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INTRODUCTION

This thesis concerns the role of recursion in human cognition and natural language, especially in syntax, since it is considered to play a crucial role in human language ability. Most attention in this field, however, has been drawn towards such sentences that contain more than one clause and thus yield hypotaxis. Besides the question which role recursion plays in the human ability to process language, this thesis is also concerned with the question, what exactly is recursive in natural language syntax, since this also is important to the question how, and especially why, language evolved in humans and did not in any other species. For this purpose it has to come clear in how far language differs from other communication systems and what exactly these mechanisms are, how they are processed in the brain, whether and where they appear in non-linguistic domains, and in how far other species than humans are capable of these mechanisms.

The 1st chapter introduces the term *recursion* and the concept that stands behind it, and moreover shows its application in different fields. Further, this chapter presents and discusses possible differences between recursion and other types of repetition, such as iteration.

Chapter 2 presents recursion in linguistic theory, particularly generative theories as phrase structure grammar and the Minimalist Program. Moreover, within this chapter, it is discussed, what the mechanism is, that makes syntax recursive, and whether there is good reason to believe that all sentences yield recursion, or if there are special properties that make only sentences recursive that contain subordinated clauses.

In Chapter 3, brain structures that are considered to represent the activation pattern during syntactic and recursive processing, within and outside the linguistic domain, are looked at more closely. Additionally, it is investigated which role has to be dedicated to working-memory, concerning this issue.

Chapter 4 is about recursion within human cognition and the cognition of non-human species. More particular, the first part of this chapter is concerned with the role recursion plays within domains outside language, and what this means for recursion

in linguistic syntax and for the human language ability as a whole. Moreover, this part of the chapter also discusses the need for recursion in human language on the example of the language Pirahã, which had been considered by Daniel Everett to be a non-recursive language.

The second part of the 4th chapter is concerned with probable language-like processing and general cognition in non-human species. As an example for this, songbirds and non-human primates are looked at in particular. Songbirds are looked at on the one hand, since they are considered to have syntax-like dependencies within their songs, and also share some crucial features of human language faculty in terms of acquisition, and non-human primates are considered on the other hand, since they are the closest relatives to humans. Moreover, genetic differences that are related to human language ability are considered, as well.

The last chapter investigates recursion within the framework of language evolution and especially the evolution of syntax. For this purpose, different theories on language evolution are discussed as well as the evolution of the human brain with respect to syntax. Moreover, the role of recursion for the human language ability is looked at more closely.

CHAPTER 1

WHAT IS RECURSION?

1.1 THE GENERAL CONCEPT BEHIND THE TERM RECURSION

The aim of this chapter is to give an introduction and a first idea about what recursion is, and about the debate which unfolded after Hauser et al. had published their paper in 2002. Before coming to specific examples, a general description about what is behind this term is given.

The term recursion comes from mathematical logic and number theory and describes the concept of repeating itself in a self-similar way. To repeat itself in a self-similar way means that a recursive function calls up itself by using its output as the next input. Roughly speaking, this means, a function which is recursive, defines its values via itself (Luuk et al. 2011:2).

One of the characteristics of recursion is its complexity, because of the fact that the usage of one output as the next input can theoretically go on ad infinitum. A special feature of recursion is that it can compute infinite structures by using a set of finite properties or rules: Recursive functions are able to describe infinite sets by a finitely definable set of properties (Luuk et al. 2011). However, recursion is not only present in mathematics, but also in a variety of fields including plant growth (Prusinkiewicz et al. 1990) and preeminently in human behavior and thinking (e.g. Corballis 2011). A good working example for recursion in human thought is theory of mind, holding thinking of thinking. Processing recursion in every-day life includes multistage problem solving like using tools to reach a certain goal, e.g. using a ladder to reach an item which is out of reach, or even action planning like making coffee. Which role recursion plays in human cognition shall be discussed in Chapter 4.

However, concerning cognition and linguistics in particular, there is a debate going on about what recursion exactly is. This debate led partly to some confusion about

certain terms, like *hierarchy, recursion* and *embedding,* which are associated with the concept of self-similar repetition. Hence, the most frequent terms concerning this topic are looked at more closely to be able to find out, whether there is a proper assumption in distinguishing between different types of recursion with respect to syntax and cognition.

First, we will take a look at the concept of recursion in different fields to get a better idea of what it is all about. After that, some of the problems concerning the probable differentiation between recursion and other types of repetition are considered.

1.2 RECURSION IN DIFFERENT FIELDS

The first field, we are looking at in particular, is mathematics. Recursion plays an important role in the superordinate domain of logics as well as within different subfields of mathematics, like geometry, for example.

A perhaps rather plain example for recursion in mathematics is factorials: 5! equals 120, because 5! is 5*4*3*2*1, which is 120. A defining equation for this looks like that:

(1)   0! = 1
        n! = n * (n–1)!   [where n > 0]

<div align="right">(Corballis 2011:5)</div>

The recursive step here falls into the point where the outcome of e.g. 5*4 is used as the input for the following multiplication with the number 3.

Another example is Fibonacci numbers, which were used by Fibonacci, an Italian mathematician, to predict the growth of a hypothetical population of rabbits. (Corballis 2011:5)

(2)   1,1,2,3,5,8,13,21,…

(3)   fibonacci (0) = 1
        fibonacci (1) = 1
        fibonacci (n) = fibonacci (n – 1) + fibonacci (n – 2)   [where n > 1]

Indeed, these numbers do not just reflect something theoretical, but are also present in the structural composition of a sunflower's flower head, to give only one of multiple examples.

Also, recursive functions deal with the problem of computability of algorithms. An algorithm, in terms of mathematics, is a problem which can be defined through a set of rules. Furthermore, recursive functions in a mathematical sense are characterized through their property of describing a *solution* to a problem rather than the individual steps towards a solution (Erk 2008). A problem in this thematic environment is the question, whether a particular feature is true for a particular object or not. For this purpose, objects *o* from a universal set *O* are considered. Solving a problem in mathematics by recursion is a method by which the main problem is divided into smaller sub-problems to get solved (Erk 2008).

Recursive definitions, in general, consist of two computational steps, which refer to each other: The first one determines the condition, which ends the recursive process, while the second forms the recursive step. Formally speaking, this looks like the following, taken from Tomalin (2006):

(4)   1) f(0) = q
        2) f(y') = (x(yf(y)) [where q,y,y' $\in$ N]

The first equation in (4) determines the termination condition defining that if 0 is the input to the function it will return to the natural number q. Returning to the natural number q ends the computation because no further recursive step follows. The second equation in (4) shows the recursive step, since, if the natural number y' is used, the value of y' is computed by calling up the function x, which needs two arguments: First the natural number y (y = y' − 1) and second the function f(y) (Tomalin 2006:80).

The following example, also taken from Tomalin (2006), illustrates counting, which is also recursive, as formal definition:

(5)   add(4,1)=add(3,1)+1
        add(3,1)=add(2,1)+1
        add(2,1)=add(1,1)+1
        add(0,1)=1

Another very common example for recursion in mathematics is the inductive function. Mathematical proofs are often defined through induction. For example, to show that all natural numbers have a particular property, it is sufficient to show that 0 has this property and if a number n has this property, to show that n+1 has this property, too (Erk 2008:6).

The logical formula for induction, taken from Erk (2008), looks like that:

(6)   P(0)∧ ∀n(P(n) => P(n+1)) => ∀n P(n)

The first part in (6) before the conjunction means that, in order to fulfill the proof, it has to be shown that 0 has a particular property, since P(0) equals 0. The second part after the conjunction says that in order to show that all other numbers show this property, it has to be shown that first, P(n), which resembles any integer, let's take 5, has this property, and then it additionally has to be shown that P(n+1), which means 5+1, which equals 6, has this property, too. The last part of the equation after the arrow shows that, if it has been proven that, both 0, n, which is in our case 5, and n+1, which is in our case 6, all have this particular property, every natural number must have this property. The recursive step within this equation is that, if I want to show something by taking any number and then proof that this property is true for n+1, n+1 is recursive, since it uses the last output, namely 5 as the next input, which is a property of recursion.

Moreover, in geometry, recursive structures can be very fascinating. Fractals are geometric objects with a structure that consists of an increasingly smaller copy of itself which makes it recursive, since the former output retains and as the more steps are added, the object gets bigger and more complex. Thus, the individual figures within a fractal have hierarchical relationships to each other. Fractals have decimal numbers as dimension, such that they have neither the dimension 1, nor the dimension 2, and thus suggest a different thinking about the term dimension than classically assumed (Haftendorn 2009:80).

