Friederici 2017 explain, and as it will be discussed further in the chapter on evolution, it appears that only humans have the ability to use hierarchies of this kind within their communication system.

In summary, mathematics and language seem to share some properties, such as that of recursion (Lannin et al. 2006, Chomsky 2014) and that of hierarchy (Pallier et al. 2011), and they also appear to work in concert for the resolution of problems (Pica et al. 2004). From a neurocognitive point of view, some brain circuits are likely to contribute to both language and mathematics, but it is also clear that the two skills are based on largely separate networks (Fedorenko et al. 2013).

5 Computational core and evolution

The idea that there is a domain-specific biological foundation of language entails specific predictions about the evolution of language, namely that humans' ancestors accidentally developed some kind of grammar (if the computational-core idea is appropriate), and that this proved to be adaptive. The opposing view, refusing any domain-specific foundation of language, assumes that the skill that emerged during evolution and that proved to be adaptive is rather a social skill, a skill that then became the basis of our culture (and thus of our language, since language is seen as a cultural invention). This chapter presents these two opposing positions. Finally, the chapter presents the evolutionary consequences of the hypothesis outlined in this volume. This account mirrors the neuronal recycling hypothesis made for the evolution of the Visual Word Form Area. In short, the proposal is that humans developed an area that can perform the computational core operation, since this proved to be adaptive across domains. This area is not domain-specific when children are born, but it becomes domain-specific during development, similarly to what happens for reading.

5.1 Language as an adaptive skill during evolution

About two centuries ago, walking the alleys that animate the town of Cambridge, a young and unconventional student was about to forever change our understanding of biology. This student was Charles Darwin, the main proponent of the theory of evolution (Darwin 1859). It is important to briefly summarize the theory of evolution and the principles that govern it before delving into the linguistic question that follows. According to the theory of evolution, the species that are currently present on planet Earth are those that survived the pressure of natural selection (Darwin 1859). I will explain this concept with a "textbook" example: We all know that giraffes have long necks, this being one of the most evident physical traits in these animals (Simmons & Scheepers 1996). The ancestors of the giraffes had shorter necks, but as often happens with physical traits, there was a certain variation from individual to individual (and there still is, but the average value is higher today). Having a longer neck had an effect on the chances of survival and reproduction, because having a long neck meant having fewer competitors for reaching food on trees, as well as an having an advantage over vigilance about competitors and predators (Williams 2016). Only the specimens with the longest neck managed to eat enough (Darwin 1859), and, according to a more modern view, a long neck may additionally lead to more chances of mating, being it is associated with physical dominance (Mitchell et al. 2009). As a result, the specimens with the longest neck tended to survive longer and to procreate more. By breeding more, those long-necked specimens handed down the genes related to the long neck (plus all the other genes that characterized them) (Darwin 1859). Over the millennia, the genes associated with the "long neck" have become increasingly frequent in the DNA of these animals, leading to the development of the species we know today, which has, among its fundamental traits, that of the long neck (Agaba et al. 2016). Note that we can and must look at this story also from the side of plants (in this case we talk about the ancestors of acacias): thanks to natural selection, taller trees were less vulnerable and therefore were more likely to pass on their genes (King 1990). Therefore, the traits that allowed these plants to have a very long trunk have become, by the same principle, more and more frequent (Darwin 1859). At the same time, for some species it could (and may) be convenient to come in contact with animals, because these can facilitate the dispersal of their seeds. For those species, the features that characterize the short trunk have become increasingly frequent (Stiles 2000). Each species is confronted with a series of environmental situations which either favor or do not favor its likelihood of transmitting certain characters to subsequent generations, and these situations are the result of an intricate system that relates all species (Odum & Barrett 1971). The traits of a species that prove favorable in a given context are passed down to the next generation, for the simple fact that those traits allow the individual to survive longer and provide more opportunities to pass on its DNA. This same phenomenon is repeated every day on the planet: some species thrive while others don't, depending on the physical conditions of their environment (Rahel & Olden 2008). Crucially, natural selection is the principle behind the very existence of the species we know (Darwin 1859). It is precisely with an infinite series of small steps of this type that we have arrived at the complex animal and vegetable world that we know today, through a gradual modification of the species in relation to the pressure of the environment (Darwin 1859, Fitch 1971).

From a logical point of view, it is reasonable to think that something like what I presented about giraffes' neck happened for language (no author 1992). A huge problem that occurs in the evolutionary study of language is that, unlike the neck of giraffes, language leaves no physical remains in the environment (Rutherford

2018). Consequently, the discussion on the evolution of language is speculative and is based on indirect evidence. Going back to the analogy with the neck of giraffes, we can say that it is reasonable to assume that, at some point in the evolutionary history of our ancestors, there were some individuals who, randomly, showed a trait that is somehow responsible for the complex language we have today (Hauser et al. 2002). In other words, at some point in the evolution of our species there must have been some individuals who were able to communicate more efficiently than others. This trait must have proven itself to be rapidly adaptive. We can imagine a tribe of Cro-magnon man, for example, of a hundred people. Now we can imagine that a small group of them randomly developed some genetic mutation that materializes phenotypically into a more effective communication system. That small group had a greater chance of survival than the other members of the group, and therefore was more likely to procreate and transmit that genetic mutation, or the set of genetic mutations, responsible for this communicative system (no author 1992). In a relatively short time, "language genes" can be expected to have become part of a large group of individuals, until there were no more specimens of the species without them. Some basic questions to ask are: what did this evolutionary leap consist of? And are we really talking about a jump or an incremental growth? What kind of linguistic property can we assume has emerged in an adaptive way and has transformed a communication system into language?

According to some linguists and some ethologists (the scientists who study animal behavior), the answer to this question must be sought in the traits that distinguish animal communication from human communication (Hauser et al. 2002). What are these traits? In short, the answer may lie in the ability of humans to combine words and form sentences, a capacity that appears to be absent in other species (Rutherford 2018). According to this position, in a purely speculative manner, it could be assumed that a sudden genetic mutation (or multiple mutations) allowed human beings to logically combine the symbolic signals that were already present in their communication system. This mutation quickly spread, since it was highly adaptive. This is the position of a famous article published in Science on the subject, signed by the anthropologist Marc Hauser, the linguist Noam Chomsky and the ethologist Tecumseh Fitch (Hauser et al. 2002). Even though this hypothesis sounds very logical, some scientists are in sharp disagreement it. Steven Pinker and Ray Jackendoff, expressed in this regard with the following words (Jackendoff & Pinker 2005, page 211):

> We note that despite Fitch et al.'s denial, their view of language evolution is tied to Chomsky's conception of language itself, which identifies combi-

> natorial productivity with a core of "narrow syntax." An alternative conception, in which combinatoriality is spread across words and constructions, has both empirical advantages and greater evolutionary plausibility.

As Pinker and Jackendoff note, an evolutionary hypothesis that focuses solely on the ability to combine signs may be insufficient to explain the emergence of language.[1] One of the reasons behind this limitation is that it is not entirely clear whether this combinatorial property is sufficient to distinguish the communication system of humans from that of other animals (Kirby 1998). In fact, it is far from simple to identify the traits of animal communication in common and those not in common with language with absolute certainty (Patricelli & Hebets 2016). It is even more difficult to establish whether the differences observed are caused by domain-specific linguistic properties, or whether they are the consequence of variations in general domain properties, such as memory. We all realize that our communication system is significantly different from that of other animals, even those evolutionarily closer. Still, it is not that simple to understand what these differences consist of. Furthermore, note that the Hauser and colleagues' hypothesis is based on a single property (Hauser et al. 2002), but evolutionary biologists show that gradual development of multiple properties is more common in evolution (Gould 1987). Håkansson & Westander 2013 offer an interesting and thorough comparison of animal and human communication. An extract from their analysis of mammals gives an insight into this problem (page 2-3):

> Most animals have some kind of social interaction with another member of the same species, if only in order to find a partner to breed with, but there are huge differences when it comes to type and amount of communicative behaviors. Group life is the obvious setting for rich communication. Human groups are characterized by a constant flow of verbal and nonverbal communication; people are talking, listening, smiling, gesturing, touching and laughing. Many other primate groups, such as chimpanzees and bonobos also display constant social interaction - they vocalize, play, hug and groom each other. The social behavior of wolves and dogs exhibit the same continuous communication of feelings and states, in their case by vocalizations, body postures, facial expressions, sniffling and licking. Primates (including humans, of course) and Canids (e.g. wolves and dogs) are examples

[1] Once again, this ability to combine signs is nothing but the merge operation mentioned in the chapter on language and brain, and further discussed in the chapter on music and mathematics. The productivity of language, music and mathematics depends, according to the computational core hypothesis, to the recursive application of merge.