One example for fractals is the Sierpinski triangle, which is named after the mathematician Waclaw Sierpinski who imagined this triangle like the following:

To create such a triangle in thought, one has to take an equilateral triangle and pull out a similar triangle with the half of the side length of the initial triangle. This

procedure has to be repeated with the triangles which now appear outside the new triangle. After this, the procedure, theoretically, has to be repeated infinitely (Haftendorn 2009).

An even more complicated but a very much fascinating example is the Mandelbrot set. Mandelbrot sets result from a recursive formula with certain properties. The Mandelbrot recursion looks like this (Haftendorn 2009):

(7) $z_n = z^2_{n-1} + c$

And has the carrier function:

(8) $f(z) = z^2 + c$

The variable z is a complex number and c is a constant, namely a coordinate in a circle, from where the Mandelbrot set is started. If a point is within the circle it gets the color black, if it doesn't belong to the circle, it gets colored. The color represents the number of steps which were needed until the function broke out of the circle. Once the function breaks out, it never comes back into the circle and runs to infinity. All points c which are not within the circle actually do not belong to the Mandelbrot set (Haftendorn 2009:102).

In computer science, recursion is an important element for the description of computational models. Recursion needs more computational power, which distinguishes it from an iterative process. But generally, every recursive function can be converted into an iterative one and vice versa (e.g. Lobina 2011). Concerning computational operations in computer science, to stop a recursive operation, a termination condition is needed. It is checked first, if such a condition is available and in the case of not applying, the function goes through with self-reference (Erk 2008).

In botany, recursion has its place, too. Here, growth of plants can be simulated by recursive functions. One possibility to do this is by using the Lindenmayer system, which is named after the Dutch biologist Aristid Lindenmayer, who invented this system to model natural plants. This concept of modeling can be put in context with fractals in general. By using computer simulation, natural growth of plants can be shown (Haftendorn 2009).

(9)

http://blog.ralfw.de/2010/12/maschinen-bauen-aber-software.html

To create a fractal tree, a trunk (n) is needed, of which in a y-shape, two trunks (n-1) arise, which looks like this:

(10)

http://blog.rki-home.de/2008/04/09/fraktale-spielereien
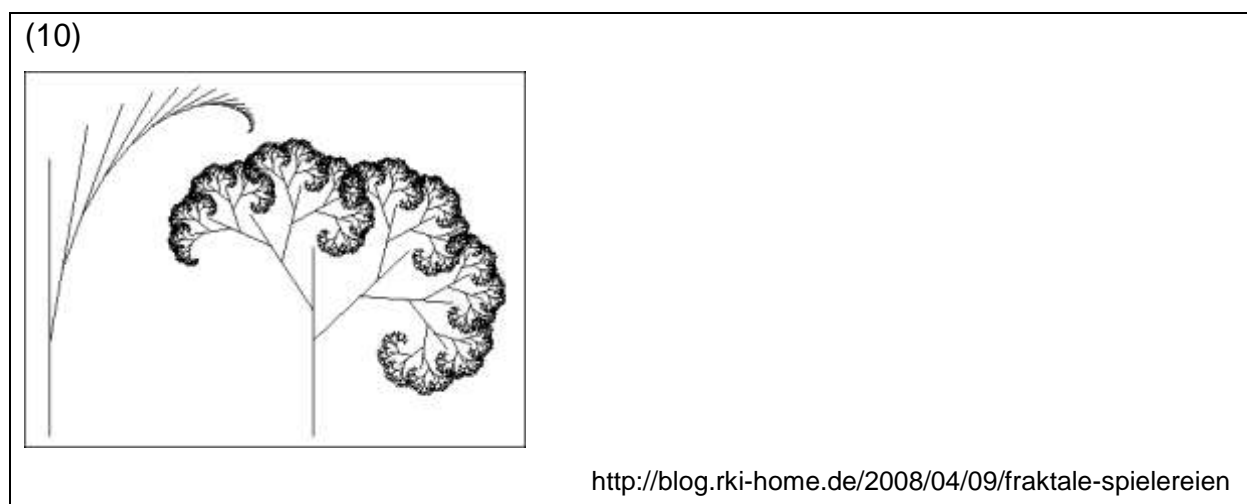
Another way to create natural growth is via *iterated function system* as used for the Sierpinski triangle. A very important feature concerning IFS is its self-similarity (Haftendorn 2009:99).

Recursive structures is not only something that can be modeled by using computer graphics, it is also a phenomenon, occurring in natural environments. For example, the cone of a pine has a recursive structure, which resembles Fibonacci numbers and looks like follows:

(11)

http://www.mat.uc.pt/~mat1164/WebFibonacci.html
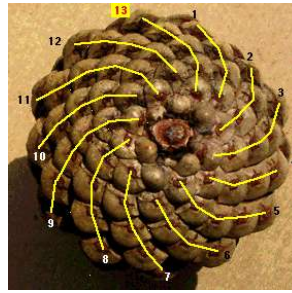
http://www.casioschulrechner.de/de/teilnehmervektoria2008/erben_des_pyhtagoras/seite%202.html

So forth, it has been shown the general properties of recursion and some fields it belongs to. The next section is about some controversy and uncertainty concerning recursion in syntax.

1.3 CONTROVERSY ABOUT THE TERM *RECURSION*

After Hauser, Chomsky and Fitch (2002) had published their paper on recursion, some criticized, that it has not been clear, whether the explanations had been done on recursion or iteration. van der Hulst (2009), for example, argued that it is important to distinguish between these two ways of repetition, and Luuk et al. (2011) suggested that recursion has to be distinguished not only from iteration but also from "simple" embedding, which does not have the same computational demands as iteration or recursion. Corballis (2011) on the other hand argued that a distinction has to be made between recursion, iteration and "simple" repetition. We now take a look at this controversy to get an idea of what is argued about.

1.3.1 Recursion versus iteration and "simple" repetition

As Corballis pointed out, recursion is not the only device which can create sequences or structures of potentially infinite length or size (Corballis 2011:9). According to him, besides simple repetition, iteration is one of such devices. Considering simple

repetition, a sentence like "It rained and it rained and it rained and it rained" (Corballis 2011:19) can be continued infinitely, but according to Corballis, is neither recursive nor iterative, since the second element of the sentence has not necessarily to refer to the first one etc. Furthermore, this sentence is also considered to lack hierarchical embedding which is one of the main features of recursive structures (Corballis 2011). Another type of repetition is iteration, which differentiates from simple repetition: Iteration compared with simple repetition and aggregation needs its output as the next input and therefore seems to be much closer to recursion than repetition in the manner described above. In fact, iteration is treated as kind of recursion by mathematicians by belonging to the general recursive functions (Corballis 2011:11). What doesn't qualify this type of repeated structure processing for recursion is the fact that each output is discarded after it has served as the next input, which leads to missing complexity that can be seen in recursive structures (Corballis 2011). This argumentation by Corballis, however, seems not to hold for syntax in natural language, since even in coordination, which is often considered iterative, the beginning of the sentence has to be kept in mind to understand the whole sentence's meaning, such that nothing is discarded.

Another view is that differences between recursion and iteration include that iteration does not involve self-reference, such that the last output is not used as the next input, but that every input has to be defined explicitly (Luuk et al. 2011:2).

To illustrate the difference between recursion and iteration, a repeated process like going down a road can be written as a recursive instruction and as an iterative instruction.

---

(13) ITERATION


```
Def going along a road ():
            from the first step to the last step:
            take a step forward
      DONE
```

---

(14) RECURSION


```
Def going along a road ():
        If goal is reached: DONE
        else:
                take a step forward
                going along a road ()
```

(Idea taken from: http://www.hib-
wien.at/leute/wurban/informatik/Rekursion.pdf)

In (13) the process is repeated by using a loop and in (14) the process is repeated by the function calling up itself again and again and doesn't need a loop to do so: Here, an ending definition and the recursive definition are given.

Iteration other than recursion, does not lead to added complexity (Corballis 2011). However, a recursive instruction can seemingly be written by means of recursion as well as iteration. Luuk et al. (2011) point out that, in terms of computation, a clear difference between these two devices can be observed: Recursive functions need more time and computational power, because they need to store information in some kind of memory device, but are a more elegant solution in solving problems. In terms of computing problems in a mathematical sense, recursion and iteration are the only devices that can handle repetition (Luuk et al. 2011).

Although iterative functions are sometimes handled as general recursive functions, for natural language, it probably is important to differentiate between recursion and iteration because of the computational demands which are behind these two devices, although there are existing views which claim that there is no need for language to use recursive processes, since these can also be described in an iterative manner (Luuk et al. 2011).

Karlsson (2010) brings it to the point that the main common feature of recursion and iteration is plain structural repetition in the way of "emitting instances of the current structure or stop", while their main difference is that recursion builds up structure by increasing embedding depth. In contrast, iteration always has a flat output because no depth of embedding occurs (Karlsson 2010:43).

Harley (2007) claims that concerning syntax, iteration is the ability to carry on repeating the same rule, potentially forever, while recursion is to divide a bigger

problem into smaller ones, meaning analyzing phrase structure rules. Furthermore, he claims that iteration can be done without recursion (Harley 2007:40)

However, the question arises, if it is really necessary to distinguish between recursion and iteration, particularly in the field of recursion in syntax and cognition and more importantly, how, or rather in which terms such a differentiation has to be made.

1.3.2 Recursion versus "simple" embedding

The difference between "simple" embedding, how Luuk et al. (2011) called the idea that embedding does not always refer to recursion, and recursion itself, is partly determined by the scientific field it is used for, if a difference is made, anyway. In computer science, as Luuk et al. point out, for example, that recursion is related to the concept that a procedure definition refers to the procedure itself. In Chomsky's phrase structure grammar, recursion is a property of rewrite rules, which resembles that what is on the left side of the arrow repeats on the right side of this arrow, e.g. A→AB, where the recursive step is as follows: A→AB→ABA→ABABA and so on (Luuk et al. 2011).

Another view of recursion is that it is a structural property, where an instance of an item is embedded in another instance of the same item (Luuk et al. 2011:4). Thus, Luuk et al. argue that recursion can be defined as the procedure of self-embedding and self-embedding in turn is the structure of the procedure that led to a structure with self-embeddings. Furthermore, he argues that embedding and recursion can apply independently from each other (Luuk 2011:4). This independence goes back to the difference between recursion as a procedure and recursion as structure (Luuk et al. 2011). However, to take Luuk et al.'s example, a self-embedded structure doesn't have to be generated recursively, since, taking their example, a box within another box is self-embedding, but not recursive, since to recognize an object within the same object does not need recursive abilities. The same, according to them, applies for an NP which is located within an NP. Take the following phrase as an example for this:

(15)   *The book and the pen*

   [NP[NP The book]and[NP the pen]]

Here, two NPs are located within another NP, but this, according to Luuk et al., makes neither the structure nor the process that generates it recursive (Luuk et al. 2011). Although Jackendoff and Pinker (2005) took a picture of a particular form within the same form to illustrate recursion on a visual level, Luuk et al. argue that this is not what is behind the idea of recursion, and that the ability to process recursive structures is not needed to understand such visual stimuli, like it is not needed for recognizing a box within a box (Luuk et al. 2011:4). The same thing, according to Luuk et al., holds for some syntactic structures, like NPs within NPs, which have embedded items, but are obviously to them not recursive and come from syntactic rewriting in phrase structure rules: These rewrite rules do not have to be generated recursively, but can also be generated iteratively (Luuk et al. 2011). Furthermore, Luuk et al. postulate that, considering the rewrite rule from phrase structure grammar, AB→AABB, which generate the strings AAABBB, AAAABBBB and so on, it is impossible to tell whether these strings were generated by a recursive or iterative process, or by neither of it (Luuk et al. 2011:5).

I suggest that the example given by Luuk et al. is not helpful to constrict what is behind the idea of recursion. It is true that a box in a box does not yield a recursive structure, but also, it cannot be compared neither with the example by Pinker and Jackendoff, nor with a box within a box. The reasons for this are that if an object is located within another object it does not play any role, if the object is the same object but smaller or a completely other object and small enough to fit into the first object. For example, a ball within a box is the same as a box within a box and both examples do not have anything to do with recursion or iteration for the reason that the smaller object is not structurally, nor computationally related to the bigger object. In the case of recursion or iteration, the part that is repeated, is somehow related to the first part of the whole structure. Concerning a box within a box, the former output is not used as the next input, if there is something like a former output and a next input, at all.

It has also been suggested that there are different types both of recursion and iteration which are considered to have different properties. To get a better impression about this, we take a look at what is referred to as "different types of recursion".

1.3.3 Different types of recursive and iterative structures

Karlsson, among others, proposed that there are different types both of recursion and iteration (Karlsson 2010).

Iteration occurs in six different types: coordination, apposition, reduplication, repetition, listing and succession (Karlsson 2010:46).

Coordination is the most frequent subtype of iteration, which can occur with or without explicit conjunction. Here, a further instance of the same structural type is added. The types that can be iterated in this way are all maximal projections like NPs and VPs, grammatical functions, like subject and object and clause types, like relative clause, and *if*-clause, for example, but mostly, clauses, or NPs in clauses are coordinated. Although clauses can be repeated by coordination, there occurs no increasing depth within the utterance (Karlsson 2010:46). In the following, the C-1, C-2 and so forth, stand for coordination-1, coordination-2 and so on.

(16) [$_{C-1}$The man] and[$_{C-2}$the woman] and [$_{C-3}$the two children] went to the theater.

The next type of iterative repetition is *apposition*, by which typically, NPs are repeated. What distinguishes this kind of repetition from coordination is that apposition is semantically motivated and thus the number of cycles that can occur with this type are constrained (Karlsson 2010:47).

Another type of iteration, according to Karlsson, is *reduplication*, which is also often called repetition.

(17)   a. It is a **long long** way.
          b. It is **much much** better.

(Karlsson 2010:48)

Reduplication has no limits on the number of cycles.

The next type of iteration can be named as non-content *repetition*, since it occurs, often involuntarily, when speakers repeat certain part of a sentence in order to gain time to complete planning the message they want to utter and occur logically only in spoken language. Mostly, words belonging to closed grammatical classes are part of

this kind of repetition, but the outcome of this type is always ungrammatical (Karlsson 2010:49).

(18) **And and if if if** you know they had none at all.

(British National Corpus, FMD 321 *via* Karlsson 2010:49)

Listing is an iterative way of enumeration and mostly used in "restricted lexical taxonomies" (Karlsson 2010:49).

(19) Monday, Tuesday, Wednesday

As a special kind of listing, Karlsson names succession, which contains numerosity and can be paraphrased with the formula n+1, and is what we know as counting. At this point, I doubtlessly disagree with Karlsson, because if there is a meaningful distinction between recursion and iteration, counting belongs to recursion because the output is not discarded before the next cycle begins, since the next cycle embeds the last output, and that is the way numbers grow bigger.

In the superordinate field of *recursion*, Karlsson distinguishes the types of recursion in the following ways: Direct and indirect recursion, counting recursion and mirror recursion, and simple and productive recursion. To get a picture of the structural form, let's take a look at the phrase structure rule and the actual structure of each of these types.

First, the types of recursive structures can be divided into two subtypes of the directness of application, which is reflected in the form of the rewriting rule (Karlsson2010):

(20)   a. **Direct recursion**

A → AB

```
                    A
                   / \
                  A   B
                 / \
                A   B
               / \
              A   B
```
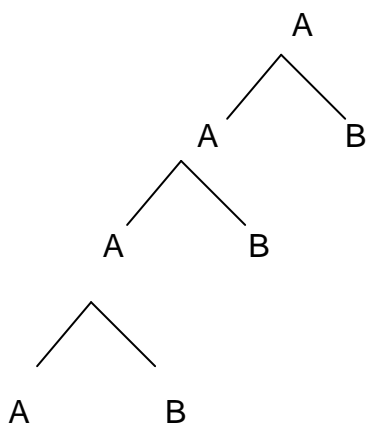
b. **Indirect recursion**

A→B, B→A

```
              A
             / \
            B   B
           / \ / \
          A  A A  B
```
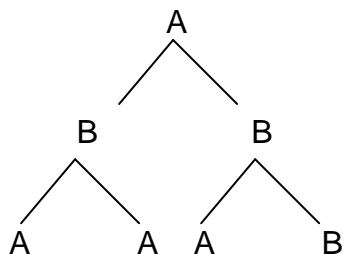
Second, the types of recursion can be divided into the kinds of strings, they generate, and the rewriting rules they need to be generated (Karlsson 2010):

(21)

a. **Counting recursion** (AB, AABB, AAABBB) with the rewrite rules

X→ aXa

X→ {}

When applying the formal type of counting recursion to natural language, the following right branching sentence gives an example of what this type of recursion looks like.