> of individualized groups, where members recognize and know each other, have complex greeting ceremonies and other formalized means of communicating group membership. At the other end of the continuum, there are animals that lead solitary lives, such as the tiger. The social life of the tiger is mostly about bringing up the offspring. The adult female and male meet to mate, but spend the main parts of their lives apart. The cubs stay with their mother for around two years, and then they are independent enough to be on their own. Tigers do keep track of others, however, by the scent markers they leave on territory borders.

As it may be noticed, even if we do observe some superficial similarities between human and animal communication, there appear to be important qualitative differences. Understanding whether combinatoriality is the key selective property is not simple for observational studies: animals do not appear to form long and complex sentences like the ones we produce[2] , but this does not give certainty as to whether they could. A complementary approach to observational studies consists in experimental work where animals are trained to use human language.

The following section puts the idea of saltatory evolution of language under scrutiny by discussing how other animals perform when dealing with human language. A provocative question one may ask is the following: why do other animals never develop a language like ours? A first intuitive answer to this question is that animals do not have a system for articulating sounds comparable to ours. However, this type of response does not apply to all animals. For example, parrots can notoriously imitate the linguistic sounds of humans without any problem, and even extract some phonological rules from the input (Pepperberg 2007). Why do parrots simply imitate the sentences spoken by humans, without producing new sentences? In the 1970s, linguists addressed this question, and some assumed that, at least for the most intelligent species, the answer was that no one had ever tried to teach them how to use language. It was then decided to try teaching language to non-human primates (chimpanzees, gorillas, etc.), our evolutionary cousins (Harnad et al. 1976, Patterson 1978, Premack 1971, Hess 2008).

A first problem that arose is that of the articulation of sounds, already described above. Non-human primates cannot produce the sounds of human languages with their vocal tract. This problem, however, can be easily overcome: In-

[2]Some species of birds are shown to produce very long calls, but these calls are typically composed of a limited set of items repeated. As such, one may argue that we do not observe recursive communication by animals in the wild.

stead of teaching primates a vocal language, one can teach them a sign language. In terms of complexity, sign languages are comparable to vocal languages, and the same is true of their expressive quality (Emmorey 2001). Thus, it was decided to teach sign language to non-human primates. Several animals were chosen in various projects around the world (Harnad et al. 1976, Patterson 1978, Premack 1971, Hess 2008). What were the results of these studies? The primates, in the first place, had a moderate success in learning words. In fact, some of them learned up to 500 words (Premack 1971). What does it exactly mean to learn a word? One of the fathers of modern linguistics, Ferdinand de Saussure, elegantly described the two-component nature of the words of language. On the one hand there is the form of the word, which De Saussure described with the term *signifier*, on the other there is what the word represents, which De Saussure described with the term *signified* (De Saussure 2011). When someone teaches us a new word, what we do is learn that such specific form, or sequence of sounds, corresponds to a specific meaning. The classic view insists on the fact that the signifier and its meaning are arbitrarily associated. Recent work suggests that arbitrariness is only one of the principles guiding the relationship between sign and meaning (Perniss et al. 2010): First, many signs are iconic, which refers to the fact that the properties of their sound and/or gesture are related to the meaning conveyed. A typical example of signs being highly iconic is onomatopoeias, where the sound itself suggests its meaning. A less frequently mentioned example is that of ideophones, where the word does not mimic the "sound" of its referent, but rather a property of its meaning: a good example recurring across a variety of languages is that of words that contain repetition of syllables and often refer to repeated or iterative events (Dingemanse et al. 2015). Another principle that we observe is systematicity. Within a language, we can find reliable patterns that can help predict the meaning of a form. This systematicity mainly manifests with phonological patterns. For example, in Japanese, nouns tend to contain fricatives and rounded vowels, while verbs tend to contain coronal consonants (Monaghan et al. 2007, Dingemanse et al. 2015). These three principles (arbitrariness, iconicity and systematicity) interact, and they play different roles in shaping our lexicon. Arbitrariness gives the lexicon the wide freedom needed for it to be informative; iconicity helps ground the lexicon to sound and gesture articulation; systematicity improves learnability, by providing patterns that simplify the problem of lexical acquisition (Dingemanse et al. 2015). From a cognitive point of view, the question of how meaning is represented in our mind is extremely complex. One first aspect to consider is that languages do not exist independently of human beings, as they are not separate entities from our mind and from our brain. A superficial look may mislead us into thinking that languages are self-sufficient entities, but a brief reflection on how communication takes place can lead us to a different thought. Successful communication between two speakers is achieved only when they both know the language used. This can seem trivial, but it is not. For example, we can imagine communication between the two people, a man and a woman. Suppose that both of these people are speakers of English. If the man says to the woman: "the chicken I ate at lunch was delicious", this will trigger in the mind of the woman a certain system of representations. First, she will "see" the picture of a chicken meal, and if she likes chicken, this image will certainly also activate the areas involved in pleasure and desire. How does her image of the meal compare with the image the man has in his mind? Probably the two representations are similar but not identical. This is because the system of representations in each of us is not the same. The same words will have slightly different meanings for these two speakers, for example depending on how they cook their chicken. Each individual has slightly different representations for every word, and consequently each speaker has a slightly different interpretation of every sentence pronounced. Successful communication is based on the overlap of these representations, but the overlap is far from being complete even when communication is efficient. In this specific conversation the overlapping features are probably numerous. For example: surely, both speakers start thinking of the same animal when they think of the word chicken (although their representations of this animal may vary substantially). They both have a representation of a cooked meal. Surely, they both assume that what was delicious was the chicken meat and not the bones. The more the representations between speakers are superimposed, the more effective the communication is. We can go further and imagine a different scenario, in which the woman says to the man: ”Yesterday I went to listen to a string orchestra". For the sake of exemplification, we can suppose that the woman is a violinist, while the man does not play any instrument. Successful communication in this case is more complex, because the representations activated are quite different. First of all, the man may not know what a string orchestra is. In this scenario, the communication between the speakers would not be particularly successful, because the representations activated in the man could be very different from those in the woman's mind. But also, in the case where the man knows what a string orchestra is, the representations that he experiences will be different from those of a violinist. The word ”strings", by itself, will trigger very different representations in the two speakers and the intention to communicate the message will have probably considerably less success than the intention in the conversation about chicken. Given that each word generates different representations in each speaker, based on the life experiences of each speaker, how can we decide which system of representations for a word is the correct one? The people who create dictionaries try to offer complete definitions of words, but surely these definitions (although useful) are partial in one direction or another and depend in part on the personal life experiences of those who write them. Definitions in dictionaries, however, are the best attempt we make as a species to define the meaning of words. A perfectly reliable system for deciding which representations must be activated when you listen to a word does not exist, because that is not how language works. The attempt to define the meaning and use of words makes little sense, when one looks at it from a cognitive point of view. The use of words, phrases and constructions is ”pragmatically” justified. We talk, we understand each other to some extent, we misunderstand each other to some extent and as long as the first phenomenon is stronger than the second, we can continue to communicate. A language is an amalgam of overlapping and non-overlapping representations of words and phrases in each speaker. When several speakers have substantial overlap of representations associated with words and constructions, then we have a language.