(22) [[$_{A1}$If the sun is shining] [$_{B1}$if the sun rises]], [[$_{A2}$then the sun is upon the sky], [$_{B2}$then I like to go out]].

b. **Mirror recursion** (ABBA), which follows the rewrite rule

X⟶aXa

X⟶bXb

X⟶ {}

This type of recursion in natural language resembles what is called center embedding:

(23) [[[$_{A1}$The cat] [$_{A2}$the dog]] [[$_{B2}$bit] [$_{B1}$ran away]]]

(Christiansen 1999)

Christiansen et al. (1999) also distinguishes a third formal type of recursive structure, namely identity recursion, which generates strings of the form *aa, bb, abab, aaaa, bbbb, aabaab, abbabb* and is generated by the following rewrite rules:

S⟶W$_i$W$_i$ X⟶bX

W⟶X   X⟶{}

X⟶aX

The third type of formal recursion is called cross-dependency recursion in linguistics and can be illustrated by this sentence, which is ungrammatical in English:

(24) [[$_{A1}$The boy] [$_{B1}$[$_{A2}$girls]] [$_{B2}$runs] like].

(Christiansen 1999)

And finally, besides the already mentioned criteria, recursive structures can be determined by how many cycles of application they produce:

    a. **Simple recursion** only has one cycle of application:

    (25)   I like to go out, because the sun is shining.

    b. **Productive recursion** has more than one cycle of application:

    (26) I like to go out because the weather is good, because the sun is shining, because there are no clouds at the sky.

More particular, the following types or sub-types, if you will, can be distinguished like follows: Left-recursion, which, in linguistic terms, is called left-branching or initial embedding, right-recursion, or rather right-branching or final embedding and nested recursion which, in linguistics, is often paraphrased with the term center-embedding (Karlsson 2010:50). According to Karlsson, the two types of tail recursion, namely left- and right-recursion, can be converted into iteration, because these two types do not create increasing embedding depth, which means no further memory device is needed (Karlsson 2010).

So far, the most crucial factor that seems to distinguish iteration from recursion is the additional memory device that is needed for the increasing depth of embedding. A question, coming up at this point, is whether the two recursive types that can be converted into iteration, need less memory capacity, since the beginning of the sentence has to be kept in memory, anyway.

According to Karlsson, all the subtypes just mentioned, can be assigned to the two upper groups of *general* and *specific* recursion. All the types of recursive structures that do not create increasing embedding depth, in the sense of center-embedding, fall under the term of general recursion, and all types of recursion that do create increasing depth in this sense, are what is called specific recursion. This means that center-embedding is the only identified type of so called true, or rather specific recursion and all types of iteration and both types of tail recursion belong to the group of general recursion (Karlsson 2010).

1.4 SUMMARY AND DISCUSSION

Summarizing the properties of recursion, it can be said that this is the mechanism that makes it possible to create infinite structures or sequences by finite means. Thus, it seems to be a hallmark of natural language, particularly in syntax.

Concerning recursion in language, there is an ongoing debate, or rather some uncertainty about the term recursion and what it exactly is with respect to natural language. While Corballis (2011) claims that there is a difference between simple repetition, iteration and recursion, Luuk (2011) claims that a difference has to be drawn between iteration, recursion and simple embedding. This, however, seems rather unlikely, at least for the reason that a recursive process can always be reduced to an iterative one (Lobina 2011).

I suggest that the idea behind what is referred to as simple repetition by Corballis (2011) is not given in any sentence in natural language, because it is never the case that constituents of a sentence are "only attached" to the former constituent. Concerning a possible difference between iteration and recursion, where Corballis (2011) argues that both recursion and iteration use their former output as the next input, while Luuk argues that using iteration, each input has to be formulated independently, it can be said that if there really is a crucial difference between recursion and iteration, this would be fact that the output of an iterative function seems to be always flat, while the output from a recursive function yields hierarchical structures. If this is the case, nevertheless, language more likely would be recursive, since it forms hierarchical dependencies.

Furthermore, Luuk distinguishes between recursion and simple embedding, using a picture of a box within a box as example for the independence of recursive structures and recursive processes, or rather that embedding can exist without recursion. A box within a box really doesn't need an understanding of recursion to be processed, but to compare this to an NP within an NP and thus to recursion in general is not reasonable for at least two reasons: First, the two NPs are linked to each other which clearly differentiates them from two objects which are placed into each other, and second, the two boxes are neither a recursive structure nor formed by a recursive process, which also clearly disqualifies them as an example for the supposedly independence of recursive structures and recursive processes: A visual scene of two objects, whereof one is located within the other one, do not yield embedding. And

this, of course, is the same with a box within another box. The term embedding, needs to be more than the location of objects within other objects to be worth being noted in a discussion about recursion. Further, this example with only *two* boxes appears to be a bad one, because if one can imagine this structure of boxes within boxes to go ad infinitum, this person seems to understand what recursion is; one box within another single box really doesn't show that recursive structures and processes possibly do not depend on each other.

Furthermore, Karlsson's classification and division of recursive and iterative structures by only accepting center-embedded structures as truly recursive cannot be correct, since in the case that center-embedded structures are recursive, while others are not, or only to a limited extend, there would have to be a specific rule that creates center-embedded structures, a specific rule for tail-recursion, and so forth. This has, as Lobina points it out, nothing to do with recursion in language and in all other domains (Lobina 2011:160). Furthermore, this also neglects the fact that recursion can always be converted into iteration and vice versa. More on this is discussed throughout the next chapter.

Moreover, how recursion is related to syntax, the Faculty of Language, to cognition, the brain, linguistic theory and language evolution is discussed throughout this thesis, beginning with recursion in linguistic theory.

CHAPTER 2

RECURSION IN LINGUISTIC THEORY

In the following, recursion is examined in terms of linguistic theory, based on structuralist theories such as Generative Grammar and the Minimalist Program.
Before looking at these topics, we will take a brief look at formal language theory to get an idea of the terms and concepts behind it, because some of these terms are used throughout the chapter and are also referred to during the whole thesis.

2.1 FORMAL LANGUAGE THEORY WITH RESPECT TO LINGUISTIC THEORY

As Fitch pointed out, concerning formal languages, the term *formal* describes a system in which algorithmically specifiable notions, which delineate representations, rules and links between them are included (Fitch 2010:111).
In computer science, a language is a set of symbols which is distinct from any other set by having non-atomic units. To describe such a language, a grammar can be used. Just like in natural language theory, in computer science, languages are describes by a grammar (Schöning 2009). These grammars consist of rules which generate a particular language. A language in computer science exists always over an alphabet. Formal languages in contrast to natural languages do not generate whole sentences, but instead generate words, which are in terms of formal languages, elements of syntax (Schöning 2009). Formal language theory makes use of the same terms as linguistics, but at some points in a slightly different way (Fitch 2010): First, by the term grammar, a finite system of rules is meant, that can generate a set of sentences, which in some languages can be infinitely large. Second, a sentence other than in natural language, is a string made up by symbols that are contained in a finite set, the alphabet. Third, the sentences that can be made up by

such a grammar is named language (Fitch 2010:111). To generate a language by using a certain grammar, a starting symbol is always used at the beginning, mostly named S. With respect to certain rules of the particular grammar, S is replaced by another unit, which can contain a variable that can be replaced again until it is replaced by a terminal symbol. This replacement stops as all variables are replaced by terminal symbols and a word is obtained (Erk 2008:54).

Accordingly, a language consists of the set of all words that can be generated from the starting symbol using the rules of the particular language (Erk 2008). Roughly speaking, a formal language is generated by an algorithm. The particular algorithms by which the associated language can be generated differ with respect to the particular language (Fitch 2010:107). In contrast to natural language, a sentence in formal languages is finite and thus constrained. It can be compared with integers, where the whole set of these is infinite, but every single integer is generated by a finite set of particular symbols (Fitch 2010:111). For example, the abstract idea of the set {4} is generated by a particular symbol and its rewrite rule:

(1)   4→3+1
         3→2+1
         2→1+1
         1→1

No natural language has been formalized in the way shown in (1) yet (Fitch 2010:111). Thus, natural language differs at least in its complexity from formal languages. But nevertheless, formal languages and particularly the automata that can or cannot process a certain kind of formal language are useful for the understanding of natural language and what is needed to process it.

2.1.1 Finite-state grammar versus natural language

A finite-state grammar has the following properties that characterize it: It can generate any of a finite number of states and it has no memory device, or at least a very limited one (Isac et al. 2008). A finite state grammar that is able to process two sentences looks like this:

(2)
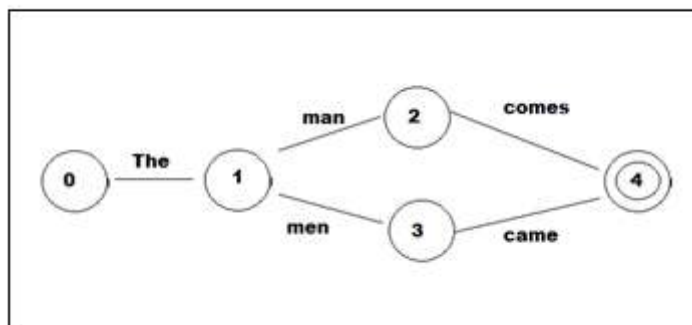
<div align="right">(see Isac et al. 2008)</div>

This grammar can process the sentences "The man comes" and "The men came". Such a grammar can perform a language like A^nB^m, where n and m stand for different numbers, but it cannot perform a language like A^nB^n, because here, A and B have to appear both n times, and thus the number of Bs depends on the number of As and vice versa. A finite state grammar, which as mentioned above, has no memory device, cannot remember the number of As, such that the number of Bs could equal the number of As. Because of that, a finite state grammar is not sufficient for a natural language, like English, for instance (Isac et al. 2008).

Because of the lacking memory device, in a finite state grammar, for every sentence, there has to be a separate path, such that a finite state grammar, that can perform two sentences, has to look like in (1). This leads to the fact that a finite state grammar can generate all and only the sentences of a finite set, like a certain book, or a certain newspaper (Isac et al. 2008). When a language needs a path for every sentence, it will require lots of redundancy, where words and even identical strings of words have to be repeated (Isac et al. 2008:96).

Natural language, in contrast, needs a memory device, such that it is not necessary that each and every sentence has to be stored explicitly, but can be generated by a finite set of rules.

2.2 RECURSION AND GENERATIVITY

Recursion is considered to have played a significant role in the development of linguistic theory, which is especially true for Generative Grammar. This is the case,

because recursion bears an elegant possibility of generating strings of infinite length by using only a finite memory space (Sauerland et al. 2011).

Chomsky, not yet talking about *recursion* in particular, defined the human property of using this mechanism under the term of *self-embedding* as follows:

(1) A language L is s*elf-embedding* if it contains an A

such that for some φ, ψ (φ ≠ l ≠ ψ), A ⟹ φ A ψ

(Chomsky 1959)

In a paper from 1959, Chomsky showed that the concept of self-embedding sets apart context-free grammars from less powerful grammars like a finite state grammar, which means that the languages, produced by a context-free grammar, cannot be analyzed by less complex models of grammar. Chomsky furthermore showed that English is self-embedding and satisfies the definition given in (1), what he showed by this formal example:

(2)   a.   S ⟹ If S, then it's true.

        b.   S ⟹ Either S or not.

(Chomsky 1959)

In contrast to natural language, a finite state grammar is not capable of the long-distance dependency between *if* and *then* in the first case and *either* and *or* in the other case. This is, because a machine, that can process a finite state grammar, lacks a memory device by which it could keep track of the *if* while going through the rest of the sentence until reaching the *then* (Chomsky 1959).

The concept of recursion was important for generative theory in so far, that Chomsky could show with its help that a behaviorist model of language was not sufficient, and henceforth was crucial in the development of phrase structure based approaches to language description (Sauerland et al. 2011).

2.3 RECURSION WITHIN THE MINIMALIST PROGRAM

Roughly speaking, the Minimalist Program aimed to show, why the language principles captured within the term 'Universal Grammar' are what they are and nothing else. By doing this, the computational mechanisms that are needed to produce and comprehend language, can be summarized within two basic syntactic operations called *Merge* and *Move* (Di Sciullo et al. 2010).

Merge is considered to be the operation by which recursive structures are built up in syntax, and by which the infinity of natural language is achieved.

Merge within the Minimalist Program is a structure building device that uses a combinatorial operation that takes two syntactic objects to form a new object. Syntactic objects that can be merged together are for example lexical items or previously composed pieces of syntactic structure (Di Sciullo et al. 2010). The important thing about Merge in human syntax is that by using *two distinct* items a new one with *altered meaning* emerges:

    (3)   a. The bird sings a song.
            b. The man sings a song.

The sentence has another meaning than the single words in it. Furthermore, the two sentences in (3a) and (3b) have different meanings since different lexical items are merged together. Through the operation Merge we get the meaning from a sentence as a whole, if you will: A whole that is built up from small single items, but then gets a new meaning as the whole it builds. Another important fact here is that the merged sentence contains a truth value which the single words lack. But not only the use of different lexical items gives the sentence another meaning, also the merging of different functional categories like *tense* can alter the meaning of a merged clause or a sentence:

    (4)   a. The bird sings a song.
            b. The bird sang a song.

Formally speaking, Merge looks like that:

(5)   {A,B} = C

Since the operation Merge can take two lexical items and combine to form another one, and then use the new lexical item to form in turn another, even bigger item, this syntactic operation is recursive, using its last output as the next input.

(6)   a. {A,B} = C
        b. {D,C} = {{A,B}D} = E

Merge is an operation, which occurs binary, always combining two items together to bigger outputs (Lasnik 2002). Another property of Merge is that it is asymmetric by either projecting A or B within the operation Merge {A,B} (Lasnik 2002).

A differentiation can be made between internal and external Merge. While external Merge combines lexical items and phrases, internal Merge contains the other syntactic operation that occurs in the Minimalist Program, namely *Move*.

(7) *Internal Merge*
What$_i$ do they eat t$_i$?

With respect to the operation Merge, natural language is recursive, because every lexical item is combined with another one to build up a bigger structure that can be combined with another lexical item or a previously merged phrase to build up an even bigger item, which definitely corresponds to the definition of recursion. This structural combining operation goes on until the structure, needed for a grammatical utterance, is reached. Internal Merge is recursive in the sense that it determines *how* constituents are merged and put together before spell-out (Carnie 2008).

However, Progovac (2009) argues that there is a type of sentence that is not recursive, namely sentences that she calls *Root Small Clauses* of the type "Everybody out!" or "Case closed". She claims that since these clauses cannot be embedded into each other, they refuse to be recursive (Progovac 2009:193). Nevertheless, it has to be mentioned that Progovac uses the term recursion synonymously to subordination. I argue that Root Small Clauses, though being

ungrammatical when embedded within each other, show recursion, since they are Merged like all other sentences, since I can produce and understand new and never heard ones, and further, they also can yield infinity using a conjunction like *and*, which is also recursive. Furthermore, though being ungrammatical in English, Root Small Clauses perhaps can yield multiple center-embedding in other languages. Moreover, Progovac argues that Root Small Clauses are fossils from an earlier grammatical stage of language evolution that formed the basis for a more complex grammar to evolve (Progovac 2009:206). I argue that even if these clauses display a kind of earlier grammatical stage in humans, which indeed seems rather plausible, the computational mechanisms for language that humans use today compute these sentences as it does for all other sentences and these clauses thus belong to today's complex grammar and not to any earlier, simpler grammar. From her argumentation, she further comes to the conclusion that Merge is not the only computational breakthrough in human language evolution and that Merge does not automatically mean recursion, which Root Small Clauses are, according to her, evidence for (Progovac 2009). Of course it is questionable, why such clauses as Root Small Clauses cannot be embedded into each other, but I find it rather unlikely that this is due to something like a lack of recursion.

Summarizing this, it can be said that clauses that cannot be embedded within each other are nevertheless recursive, using Merge and showing a hierarchical structure, in terms of X'-Theory. Furthermore, the terms *recursion* and *subordination* may not be confused, since they describe different things. Subordination means the embedding of whole clauses within each other, while recursion does not focus on CPs, but also applies on other phrases. The connection between these two concepts is that though recursion does not necessarily yield subordination, subordination is achieved by recursive means.