Interestingly, the understanding of the meaning of words is something that is not unique to humans. Dogs are a species that can learn words of language with moderate success. Many dogs learn to recognize the sound of their name (Andics et al. 2014), but also numerous commands: sitting, standing, lying down (Andics et al. 2014). Many learn to recognize the bell ringing, their name, food names and so on, and neuroimaging studies show that learning words activates regions in dogs' brains that are homologous to those that are activated in humans (Andics et al. 2014). The primates studied in the 1970s did even better, as they managed to learn a few hundred words (Premack 1971). The words learned were of various kinds: There were both concrete words, such as names of fruits (banana, apple etc.) and abstract words, such as moods (sad, happy) (Patterson & Gordon 2001). However, it was very soon clear to linguists that there was a substantial difference in how primates used these signs when compared to how children use them: primates were unable to combine the signs sensibly to form sentences (Rivas 2005). If one reads the sign sequences produced by primates in these studies, one can observe how the sentences have no precise structure. Words are used randomly (even if the choice of words is semantically correct). This type of evidence appears consistent with the statement that the aspect that makes animal communication systems different from language is the absence, in the former, of syntax (Hauser et al. 2002, Rivas 2005). Humans combine words by creating complex hierarchical structures, sentences, while animals use signs in isolation, or when they combine multiple signs, they do not do it by following syntactic rules. It therefore seems clear that animals cannot master human language, even after training. Although many animals can learn words and other signs in isolation (Randall 2001), it is impossible for them to organize these words sensibly and create sentences, which instead very young children, already from the age of three, do naturally (Pinker 2003). According to the saltatory theory of language evolution (Hauser et al. 2002), our ancestors accidentally developed the ability to put signs together, and this quickly led to language as we know it today.

An alternative theory where language is a central skill but no saltatory evolution occurred is that of language evolving from gestures. One of the most important neuroscientific findings of the last decades is that of a class of neurons known as "mirror neurons". Mirror neurons are a type of cell in the motor cortex that respond both when an individual is performing an action, and when the same individual is observing someone else performing the same action (Rizzolatti 2005). One crucial property of these neurons is that they offer a form of conceptual abstraction directly implemented in the brain. A neuron that spikes both when an action is completed or when an action is observed is a neuron that embodies an abstract representation of that specific action. The discovery of mirror neurons fueled important research that spans beyond neuroscience, and a group of researchers believes that this class of neurons may be at the foundation of our linguistic skills. In a study assessing the monkey's premotor cortex, Kohler et al. 2002 showed that several neurons belonging to the mirror neurons system spike not only when an action is seen or completed, but also when the sound for that action is heard. This phenomenon appears to be particularly strong in the monkey brain when the sounds investigated are related to food (for example, the effect is strong for the sound of peanuts being broken), but it is observed also for actions that are unrelated to food (for example, the sound of a hand grasping a metallic object). These neurons are located in the left frontal hemisphere of the monkey brain, in an area that is homologous to the human Broca's area. According to the hypothesis of this team of researchers, the emergence of language was not the consequence of saltatory evolution, but rather the gradual extension of this system to items of growing complexity. If a neuron can associate a sound with a certain abstract meaning, the next step would be to use an arbitrary sound and associate it with that abstract meaning. The neuron that responds to the act of eating a peanut and the sound of a peanut being opened, may easily also respond to an arbitrary sequence of sounds, such as "eat" /iːt/. According to this line of research, gradual adjustments of this kind may have facilitated the change from a simple associating system to a complex language, within a slow evolutionary process lasting millennia. This account does not see gesture as a scaffolding system, bridging the gap between gestural communication and spoken language. It rather sees gestures and speech as tightly interconnected aspects of communication, where language is "a system of systems", and gestures, pointing and voluntary speech now co-exist, and emerged at different times in evolution (Levinson & Holler 2014).

Certainly, this proposal may seem hasty in its treatment of combination (it explains well how monkeys or humans could learn to use words, less so how humans developed the ability to put them together), but nonetheless this idea is extremely important because it puts language at the center of the evolutionary picture, without relying on a phenomenon that is relatively rare in evolution, which is saltatory evolution. This gives this proposal important plausibility. Critics, however, stress that nothing like human language may be found in the other animals, and thus the presence of some proto-systems in monkeys is interesting, but fails to capture the qualitative distinctions there are with human language (Håkansson & Westander 2013). As MacWhinney 2002 explains, it is unlikely that gestures per se may be the key to the emergence of language, but they may indeed be a co-factor in an account where language emerged gradually, by means of several small steps involving evolution or our brains, of our posture, of our sociality, of our vocal tract, and so on (MacWhinney 2002: 5):

> Upright posture and full eye contact also provided room for the emergence of the first gestural signals between early hominids. As many have argued, it is likely that hominids went through a period of relying on some forms of gestural communication. It is clear that upright posture provides room for such a development. However, the evolutionary advantage of early gestures may have been overestimated, since the first bipedal primates had cognitive resources that were not yet greatly different from those of today's apes. Although we know that apes can learn and transmit a system of signs, there is little evidence that the level of sign use they display in natural contexts would provide any major evolutionary advantage.

This suggestion naturally brings to the second account of language evolution, the proposal that language is a "secondary skill" of our cognition, and thus developed only as a consequence of other skills evolving.

5.2 Language as a secondary skill

As a starting point to the evolutionary theory of language as a secondary skill, we shall notice that some scientists disagree with the claim that there are substantial qualitative differences between human and animal communication. Arnaud Rey, for example, a researcher at the French National Centre for Research (CNRS), recently conducted a study that does not appear to support this distinction (Rey et al. 2012). In the study, the author and his colleagues showed that after intense training sessions, non-human primates organize visual information using complex structures reminiscent of human syntax. According to the author and his collaborators, this would indicate that the ability to combine linguistic signs is not so much a capacity in itself, present only in human beings, but rather an ability emerging and dependent on other general structures that we also share with other species, such as memory (Rey et al. 2012). Understanding if these claims are correct is not easy, because *there are* important cognitive differences between humans and other species. For this reason, it is difficult to understand whether the differences observed in human and animal communication systems are due to the differences in general cognitive systems, or whether they are the manifestation of two qualitatively different communication systems (Santolin & Saffran 2018). A recent work by Ganau 2025 analyzed the multi-sign productions of a wide range of animals in the wild (birds, primates and cetaceans), and reached two conclusions that can help us proceed with our discussion: A. Some species do display an ability to combine two items successfully, with a procedure that resembles syntactic merge. B. No species investigated so far can do that recursively: their combination seems to be limited to two items. Longer sequences of signs appear to only be repetitions of the same two-item combinations.

It is interesting to notice that sensitivity to structure has been observed in some animals that are evolutionarily distant from humans, and certainly do not have language (Håkansson & Westander 2013). Research conducted on birds shows that some species can learn syntactic structures in a fashion that reminds humans. For example, a pioneering study directed by Timothy Gentner, of the University of Chicago, shows that starlings can be trained to recognize sound sequences organized according to syntactic rules and to discard sequences that do not respect these rules (Gentner et al. 2006). This ability is incredibly similar to our ability to judge a sentence as grammatical or non-grammatical. According to some linguists, the natural interpretation of these data is that the foundation of our grammatical skills is neither human nor specific to language. Another example is the ability to discriminate languages. A study by Ramus et al. 2000 showed that both infants and monkeys succeed in the discrimination of languages from different rhythmic classes, suggesting that this skill depends on a domain-general ability to discriminate sequences of vowels and consonants[3]. For this and other

[3]See the chapter on language development for a thorough discussion of this ability. In short, languages differ in their syllabic structure, and newborns are able to use these differences to

reasons that we will see shortly, the narrative that puts syntax at the center of the evolution of language is not universally accepted by scholars (Everett 2012, Christiansen & Kirby 2003). The proposal above sees language as a relatively independent system of our brain, which is based on circuits specific to grammar (Pinker 2003). This assumption is necessary if we describe the emergence of syntax in terms of natural selection, because it is necessary to identify a trait that we consider adaptive (something independent that gives a benefit to the species - Darwin 1859); but what if language was not an independent system based on separate circuits, but rather an instrument that emerged from our culture and therefore a by-product of a cultural brain (Tomasello 2009)? The idea of language as a cultural invention is not insensitive to the principles of natural selection, but rather shifts the focus from language to other cognitive skills (Tomasello et al. 2005). According to this proposal, language is an invention and the adaptive capacities that triggered the evolution of Homo sapiens are others (Tomasello 2009). An influential position is the one introduced by Michael Tomasello and his colleagues from the Max Planck Institute for Evolutionary Anthropology, in Leipzig. According to this proposal, the trait that differentiates humans from other animals is the ability to understand the intentions of others and the ability (or, better, the natural tendency) that humans have to collaborate to achieve shared goals or simply to share feelings and emotions (Tomasello et al. 2005).

In evolutionary terms, their hypothesis is that, approximately 150,000 years ago, some specimens of our ancestors "accidentally" developed these skills and thus became better than others at cooperating and achieving their aims. This group of individuals was therefore more successful in the struggle for survival and the traits that were responsible for understanding and sharing spread quickly, leading to the development of the modern Homo sapiens (Tomasello et al. 2005). The hypothesis of Tomasello and colleagues goes further and tries to explain how these traits could be the basis of our cultural cognition, and therefore of our culture (Tomasello 2009). According to this view, the ability to understand the goals of others, the desire to share our goals with others and the tendency to work with others (both in profit-oriented activities, but also in pure interaction), could be the pillars of our cognition. During development, thanks to this biological endowment, the child quickly constructs representations that contain cultural norms (Tomasello 2009), symbolic behaviors and various kinds of artifacts (Tomasello et al. 2005). For example, the child can quickly grasp the

discriminate languages. Infants in fact classify languages according to their rhythmic class, meaning that they discriminate languages only if they differ in their distribution of vowels and consonants. For instance, newborns succeed in discriminating English from Spanish, but they do not succeed in discriminating English from Dutch.

social norms that regulate the preparation and consumption of meals, since these are well captured using the skills described above: there is an intention in the action of the caregivers, which the child can read, and there is a collaboration and commitment of different individuals (in the vast majority of cultures) ranging from the preparation to the eating of the meal. According to this proposal, all cultural norms are developed thanks to this biological substrate (Tomasello et al. 2005) and this natural tendency allows for the existence of complex cultural artefacts such as marriage, nation-states or orchestras (Tomasello et al. 2005). Where is language in this theory? In this perspective, language is nothing but one of the artifacts of our cultural brain, an invention that proves particularly powerful in helping humans collaborate, sharing intentions and sharing emotions (Tomasello et al. 2005, page 690). A short excerpt from one of the articles by this research group can help explain their position. In this passage, the proposal of a cultural brain as discriminating other species is compared with the proposal of language as discriminating other species (the position outlined in the first part of this chapter):

> There are two other main theoretical contenders for what makes human cognition unique in the animal kingdom. First, of course, many theorists point to language, and without a doubt language must play a central role in all discussions of the evolution of human cognition. But saying that only humans have language is like saying that only humans build skyscrapers, when the fact is that only humans (among primates) build freestanding shelters at all. Language is not basic; it is derived. It rests on the same underlying cognitive and social skills that lead infants to point to things and show things to other people declaratively and informatively, in a way that other primates do not do, and that lead them to engage in collaborative and joint attentional activities with others of a kind that are also unique among primates. The general question is What is language if not a set of coordination devices for directing the attention of others? What could it mean to say that language is responsible for understanding and sharing intentions, when in fact the idea of linguistic communication without these underlying skills is incoherent. And so, while it is true that language represents a major difference between humans and other primates, we believe that it actually derives from the uniquely human abilities to read and share intentions with other people – which also underwrite other uniquely human skills that emerge along with language such as declarative gestures, collaboration, pretense, and imitative learning.

As one can imagine, this position triggers heated debates because it is in profound disagreement with any position that places language at the center of the scene. As Derek Bickerton, of the University of Honolulu, points out in a response to the article mentioned above, the question ”what is language if not a set of coordination devices to direct the attention of others?” is not rhetoric as the tone would suggest (Bickerton 2005). Language is also other things. For example, it is a system qualitatively different from the other systems observed in nature (Håkansson & Westander 2013, Hauser et al. 2002) and, moreover, it is a powerful tool to give structure and shape to experience (Bickerton 2005). What evidence do we have that our cultural knowledge allowed the invention of language and not the other way around? Can we rule out the idea that language emerged through evolution, and this has allowed the creation of culture? Is language an invention (like skyscrapers) or is it a biological skill (like vision)?

It is difficult to establish with certainty whether it is actually language (and in particular syntax) that distinguishes us from other animals or our ability to interact, with language following (Ambridge & Lieven 2011). The question is of crucial importance for the understanding of our species. Depending on whether one or the other hypothesis turned out to be correct, the role of language would assume a different importance in explaining the macro-differences that are observed between humans and other species. There is no doubt that the human being is only one of the many animal species living on earth today, but it can also be noted, without taking the risk of appearing anthropocentric, that the human being is the only species to exert a huge modifying force on the planet, for better or for worse (Steffen et al. 2011). Birds create nests, beavers create dams and bees create hives, but only humans build metropolises, hospitals and spaceships. Whether at the basis of these enormous differences between humans and other animals lies a uniquely linguistic property, or a set of properties of general domain[4], is an unresolved question.

As an additional step, it seems important to offer also some information on the temporal evolution of language, so that one can see what other developments humanity experienced at the same time. If we look at the problem from a temporal point of view, we may also feel more insecurity and a sense of modesty, which can help us place our species and its role on the planet. We have seen that language is a very powerful tool, which has certainly had an important impact on the development of human societies as we know them. According to researchers' estimates, complex language appeared in a time-window roughly corresponding to the emergence of Homo-sapiens, 300,000-200,000 years ago (Corballis 1992).

[4]Meaning the combination of interactive skills and logic, memory and computation.

Even assuming that the most distant date is the correct one, we will quickly realize that these numbers are very little if we look at the age and development of our planet (Dalrymple 2001). If we start from the assumption that the existence of language is what makes us "humans", we can say that the human being has inhabited the planet for about 200,000 years (Hublin et al. 2017). It looks like a large number, but this is not a very long time. Some species have inhabited the planet for much longer periods, with very few genetic modifications (Eldredge & Stanley 2012). A good example of these so-called living fossils is the American alligator. American alligators are the same alligators that lived on the planet nearly 100 million years ago (Grigg 2015). Following a principle known as stabilizing selection (Gibson & Bradley 1974), evolution has favored intermediate rather than extreme phenotypic traits, making the species stable over time. According to some scholars, this principle could actually be the dominant principle of natural selection (Barton & Partridge 2000), which would guarantee the relative stability of the species throughout the planet's history. If we represent these figures with scaled lines, it will be easy for us to understand that our species is nothing but a newborn of planet Earth. For the sake of visual representation, we can imagine that the underscore character of our keyboard, "_", stands for 2 million years. If we use this symbol as a scale, then the alligators have been on the planet for an amount of time that corresponds to this line (see below the combination of underscores):

- ____

Homo sapiens, having spent about 200,000 years on this planet, should be represented as 1/10 of _. Dinosaurs, which appeared on Earth some 240 million years ago, inhabited it until their extinction 66 million years ago (Archibald & Fastovsky 2004). They have spent more than 170 million years on the planet, or about 1700 times the time that the human being has existed. And yet, if we still look back in time, we realize that even dinosaurs are but a small event in the history of our planet. Earth has existed, in fact, for 4.6 billion years. If I represented the history of the Earth with a line on this page, as I did a few lines above with the history of the alligators, the entire duration of humanity would only be a dot invisible to the naked eye. While language is a powerful and fascinating property of our species, we should never forget that we are only among the latest arrivals on a planet that has existed and will exist without us. The existence of language does not make us more unique than the giraffe's neck or the spider's web make those animals unique (a metaphor originally introduced by Pinker 2003).

It is important to notice that a domain-general account of language evolution does not deny that language may have been adaptive (and is adaptive right now) within the realm of natural selection. Thanks to the combination of a number of domain-general skills, humans may have developed the ability to communicate effectively with each other, and this ability became quickly adaptive and may have led to the extensive spread of humans in today's planet (MacWhinney 2002). However, language evolution, observed from this angle, avoids giving any special status to humans and to their communication system, and all would be explained within the tenets of common evolutionary principles.