Since Merge, though showing properties of recursion, does not necessarily yield center-embedding, which is considered to be the only truly recursive device in natural language syntax, the possibility of having different, more or less recursive "types" of recursion in natural language has to be looked at more closely throughout this chapter.

2.4 RECURSION AND PHRASE STRUCTURES

Phrase structures show, by means of their recursive rewrite rules, how recursion is applied on the structure of natural language.

In phrase structure grammar, a constituent of the same type can stand on both sides of the rule, yielding infinity:

VP→DP, V, VP

However, the appearance of the same constituent on both sides isn't even necessary to create infinity:

NP→ Det, N, PP

PP→ P, NP
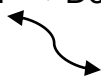
According to these rewrite rules, a phrase, generated by these rules, can go on forever, which can be illustrated by a sentence like this one:

> (7) The girl at the table in the garden in the town at the lake in the mountains at the boarder […]

Tree representations provide a powerful and at least useful method of applying phrase structures to a visually hierarchical representation. While the terminal branches represent individual words, the non-terminal branches represent abstract grammatical constructs (Russo et al. 2011:139). These abstract constructs do not appear overtly in language, but are nevertheless thought to have a neuronal representation (Russo et al. 2011).

According to Stabler (2011) the deeper a recursive structure is, the more it can reveal about it. Depth in this sense is measured in terms of steps it takes to get from the root of a structure tree to its leaf. This in turn means that the recursive definition of phrase structure building is used the time of steps it needs (Stabler 2011).

For example the sentence "I like apples" has a depth of three since it needs three steps to get from the top to the bottom:

(9)
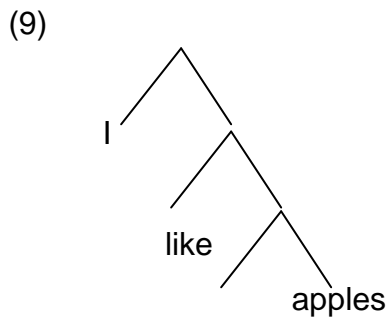
Concerning such a simple sentence, one might think to find no recursion according to the view that only center-embedded sentences, like shown in Chapter 1, are recursive, since they have a structurally complex hierarchical structure.

According to Stabler (2011), the view of whether a sentence is recursive depends on the underlying structure it has. Consider the sentence "Drink, drive, go to jail": Here, the sentence can be defined in a flat structure which has the depth of 1 or with a hierarchical structure which leads to a structure showing a depth of 3:

(10)   a.
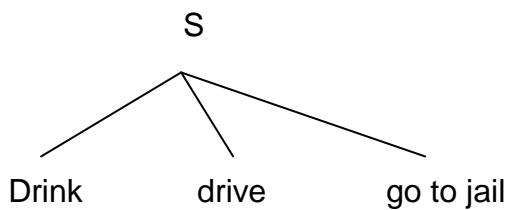
                                                                        (Stabler 2011)

        b.
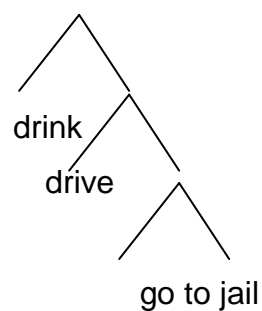
                                                                        (Stabler 2011)

A grammar, which can produce structures of different depth, can produce complementizer clauses like "who I saw yesterday". These CPs can produce

countable infinite recursion by embedding one CP into another one again and again (Stabler 2011).

However, it had been suggested that every sentence in a natural language is represented in a structure with hierarchical dependencies, (Carnie 2011) such that a sentence that would look like (11a) in flat structure, is considered to rather be represented like in (11b).

(11) Mary eats apples.

a.   S

          Mary   eats   apples.

b.

CP

Mary   C'

                TP

                    T'

                        VP

                            V'

                        eats   DP

                                  apples
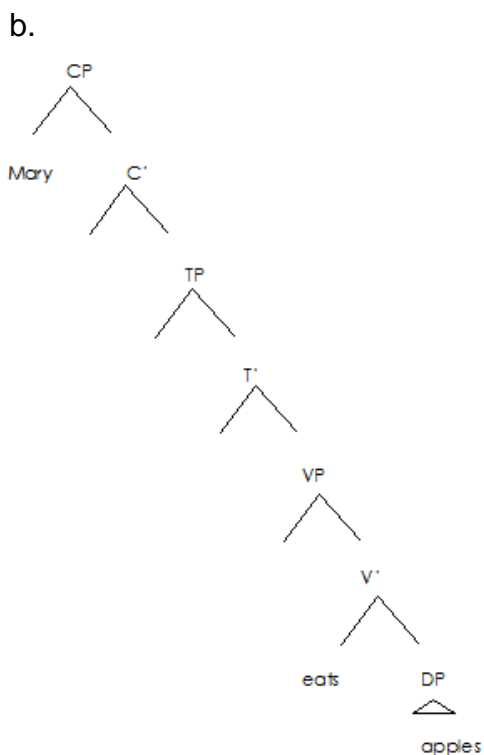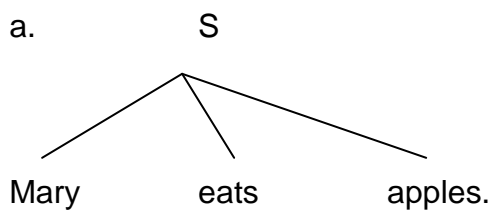
The tree structure of a simple sentence as in (11) shows that, according to X'-Theory, every sentence yields hierarchical dependencies in the form of nodes that dominate other nodes. A structure like that in turn is generated by recursive rules, and combined by Merge or another recursive combining process to gain meaning. This

suggests that it cannot be the case that only center-embedded sentences are recursive.

Lobina (2011) argues that recursive structures and recursive rewrite rules in form of phrase structure rules have to be separated, since he argues that PSRs are linear, while a recursive (self-embedding) structure is hierarchical. However, this argument seems weak, because the output of PSR can, as we have already seen, also be arranged hierarchical. Furthermore, phrase structure rules themselves show a hierarchy, since one constituent contains another one (Ullman 2004), which yields hierarchy, even without any hierarchical tree structure. Thus, the question of the relation between phrase structure rules and overt hierarchy seems to be a matter of visual representation, only.

2.5 RECURSION IN ITS ‚WEAK' AND ITS ‚STRONG' FORM

The question that has come to one's mind by now is, in how far it could be true that two different forms of recursion exist: *Two* forms in the sense that there is one form that produces embedded sentences which show "complex" structures and are sometimes hard to understand, and another kind that occurs in every sentence, even in simple root sentences like "She sleeps", but which, like the complex embedded form, can theoretically produce sentences of infinite length: More than two forms, or rather types, of recursion could exist in the sense that the different methods of forming an "embedded" or "coordinated" sentence are differentiated even closer, like Karlsson's differentiation in Chapter 1. To prevent confusing the two ideas of having different *forms* or *types* of recursion, the former is referred to as the different *forms* of recursion while the latter will be referred to as the different *types* of recursion.

One theory about this is the one pointed out by Luuk et al. (2011) who claimed that there is a difference between recursive structures (self-embedding) and a recursive procedure. Furthermore he argues, as we have already seen in Chapter 1, that the embedding of phrase structures of the form NP(NP) does not yield recursion, since it is, like for a box in box, to use his words, no recursion is needed. This would mean that a merged phrase like "the book and the pencil", which in turn can be merged with the merged phrase "are on the table" is not recursive and does not need a recursive device to be understood or produced. The thing here is, that it seems unlikely that

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these phrases are not recursive since they are, like already pointed out in 2.3, big items that are divided into smaller ones in order to understand it, which is characteristic for recursion.

Another explanation for these seemingly different forms of recursion is that they differ from each other in terms of *degree*. This means that they basically are the same form of recursion, but at a distinct level, such that the weaker form yields simpler structures and the strong form yields more complex structures (Russo et al. 2011), which contain center-embedding or tail-recursion.

A further observation is that while embedding of all phrases, except CPs, into each other seems to yield the weak form of recursion, while embedding of CPs seems to produce the complex strong form.