In the table 1 above we can observe some fundamental steps in human history and pre-history. As it often happens when we describe history and prehistory, the various phases are analyzed with very different timescales. The first block, the Paleolithic, has a duration ranging from 3 million years ago to 10000 BC. The Neolithic, immediately after, has a much shorter duration: from 10000 BC to the invention of writing systems, 3000 years before Christ. The use of this ”irregular” scale is not accidental but is due to the fact that for a long period of time we have not observed many changes in the behaviors and practices of our ancestors (Ramachandran 2000, Diamond 2005). The only major change that we observe throughout the Paleolithic phase, about a million years ago, is the use of fire (Roebroeks & Villa 2011). The use of fire certainly had an exceptional impact on the development of our ancestors (James et al. 1989, Diamond 2005). The advantages of using fire are many: cooking meat facilitates the absorption of nutrients. Having control of the flame can serve as protection and light at night. Sitting around the fire can help individuals socialize (Ambrose 2001, Diamond 2005). While we can establish dates for the use of fire, because we can find remains of ancient fireplaces, it is difficult to establish the exact origin of sociality in man, even if it is assumed that the two are to some extent related. However, we know that in the final phase of the Paleolithic, in the last two hundred thousand years, humans have rapidly developed a series of skills and objects that led to the introduction of agriculture, about 10,000 years before Christ (Richards 2002). This change from a very long period of stability during the Paleolithic to a new phase of rapid development has been dubbed ”the great leap forward” (Diamond 2005). We cannot be sure, but it is likely that at the basis of this leap forward there is the emergence of a new and powerful competence: language (Tallerman 2007, Tallerman & Gibson 2011, Smith 2006). At the end of the Paleolithic (intended as the last 200,000 years) and with the beginning of the Neolithic, our ancestors began to show the first cultural systems (Thomas 1991), the first practices codified by groups of individuals. Ceremonies for the dead, for instance, are crucial in helping us understand the minds of these individuals. During the Neolithic

Table 5.1: Prehistory and history (in different scales)

Prehistory 3 Million years to 3000BC		**History 3000BC to nowadays**			
Paleolithic	Neolithic	Ancient Age	Medieval Age	Modern Age	Current age
3 Million to 10000 BC	10000 BC to 3000 BC	3000 BC to 476 AD	476 AD to 1492 AD	1492 AD to 1789 AD	1789 AD to today
Starts with: First human species	Starts with: Invention of agriculture	Starts with: Invention of writing	Starts with: Fall of Western Roman Empire	Starts with: Columbus' arrival in America	Starts with: French Revolution

period, many human communities began to practice the cremation of the dead and to build huts with the sole purpose of collecting the ashes and remains of the dead (Larsson 2003, Pettitt 2013). It is likely that the emergence of language is at the basis of the more complex burial practices that we observe in the Neolithic with the advent of Homo sapiens (Pettitt 2013)[5]. We can be relatively confident in our claim that humans had language during the Neolithic.

The study of the evolution of language is problematic because language, unlike bones or burnt wood, leaves no physical trace. The earliest evidence of written language is from around 5,000 years ago, However, considering that Homo Sapiens has not undergone any major physical modification for at least 100,000 years, it is almost certain that language existed for a much longer time than writing (Menary 2014), and it may even have emerged in hominids prior to Homo sapiens (Tallerman 2007). The cultural practices we trace in the Neolithic and partly in the Paleolithic suggest that our ancestors had a complex system of communication, and that they already built complex societies even then (Whittle 1996). The emergence of language is normally located between 400,000 and 200,000 years ago, in the last phase of the Paleolithic, and after the control of fire. Basically, we can indicate this moment as the beginning of modern man, as there are no physical differences between those men and us (Ammerman & Cavalli-Sforza 1984, Richards et al. 1996). If I had been born with the same genotype 200,000 years ago, I would no doubt have been comfortable living with other humans in my community. These changes are further summarized in Figure 5.1, below:

Finally, a few words should be spent on explaining why evolution matters in a book on language acquisition. The study of evolution is important in a book on the biological foundations of language and language acquisition because evolution and the biological foundations of a skill are two sides of the same coin (Roth & Lawless 2002). This concept is easy to explain if one thinks about physical "skills": A camel has the ability to store large amounts of water in its humps. It is obvious that this competence has a biological foundation: it is possible because the camel has a physical structure that allows for water to be collected

[5]Primate studies show us that one does not need to be human to have an understanding of the concept of death. Chimpanzees, for example, exhibit some practices that indicate an understanding of death as a negative event (Pettitt 2013). However, these practices are not codified (Goodall 2010). Each individual responds in an unpredictable way, for example by shouting, carrying around the corpse of the dead companion, or closing up in periods of silence (Pettitt 2013). We have no evidence that chimpanzees have a more general understanding of the phenomenon of death. In other words, we do not know if they realize that one day what they are observing in the individual next to them will also be their destiny (Pettitt 2013). We have indeed no evidence that this was the case even for hominids in the Paleolithic (D'Errico & Vanhaeren 2015).

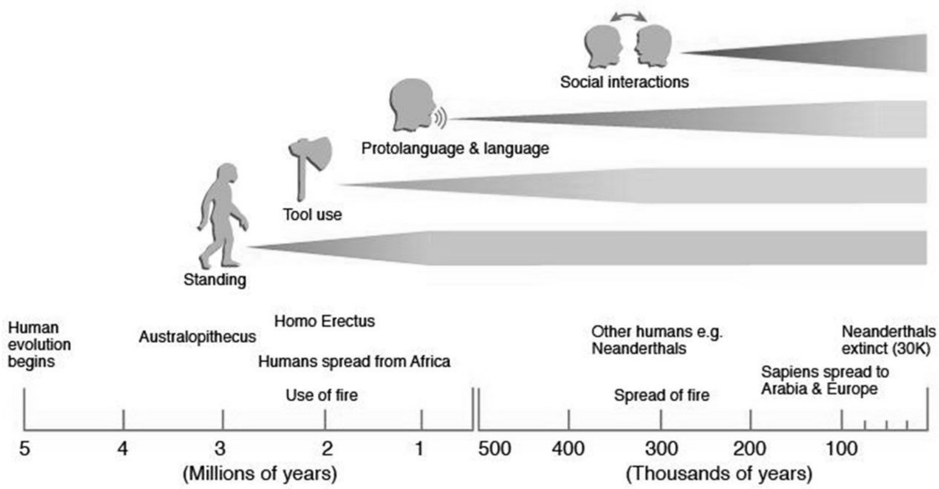

Figure 5.1: Fundamental steps in human evolution. (CC BY-NC 4.0, Henderson et al, 2018, original source: doi:10.1136/jnnp-2017-317245)

(Candlish 1981). It is also obvious that this competence depends on the evolution that the camel and its ancestors went through (Wu et al. 2014). In essence, individuals who accidentally managed to store a greater amount of water tended to live longer, procreate more, and therefore to pass on the genes related to that particular physical structure (Arieli 2001). Today, camels have on average physical structures that allow the collection of large quantities of water (Candlish 1981).

This reasoning also applies to mental skills. To present this reflection, we can discuss a cognitive skill that is shared by many species: short-term memory. First, we can safely talk about the biological foundation of short-term memory. Short-term memory is possible because in the brains of animals that have a memory of this type, there are a series of circuits that allow for it to exist (Christophel et al. 2017). At the same time, it is obvious that these circuits have evolved within the evolution of that specific animal. Accidentally, some individuals exhibited a series of connections that resulted in increased short-term memory skills (Shafi et al. 2007). With short-term memory being an adaptive skill, those individuals were more likely to survive and procreate, passing on genes related to those circuits (Read 2008). Something along these lines must have happened for language. However, as we have seen, our understanding of language and its implementation leaves room for multiple hypotheses on its evolutionary steps.

The hypothesis we outline in this volume about the emergence of domain-specificity during acquisition[6] is compatible with only one account of language evolution: during evolution, the properties that are physically represented in the areas of the brain that are responsible for linguistic syntax must have emerged accidentally and they must have become adaptive. Similar to what was discussed for the evolution of "reading areas" in the brain (see chapter on Language and the brain), certainly the circuits responsible for human syntax evolved accidentally and were potentially used for other tasks for centuries or millennia. With reading, we can safely assume that those circuits initially tackled different tasks (such as shape recognition); in the case of spoken language we might also reasonably assume that what we currently identify as language circuitry had a less specialized use. The skill emerging from this circuitry might have been the ability to combine signs, or, more generally, an ability to combine "items" together. Today, the circuitry quickly becomes domain-specific: Every child being born today is exposed, from day zero (or, in fact, from the womb) to a complex system of communication that strongly relies on the combination of signs. As such, these combinatorial circuits that are present in every human being may automatically "take the job" in all children, leading to an instance of neuronal recycling[7].

[6] Which is, the hypothesis that language areas become domain-specific during development because they are the most naturally qualified regions of the brain, due to their connectivity, to take that job.