(12)   a. weak form of recursion

[$_{CP}$ Mary likes [$_{NP}$ apples] and [$_{NP}$ oranges]]

b. strong form of recursion

[$_{CP}$ Mary likes [$_{NP}$ apples] [$_{CP}$ that are red]]

2.6 WHAT IS RECURSIVE IN SYNTAX?

According to the differences between types of recursion, as discussed in Chapter 1, four kinds of sentences in the sense of their recursiveness can be distinguished:

(1) The "most recursive" sentences are such that contain what is referred to as "true recursion" or "specific recursion". This is, according to Karlsson, center embedding. Center-embedding embeds multiple CPs within each other and is considered recursive, because the more CPs are embedded into each other the more complex the structure gets in terms of subordination.

(2) Sentences that are recursive in a broader sense are sentences that contain tail-recursion, but are not "truly recursive" according to Karlsson, and thus are what is called "general recursion".

(3) Sentences that contain embeddings of a constituent within a constituent of the same type (e.g. VP within a VP) do not hold for "true recursion", since they do not fulfill the properties "involving embedded CPs" nor "being center-embedded". Such a

kind of embedding is what Luuk et al. compared to a box within a box and thus being not recursive. This kind of constituent-embedding often is referred to as repetition.

(4) The fourth kind contains all other simple sentences that do not involve any of the above properties. However, the sentence "Mary is eating an apple" does indeed involve embedding, since a TP is always embedded within a CP, a VP within a TP and so forth, but here, in contrast to sentences that belong to (3), this sentence does not involve embedding of the same type of phrase.

Within the framework of recursion types, as presented in Chapter 1, sentences of the type presented in (3) are accepted as recursive in a general sense or at least as iteration or repetition, but simple sentences such as in (4) are not. Nevertheless, I will argue that also simple sentences as in (4) are recursive for reasons of how sentences are considered to be created within the framework of Generative Grammar and for reasons of formal properties of recursion, that were presented in Chapter 1. Furthermore, to repeat itself in a self-similar way does not necessarily mean that the same constituent has to be embedded to yield recursion, since the concept of repeating itself in a self-similar way means that the same function calls itself up again and again, which is due to a syntactic operation like Merge concerning the build-up of a syntactic structure clearly the case.

One thing that could possibly have led to the controversy about, what recursion precisely is, is, that Chomsky, when talking about recursion, used the term *self-embedding*. While Chomsky used this term as referring to phrase structure rules and the general property of language to embed constituents into each other, the term self-embedding is often used with respect to what is called center-embedding, namely embedding of CPs into each other, such that the embedding yields a structure like the following:

(13)

http://biolinguistics.eu/index.php/biolinguistics/article/view/170/214

Fitch defined the term recursion as a rule "which has the property of self-embedding, that is, in which the same phrase type appears on both sides of a phrase structure rewrite rule" (Fitch 2010:78), which does not exclude structures beyond center-embedding as being recursive.

One attempt to the controversy about the term recursion and the concept behind it could be the misunderstanding about what I called *forms* and *types* of recursion. I propose that there are two different ideas behind these two terms which are important two differentiate. Distinguishing the two *forms* of recursion seems to be useful in the sense that it helps not only to clarify why both simple sentences and complex sentences are recursive, but it also could be important for examining cognitive systems and brain structures that underlie the concept of recursive processing. It is also important to note that the distinction between the two forms of recursion is rather a distinction of *degree* and not of *kind*.

It can be said that recursion is playing a major role in both the human ability to process natural language and in the generative theory of language as well. Recursion is considered an elegant possibility to generate strings of infinite length by finite means.

Recursion also plays an important role within the Minimalist Program, since Merge and Move basically are both kinds of recursive operations. That these basic operations occur in every sentence of every natural language, suggests that recursion does not only occur in sentences where CPs are embedded into each other, but also in simple sentences with only one CP.

The general assumption that sentences are represented in a hierarchical rather than in a flat structure, leads as well to the assumption that recursion and hierarchical dependencies are present in each sentence.

Concerning the issue of the controversy about recursion, I come to the conclusion that, taking into account phrase structure rules (e.g. that a DP contains an NP), the general property of language to be recursive leads to the possibility of embedding *all* kinds of phrases into each other, yielding countable infinity.

The term 'general property' here, is not referring to the universal property of language being recursive in the sense that *all natural languages* show recursive properties, but rather to a property that is present in *every sentence* of natural language and not only in those kinds of sentences shown as examples for the different types of recursion, in Chapter 1. Every sentence shows a recursive structure since it is generated by

recursive rules, which make it possible for a speaker of a language to be able to create and understand new and never heard utterances. Sentences that show hierarchical dependencies in the sense of center-embedding, and are mostly considered to be the kind of sentences that are recursive, are as recursive as all other sentences in a particular natural language. The difference is that these sentences all show an embedding of CPs into CPs, instead of other phrases.

Bickerton (2009) claims that Merge could be understood as recursive itself when adopting a looser definition of what recursion stands for (Bickerton 2009:6). But according to my argumentation a looser definition is not even needed, since merging in the simplest sentences also seems to require the properties from the concept of recursion as a complex sentence with CP-embedding does, except the higher demands on working-memory.

A phrase structure grammar has recursive rules that make it possible to generate an infinite number of possible grammatical sentences in a language from a finite set of rules. These rules are recursive, because the rule for a particular constituent that is created by combining smaller constituents may contain itself, such that the outcome in turn evokes the same rule applying again.

(3) VP→V, VP→V, VP→V, VP→V, VP→V, VP→V, …

Combining single constituents to form a linguistic utterance, Merge is considered to be the operation that makes this process possible. According to this assumption, Merge is the operation that makes it possible for natural language to be infinitive, since it makes PSRs recursive. Merge per se is recursive, because when two constituents are combined and result in a bigger constituent, and this bigger constituent in turn can be combined with another constituent, which can be combined with another constituent and so forth, until a complete and grammatical sentences is created, recursive principles are applied. What stops the recursive process in language is the outcome of a complete sentence, which is analog to the ending condition of a recursive process in the formal sciences. This speaks for Merge being the recursive process in syntax of natural language, thus forming recursive structures. Since every sentence uses the combining mechanism, called Merge, every sentence must be recursive. Furthermore, phrase structure rules show also to be recursive in constituents that are not CPs. A CP within a CP is generated by the

same rules as a VP within a VP and thus a CP within a CP is in principal the same as a VP within a VP. One thing that distinguishes recursion in CPs is that whole clauses are embedded within each other, which makes it more evident for the speaker, yielding what is referred to as subordination. Furthermore, because of the long-distance dependency, more working-memory load is caused which makes this kind of recursion more difficult to process, because working-memory space is limited.

If it is the case that only embedded CPs yield recursion, these must show a structural or computational property that sentences without CP-embedding do not show. Furthermore, it has to be argumentatively shown that only center-embedded sentences are recursive. Thus, these in turn must have a property that neither CP-embedded sentences without center-embedding, nor all other sentences have. This is examined in the following more closely.

Corballis, in his book from 2011, "The recursive mind", claimed that a sentence like "And it rained and it rained and it rained and it rained" is not recursive, because it only expresses the idea that it is raining a lot. His further argumentation is that this sentence is not recursive, because each addition of "and it rained" is not driven by the previous one, but simply added (Corballis 2011:10). Here, the first question is what it means in the case of a recursive sentence to be driven by a previous constituent or phrase.

According to my explications, a sentence like the one pointed out by Corballis to be non-recursive, must also be recursive, because of the recursive properties of Merge and the fact that phrase structure rules are recursive and thus generate recursive structures. Furthermore, to gain meaning from such a sentence, it is necessary to understand the previous phrase as related to the following one, since otherwise the meaning of a sentence like "It rained and it rained and it rained…" would be that it simply rained and not that it rained a lot. Additionally, one could go that far to claim that without any recursive device, only the meaning of one word of the sentence "It rained" could be understood, since through a recursive operation like Merge, the different constituents in this sentence are combined with each other to gain the meaning of the whole sentence. Thus, it can be said that recursion is responsible for the generativity of natural language.

Something near to my assumption that every sentence has to be recursive can also be found in a review article by Lobina (2011:166).

Perhaps the difference between a sentence like the one by Corballis and a sentence that is considered "truly" recursive can be explained by the distinction between the weak and the strong form of recursion.

Luuk et al. (2010) in this case argued that a distinction has to be drawn between recursive structures and recursive processes. He takes as example that an NP within an NP can be compared with a box within a box and is thus not recursive. Thus, according to Luuk et al.'s argumentation, a CP within a CP must be something entirely different to be in contrast to an NP within an NP, recursive.