[7] Contrary to what was done for the Visual Word Form Area, it is not possible in this case to test children before they develop a domain-specific use of this area. For reading, there is a time-window of approximately 5 years in which children are not exposed to the stimuli that will eventually lead to domain specialization. For spoken language, instead, exposure starts in the womb, making this type of experiment unfeasible.

6 General discussion

In the first pages of the introduction to this volume, I suggested that the term innate is used in the literature with three different meanings, two of which assume language to be (to some extent) a domain-specific skill (Gómez et al. 2014, Samuels 1998). I will focus here on these two definitions, since the third one is not object of debate (all scientists agree that some aspects of language are domain-general, Elman 2005). The first, the most stringent definition, states that children are born with some linguistic skills (Gómez et al. 2014). The second, less stringent, states that children develop domain-specific linguistic skills within a certain time given a standard environment (Samuels 1998, Karmiloff-Smith 2009).

The first definition clearly cannot apply to linguistic skills that require the manipulation of words, since it is evident that infants are not able to manipulate words for a few months after birth (Ambridge & Lieven 2011, Guasti 2017, Tomasello 2009). The first evidence of children segmenting and manipulating words regards infants of 6-9 months of age (Parise & Csibra 2012, Bergelson & Swingley 2012). We can thus exclude syntax among the skills potentially present at birth (Samuels 1998), and together with it we can exclude semantics and pragmatics. The only skill that may, possibly, be present at birth in some form, is phonology (Kuhl 2004, Gervain & Mehler 2010). I reviewed this idea looking at the acquisition of phonology in typically developing infants, and I also provided some relevant insights from bilingual children and children with phonological difficulties. The first section of the discussion focuses on the phonological skills of infants at birth, their relevance for a stringent definition of innatism, and their role in the notion of domain-specificity in language.

The second definition of innate can instead apply to any linguistic skill, since children develop basic forms of syntax, semantics and pragmatics within two years from birth (Ambridge & Lieven 2011, Tomasello 2009). Syntax has received an uneven amount of attention in the literature, the main reason being that syntax is seen (by one group of linguists) as the computational core of language, the fundamental skill that differentiates our system of communication from that of other animals (Hauser et al. 2002). This volume is concerned with the notion of domain-specificity, and its relationship to a biological description of language. The second section of the discussion focuses thus on syntactic skills, the debate about the notion of domain-specificity in syntax, and its role in the explanation of the defining traits of our species.

I will first discuss the strict definition of innate, and thus the role of phonology in the first stages of acquisition. According to an influential publication on this topic (Gervain & Mehler 2010), infants are provided at birth with both domain-specific and domain-general skills that are used to crack the speech code and quickly develop the ability to "tune in" to the language they are exposed to. In the chapter on monolingual and bilingual acquisition I place this idea under scrutiny, looking at what infants can do in the first days and months of their life. There is no doubt that infants use domain-general skills to make sense of the input they receive. Seminal work from Aslin et al. 1998, refined in a number of subsequent experiments, shows that children use transitional probabilities to segment the speech stream. This ability is not domain-specific, as it is used with any kind of input. Though very interesting, this skill is not the object of this volume, since this book does not attempt to see whether there is a role of domain-general skills in language (there certainly is), but rather whether there is a role of domain-specific skills. A more ambiguous domain of investigation in this sense is that of language discrimination. A large of number of studies show that infants, tested as early as a few days after birth, are able to successfully discriminate languages that belong to different rhythmic classes. I have discussed this skill in detail, showing that infants achieve it by looking at the distribution of vowels and consonants they spot in the stimuli. The distributional characteristics of these stimuli are unlikely to be recognized using a domain-specific skill. Once again, children are good statisticians, and they can apply these domain-general statistical skills to any stimulus they receive. The distribution of vowels and consonants is one example, but the skill is not tied to the kind of stimulus presented. It is worth discussing whether the actual discrimination of vowels vs consonants is a domain-specific skill. Since the distinction between vowels and consonants is the main grouping of phonemes available, one may be tempted to claim so. However, the distinction between vowels and consonants boils down to a simple perceptual and articulatory parameter. While vowels do not require disruption of the air when uttered, consonants do. The recognition of this distinction does not require language-specific skills of any sort, but only perceptual skills. Several other species can perform this distinction, including birds and rodents. The discrimination of languages, thus, does not appear to be supported by language-specific skills of any sort. One final domain that carries more promise is that of the discrimination of phonemes. A quote from Goldstone & Hendrickson (2010: 4) explains this concept:

> The degree to which categorical perception phenomena are learned rather than innate is not clear. Consistent with an innatist perspective, it appears that discriminability in some regions of acoustical continua is higher than in other regions, irrespective of category structure. Infants of only 4 months show increased sensitivity to acoustical differences in the same region of physical continua as do adults. Human languages may have adapted to use phoneme category boundaries located in regions with intrinsically higher discriminability. Thus, there is evidence that suggests that people's increased sensitivity to acoustical differences that straddle category boundaries may be a combination of innate properties of the auditory system and the acoustical signal, rather than learned. Similar claims have been made for vision, with researchers finding that color categories for 110 widely varying cultures are highly similar, perhaps even universal, that these categories may be determined by general optimality considerations, and in turn determine patterns of perceptual sensitivity.

As I have discussed at length in the chapter on monolingual and bilingual acquisition, these are some elements that fuel the debate about the presence of some innate skills related to phonology. In short, many studies show that children can discriminate non-familiar phonemes from the very first days of their life. This ability may be misunderstood as evidence of the presence of a phonological formatting in the mind of newborns. However, a domain-general explanation of this skill is possible: children may be able to discriminate non-familiar phonemes acoustically, without any need for phonological categories. For instance, the phonemes /p/ and /b/ are acoustically different, whether or not they represent separate phonemes in a given language. Nonetheless, the idea that phonological categories are innate can be scrutinized by testing whether infants perceive non-familiar contrasts categorically or not. This idea was investigated in a few studies, but the results are not clear-cut. It appears that children can perceive some differences within continua of non-familiar contrasts (a fact that would be in favor of a domain-general explanation of their skills). However, it also appears that they do treat certain different sounds as identical, suggesting that there is a form of default formatting, a formatting that McMurray & Aslin 2005 defined as "dimensional islands". It must be noted that the stimuli used in Miller & Eimas 1996 as well as McMurray & Aslin 2005 tap into contrasts that are present in the infants' L1. While their data seems to show a gradient perception of familiar contrasts, as well as the presence of proto-categories, it offers little support in favor of or against the claim that the perception of unfamiliar contrasts is categorical. In both cases, children had experience in the input of contrastive tokens differing in the VOT. Additionally, it is now accepted that sufficient sound is transmitted through the womb so that children could arguably have formed categories by exposure already before birth. This would then imply that these phonological categories are not, in fact, innate, but have formed as a result of input even before birth. The only evidence of categorical perception of non-familiar contrasts comes from old studies (Lasky et al. 1975, Streeter 1976 which are also partly in contradiction (one shows 2 boundaries in the VOT continuum, the other shows 3) and more advanced and modern analyses as well as cross-linguistic replication are needed to rely on that evidence.

Categorical perception is observed in several different domains in humans, for example in the domain of colors and in the domain of face-recognition (Kotsoni et al. 2001, Hoonhorst et al. 2011). Thus, it is important to stress that categorical perception is not domain-specific. Furthermore, as Ramus et al. 2000 point out, the ability to organize continua into categories is shared with other species – certainly primates but also, more generally, mammals. Kuhl & Miller 1975, for instance, showed that trained rodents can learn the distinction between /t/ and /d/, and that this distinction was perceived categorically with a boundary comparable to that of humans. However, this type of result is not particularly informative about the innatism of phonological categories in humans for two reasons. Firstly, animals were trained to recognize the sounds (in other words, they were not discriminating unfamiliar contrasts). Secondly, even if categorical perception as a faculty is neither language nor species specific, the nature of the categories that humans perceive may not be domain-general. The boundaries at which newborns stop perceiving one phoneme and start perceiving a different one may be based on factors attaining to linguistic formatting. For this reason, the fact that other species show categorical perception is not detrimental to hypotheses that use categorical perception as a tool to understand the extent of innate linguistic knowledge. It is not categorical perception per se which is important in the discussion about the innateness of phonological categories, but rather the hypothesized existence of perceptual categories before extended exposure to language. Despite the fact that the perception of unfamiliar contrasts is used to make claims in favor of innate phonological formatting, concrete evidence for innate categorical perception of these contrasts is quite limited. This evidence is, however, needed in order to make a convincing claim, since the pure distinction of unfamiliar contrasts may be performed acoustically, with no need for phonological categories. There is a surprising lack of studies on this issue considering how crucial the problem is. Further studies investigating newborns' perception of unfamiliar contrasts using graded perceptual tasks are needed in order to ascertain whether phonological categories are innate or not. Specifically, studies on unfamiliar contrasts in newborns are required in order to determine whether it is indeed exposure to L1 sounds in the womb that leads to the formation of categories based on input, or whether categories are indeed innate.

The one fine-grained proposal that seems to be able to capture this complex bundle of data is possibly the one by Kuhl 2000. According to the author, children perceive categorical boundaries from birth, as well as within-boundary variability. The nature (or the position) of the boundaries may not be in any way arbitrary but reflect a natural organization of the perceptual space. For example, the VOT continuum may be divided by two relatively wide boundaries organizing the perceptual space in three islands. If so, the baseline prototypical boundaries observed may be a consequence of the nature of our speech perception system, rather than representational categories encoded in our mind. In her words (Kuhl 2000: 11853):

> The initial perceptual biases shown by infants in tests of categorical perception as well as asymmetries in perception seen in infancy, produce a contouring of the perceptual space that is universal.

However, further investigations on categorical perception with unfamiliar contrasts are needed to ascertain the validity of this statement, since the data available so far is quite limited and partly inconsistent. A systematic cross-linguistic study on the categorical perception of non-familiar contrasts in newborns could finally answer one of the questions of this volume, which is whether some phonological categories are innate (in the strict sense of "present at birth"). The bundle of data available points to the existence of a number of "islands", that are perceptually bound (i.e. delimited by perceptual constraints). If this finding is confirmed with a larger amount of data, the question will become a philosophical one: shall we consider perceptual islands a kind of innate phonological knowledge? With this aleatory question I would like to close the section on the first definition of the term innate, used in the sense of "present at birth". The conclusion one may reach from this extensive amount of research is that, if there are linguistic skills that are present in a child's mind at birth, these are likely to be of a perceptual nature.

In the introduction, I mentioned that the term "innate" must be used, instead, with a different meaning when referring to syntax. Within the generative tradition, syntax is innate in the sense that "it is not expressed at birth, but the system is written in our genes and will express with maturation given a standard environment" (Samuels 1998). When it comes to syntax, psycholinguists cannot adopt as a methodology the study of infants, since scientists, even those in the generative tradition, do not expect children to show any syntactic skill at birth. The investigation addressing the concept of innatism in syntax must instead focus on the possible domain-specificity of this skill, both at the level of representation and at the level of brain implementation. Throughout the second half of this volume, I have presented a large number of studies that discuss domain-specificity and domain-generality of syntax, and I will try to make sense of these studies in this section.

Linguistic syntax is the ability to combine words to form sentences. To what extent is this ability domain-specific and to what extent is this ability domain-general? There is ample evidence suggesting that some procedures that we use in linguistic syntax are not domain-specific (Frost et al. 2015, Fedorenko et al. 2013). We have seen that violations of musical syntax lead to electrophysiological components that partly mirror those obtained with violations in linguistic syntax (Koelsch & Friederici 2003). We have also seen that Broca's area, the region of the brain normally described as the foundation of linguistic syntax, contains microregions that respond to the processing of mathematical hierarchy (Fedorenko et al. 2012). Finally, studies on different species show that other animals are capable of processing some forms of hierarchy that mirror linguistic syntax. For example, some birds can evaluate sequences that follow or do not follow hierarchical rules (Gentner et al. 2006). The combination of these studies would suggest thus that linguistic syntax is the consequence of domain-general skills, and, particularly, the consequence of our ability to combine elements (of any kind) and put them together to form hierarchical structures.

Nonetheless, other studies seem to point in the opposite direction and seem to suggest the existence of domain-specific processing for linguistic syntax. First, a direct comparison of the brain activation of individuals who are completing mathematical and linguistic problems shows that the resolution of mathematical problems that require the processing of hierarchies do not tap into the same circuitry used to process sentences that display similar levels of hierarchy (Amalric & Dehaene 2019). Secondly, the study of patients shows that a deficit dissociated to linguistic syntax can occur, and the medical literature does report cases of patients who lost syntax but retained mathematical and musical abilities (Varley et al. 2005, Warren et al. 2003). In addition, several studies report opposite cases, where patients lost their mathematical abilities but not the musical or the linguistic ones, or where patients lost their musical abilities but not the linguistic or mathematical ones (Benson & Weir 1972, Sihvonen et al. 2016). Third, and most importantly, modern fine-grained analysis of brain activation conducted using functional magnetic resonance imaging seems to identify some specific circuits of the brain that respond uniquely to linguistic syntax (Zaccarella & Friederici 2015, Friederici 2020). This small region of the brain seems to be responsible for the so-called *merge operation*, the combination of two linguistic items to form a new unit (a phrase). The region does not respond when non-linguistic elements are combined, and it also does not respond when presented with linguistic elements that cannot be combined. The region thus seems to be specialized for the combination of small linguistic units. How is this evidence compatible with the evidence previously presented showing domain-general processing in linguistic syntax? I will discuss each of the previous studies separately and in relation to the current claims on domain-specificity.

First, studies showing similar electrophysiological response to syntactic violations in music and in language do not show identical patterns in the two conditions: generally speaking, while linguistic violations generate components that spread from the left hemisphere, musical violations generate components that encompass both hemispheres (Koelsch & Friederici 2003). This, per se, does not entail that there is a dissociation between the two skills. It may be the case that domain-general circuitry is placed in the left hemisphere, and music entails additional circuitry in the right hemisphere. However, this differential pattern is also not clearly leaning towards the concepts of resource sharing and domain-generality, since it may be the case that, for music, violations are processed in the right hemisphere and the language-like brain components are just a reflection of similarities between the two procedures (and thus a domain-specific interpretation is still possible). Similar conclusions can be extrapolated from studies that compare brain activation in mathematical and linguistic tasks. While it is true that both syntax and mathematical hierarchy rely on Broca's area, several studies suggest that different micro-circuitry is involved in one task or the other (Amalric & Dehaene 2019). Fine-grained analysis of brain activation seems to suggest that there is a separation between the two skills in the brain, and two different micro-areas are involved (Fedorenko et al. 2012). These areas are adjacent, and this proximity cannot be due to chance. However, this adjacency does not entail, per se, that both syntax and mathematics rely on the same domain- general circuit. Finally, animal studies do show that following extensive training some species are able to perform "grammaticality judgments" that resemble those that we perform on syntactic structures (Gentner et al. 2006). However, these tasks are completed only following extensive training, and are not natural for any of the species investigated. If we observe the communication systems of the other mammals or of birds, we will notice that none of them uses anything resembling syntax, and that structure is substantially absent in natural environments (even though some species display the use of small combinations of sounds, Engesser

& Townsend 2019, Ganau 2025). Where do we stand then? Shall we conclude that syntax is a domain-specific system implemented in a dissociated manner in our brain? Shall we conclude that syntax is the consequence of evolution and that it evolved following the pressure of natural selection in our species (and not in the others)? The answer to this question is not unequivocal and I will try to unpack it in its subparts.

First of all, it may really be the case that some components of syntax are implemented in the brain in a dissociated manner, since some studies seem to suggest that (Zaccarella & Friederici 2015, Amalric & Dehaene 2019, Friederici 2020). However, it should be stressed that the physical adjacency of the circuitry of other cognitive skills that require hierarchy to the circuitry specialized for linguistic syntax is unlikely to be due to chance, so it might still be possible that both domain-specific areas depend on domain-general circuitry, somewhat physically proximal (Fedorenko et al. 2013). The data available does not exclude this possibility, and further research is necessary to be more certain about domain-specificity of linguistic syntax in the human brain. At the time of writing, this seems like a plausible claim, but the proximity with the processing of other forms of hierarchy invites prudent conclusions. One second aspect to consider is that domain-specificity in the brain – even if it was confirmed with certainty – does not entail, per se, that the area evolved as a consequence of natural selection during evolution (Dehaene & Cohen 2007). I have discussed at length the brain areas involved in reading and how these cannot be the consequence of evolution: in short, we know that reading is a new invention, approximately 5000 years old, and evolution operates on considerably longer times. Now, the brain is the way it is because of evolution, but, due to its plasticity, we can reasonably expect that areas that have evolved because they are adaptive in completing a certain task, might be equally fit to complete a different task that the environment requires today (Dehaene & Cohen 2007). The areas that are used for reading probably evolved because successful in processing visual shapes of some sort, possibly as a mean to recognize abstract figures (Dehaene et al. 2010). Whenever a child starts the process of learning to read, that area reveals to be “qualified” for the task and takes the job (Dehaene & Cohen 2007, Saygin et al. 2016). Can we exclude that something similar happens for linguistic syntax? It may be the case that the (few) circuits of the brain that appear to be specialized for syntax evolved for a different reason, and they are simply “qualified” to take the job anytime a child is exposed to language during infancy (an idea consistent with the neuroconstructivist approach, Karmiloff-Smith 2009). Early language exposure is the default situation for all children, and this makes experimenting on this issue very difficult, virtually impossible: We cannot deprive children of language exposure to see what happens to the circuitry devoted to linguistic syntax in that context. In addition, the (fortunately) rare cases of children growing up in environments deprived from linguistic stimuli are often investigated by large teams of researchers, and these show that, in such contexts, several issues arise that make conclusions debatable. For example, a child growing up deprived of linguistic stimulation may experience a number of psychological traumas that are not necessarily related to language. For these reasons, the best method to address the problem of domain-specificity in language development remains the study of brain activation in healthy individuals. The search for domain-specific and domain-general circuitry can help ascertain whether syntax is shared between language and other skills, or different kinds of syntax operate in different domains. However, whatever the answer to this question is, the problem of whether linguistic syntax evolved under the pressure of natural selection may remain unsolved, as we cannot look at what language areas do in children that are not exposed to language, and we cannot go back in time to when language did not exist.

The idea of neuronal recycling finds an interesting parallel in the study of computational modelling, where a group of researchers have tried to address the concept of language evolution using artificial networks (Culbertson & Kirby 2016). As the authors explain, the fundamental issue under the lens is whether evolution is consistent with the idea that domain-specific linguistic circuitry developed under the pressure of natural selection. In the chapter on evolution, I described in detail the various steps one expects in the evolution of a trait, and I have thus presented some proposals that hold that the basic principles of natural selection could have led to language. As Culbertson & Kirby 2016 point out, these proposals assume (or must assume) that domain-specific circuitry is hard-wired in our brain: a trait that evolved biologically must leave a physical trait in the nervous system. As I have discussed in the second part of the volume and in this section, the claim that syntax is hard-wired in the brain is, however, subject to debate. The regions and circuits of the brain that are supposedly specialized for language, appear to be used to some extent in a number of other tasks (such as musical and mathematical tasks). The first conclusion proposed by the Culbertson & Kirby 2016, then, is that the notion of hard-wired implementation for language, evolved through evolution, is not easily consistent with the data available. However, the authors notice that language does show some peculiarities (syntax is the most obvious one: linguistic syntax is not identical to the syntax used in other domains), and the parallels we can make with other areas of cognition do not always seem straightforward. The authors offer then a conciliating proposal between these contradicting facts: The proposal consists of two claims:

- There are biases in our cognition that lead to language being a certain way and not another.
- These biases are not domain-specific, but they appear to be particularly relevant for language[1].

Two examples provided are the bias of simplicity and the bias of compositionality, that I will present in the next section separately: Generally speaking, human cognition favors simplicity. Following Chater & Vitányi 2003, simplicity can be described as the tendency to select the explanation that requires the fewest steps, given a particular input. A well-known example comes from Gestalt psychology: the law of closure demonstrates that our minds perceive complete shapes even when visual input is fragmented. For instance, when presented with a series of disconnected lines forming an incomplete figure, we still perceive a circle or a square, despite the input differing significantly from these idealized shapes (see Figure 6.1).

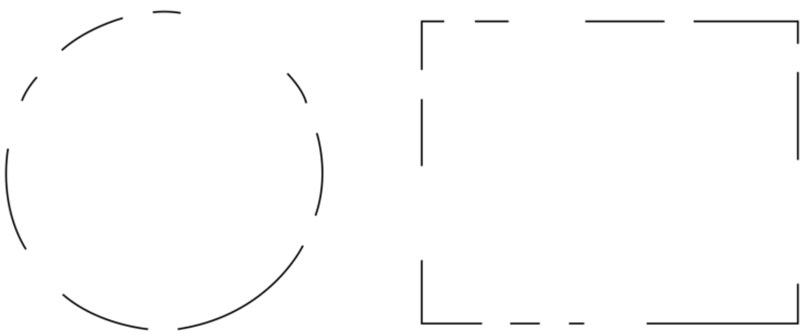

Figure 6.1: Input used in Gestalt experiments. (Public Domain, Wikimedia commons, Original source: https://commons.wikimedia.org/w/index.php?curid=3961043

[1]This proposal stems from computational modelling, but one may see the parallel with my previous statements on neuronal recycling: language areas are not language-specific, but they appear to be very well qualified for the processing of language, thus they take that task automatically. Not surprisingly, similar ideas appear in Karmiloff-Smith (1992), Karmiloff-Smith (2009).

This preference for simplicity extends to language. Speakers tend to favor the simplest explanation when processing syntactic rules or inflectional systems, often seeking patterns. From an ontogenetic perspective, young children exhibit a strong tendency to overregularize their linguistic output, applying simple rules even where exceptions exist (Marcus et al. 1992). However, while cognition is biased toward simplicity, language must also serve communicative needs, balancing efficiency with informativeness and originality. This drive for meaningful expression contributes to linguistic complexity (Culbertson & Kirby 2016). One key property that adds complexity to language is compositionality, i.e. the ability to combine smaller units to express more complex meanings. In contrast, the communication systems of other primates lack compositionality, limiting the amount of information they can convey (Fodor & Lepore 2002). Indeed, no known human language functions without combining linguistic elements into structured expressions (Nevins et al. 2009).

According to Culbertson & Kirby 2016, simplicity and compositionality are fundamental cognitive biases. But what underlies these tendencies? Is there a biological basis for them? If we accept their proposal, the answer is yes: both biases must be rooted in the neural architecture of the brain. Are these biases domain-specific? Certainly not, as evidence suggests that simplicity and compositionality operate across multiple cognitive domains, not just in language (Chater & Vitányi 2003; Fedorenko et al. 2012). Importantly, despite being domain-general, according to the authors these biases do have a domain-specific effect on language, meaning that their use is different, and probably prominent, in language (Culbertson & Kirby 2016). Mathematics, music and language are all prone to simplicity and compositional biases, but the role of these biases in language appear more important than in the other two. Evolutionarily speaking, the authors neglect the possibility of hard-wired, domain-specific evolution of these biases. They argue instead that these skills have evolved as domain-general competences, but revealed quickly, in the space of one generation, to be very applicable in one domain (language) better than in any other one (Culbertson & Kirby 2016). Their proposal, in line with my proposal, is that every individual that is born experiences this ontogenetic domain-specific transition, where a skill that is potentially applicable to many domains, and capable of doing so, becomes adopted massively for one domain, because this is a sensible use of resources. Interestingly, we are quite confident that this is what happens for reading, as extensively discussed in multiple sections of this volume. When it comes to reading, we do not have a problem imagining a scenario of this kind, because we have a relatively clear understanding about the brain foundation of reading and the domain-specificity of this skill, but we also know that reading is just too new of an invention to have a domain-specific evolved area in the brain, so we naturally recur to the idea of neuronal recycling (Dehaene & Cohen 2007). Even though it appears less intuitive, it may well be possible that something very similar happens for language. To sum up this volume in one sentence: even if language emerged in a time that is evolutionarily plausible for a hard-wired trait, the evidence of the partial domain-generality of the basic skills that constitute human communication suggests that language areas become domain-specific only because this is an efficient use of resources during development.

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Language acquisition

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