Simple sentences like "Mary is eating an apple" have to be considered recursive, because such sentences are generated by the same recursive rules as complex sentences with multiple CP-embedding or even center-embedded sentences.

Structurally, a CP within a CP is the same as a VP within a VP and an NP within an NP. Whether there is reason to believe that there are differences between CP-embedding and embedding of other phrases has to be considered.

A difference between CPs and other phrases is that a CP is a clause which distinguishes from other phrases in that it contains a main verb and other constituents that depend on the verb. Thus, a verb within a clause distributes its own theta roles. Furthermore, a clause presents the smallest unit that can be a proposition.

The embedding of CPs perhaps yields a kind of 'special' form of recursion if you will. It is special in the sense that it involves several other factors that make them complicated to understand, but these factors do not have anything to do with the 'recursiveness' of a sentence per se.

Since simple sentences also follow recursive rules, they are distinct from any sentence within a finite state language. Moreover, the argumentation, that only center-embedded sentences are recursive, because they project a structure that gets more and more complex, cannot hold, because a sentence that is not center-embedded and not even CP-embedded, also yields a structure that gets more and more complex the longer the utterance grows.

Lobina (2011) criticizes that self-embedding is used as a synonym for recursive structures (p.156), since even if there was a language that did not exhibit self-embedding this language still would be infinite, as long as it contains conjunctions, such that the conclusion to draw from this fact has to be that these two "aspects" of recursion (structure and process) must be separated, because the former relates to a

structure that the syntax of a language manifests (or not), as he puts it, while the latter relates to the algorithm that generates all natural language structures. However, according to my argumentation, such a separation is not necessary, nor adequate, since every sentence seems to be recursive both in structure as well as in its generating process. Furthermore, these two "aspects" seem to depend on each other, since a recursive process should result in a recursive structure.

2.7 SUMMARY AND DISCUSSION

As has been discussed throughout the chapter, Merge seems to be the core element of syntax that yields recursion. Furthermore the discussion has lead to the assumption that recursion is not only present in CP-embedded, or center embedded sentences, in particular, but also in simple sentences.

One apparent property of CPs, that other phrases don't have, is that CPs contain a main verb that makes it a clause that can stand as a proposition. Moreover, only CPs seem to provide the possibility to yield center-embedding. The fact that some researchers only acknowledge center-embedded structures as self-embedding and thus recursive, leads to the assumption that the term *embedding* does represent different concepts. The first concept expressed by this term is the one known from X'-Theory, namely that a constituent is embedded into another constituent until a sentence is completed. The other form concerns a figure like shown in (13), which displays center-embedding, not in X'-Theory, but in a kind of sequence structures of sentences.

It often is argued that "simple sentences", in contrast to complex sentences, are generated by an iterative process, while complex sentences are generated by a recursive process. This assumption, as I argue, seems to be due to the fact that iteration needs less working-memory load, since less information has to be maintained during the process (Lobina 2011). Since "simple sentences" need less working-memory than complex ones, it is assumed that the less demanding sentences are generated by another device than the more demanding ones. The failure here lies in the definition of what actually is demanding: Although "simple sentences" in fact need less maintenance of linguistic material within a memory device, this doesn't have to mean that they are that simple that a simpler method of

processing is needed. In fact, also simple sentences are considered rather complex in its representations.

Furthermore, I find the terms simple and complex sentences quite problematic since there are different ideas available to be meant by these: In syntax, the term complex sentence is often used to describe a sentence that needs some additional syntactic operations, like Movement, to be processed in order to understand it (e.g. Kaan 2002), while simple sentences don't need these additional operations. On the other hand, in morphology, the term simple rather refers to a constituent that cannot be divided further, while complex refers to a constituent that consists of two or more simple (undividable) constituents (e.g. Ullman 2004). Thus, it is not always clear, particularly when a finite state grammar comes into consideration, what is referred to by the term simple here. Furthermore, the term complex in syntax refers both to sentences that yield subordination of clauses (e.g. Friederici 2011) as well as it refers to such sentences that involve movement or non-canonical word-order (e.g. Kaan 2002).

But nevertheless, Merge is clearly recursive and does create recursive structures, such that simple sentences are recursive and yield embedding in the form of X'-Theory. But it also seems plausible that both center-embedded CPs, as well as CPs, that are not center-embedded, can be distinguished from other phrases that are embedded: Phrases other than CPs in turn can be differentiated in phrases that embed the same kind of phrase and phrases that embed another kind of phrase, for example an VP that contains another VP compared to a VP that contains an NP. All these forms of embedding show different "graduations" of recursion, which of both forms of CP-embedding belong to the strong form of recursion and the two other forms belong to the weak form of recursion, forming sub-kinds of weak and strong recursion. Furthermore, it appears to be the case that only CPs show the property of being able to yield center-embedding. But, nonetheless, all phrases as well as CPs are generated by the same rules and mechanisms, and thus both yield recursion.

Both the rules of phrase structure grammar and the operator Merge show that recursion is a general property of syntax in natural language and thus not only present in center-embedded sentences for the following reasons: Phrase structure grammar has recursive rewrite rules, where the same constituent stands on both sides, and in terms of Merge, syntax in natural language is recursive, for the reason

that a big problem (the whole sentence) is divided into smaller problems (phrases and even smaller constituents), in order to gain meaning.

The next chapter concerns the brain areas that are considered to be involved in recursive processing, both within and without the linguistic domain.

CHAPTER 3

THE BRAIN AND RECURSION:

NEURONAL STRUCTURES OF RECURSIVE

PROCESSING

Before looking at brain processes and brain areas that are considered to support the processing of recursive structures in particular, we will take a look at syntactic processing in general.

3.1 SYNTACTIC PROCESSING IN GENERAL

Syntactic processing in the brain can be examined by different methods. Most commonly, two methods are chosen. The first one is EEG, which can state information about the temporal relations in syntactic processing, while, by using the second method, which is fMRI, researchers can examine the spatial relations of syntactic processing by hemodynamic investigations.

Brain responses differ with respect to whether they are related to semantic or syntactic processing. Regarding syntactic processing, two different responses can be observed. These two responses seem to be related to two different types of syntactic processing (e.g., Kaan et al. 2009; Friederici 2009).

Regarding temporal relations, the first stage of processing takes place very early, namely 150ms after onset. The polarity of this response is negative and can be approximately localized at the anterior portion of the left hemisphere. Because of its early onset, its localization and polarity, this brain response to early syntactic processing is called ELAN (early left anterior negativity). It is mostly associated with

an early build-up of local phrase structure, relying on lexical information. During this stage of processing, the phrase structure is checked and compared to the phrase structure rules of the particular language (Friederici 2009:242).

A violation to phrase structure processing would be the sentence *The man has eaten the laugh* because there isn't any phrase structure rule in English, which says:

      (1) * DP→D,V

At 600ms after onset, another brain response associated with syntactic processing can be observed. The polarity of this activity is positive and it is observed to take place at the centro-parietal portion of the left hemisphere. This late positivity can be elicited by syntactic anomalies, including syntactic violations and ambiguities and by syntactically complex sentences as well (Friederici 2009:243). Mostly, this component of linguistic processing is taken to be involved in relating the different constituents of a sentence with each other, in integrating syntactic and semantic information and in revising syntactic information, if necessary, as well (Friederici 2009:243).

Another crucial factor in interpreting ERPs concerning syntactic processing, is the theoretic model on which the interpretation is based. Generally, two different models play a role here. The first one is a model which is often called *syntax-first model*, because it assumes that syntax is processed independently from semantic information and comes first in sentence processing. This model is compatible with assumptions from Generative Grammar (Sprouse et al. 2012). The other model is called Unification Model and does not grant a special status to syntactic processing (Hagoort 2009).

According to the generative theory of syntax, syntactic information is processed via structure building operations, which are based on complex syntactic rules underlying a mental model of syntactic processing. During sentence processing the structures are combined with each other, using these syntactic rules (Sprouse et al. 2012). This model is well suited for the ERPs observed in syntactic processing. ELAN is held to reflect the first stage of processing where the local phrase structure is built up by lexical information. Friederici et al. (2004) argues that there are at least three factors which suggest this: First, ELAN takes place very early at a time where only parts of the syntactic information can be processed and second, the ELAN is elicited by local

phrase structure violation more likely than by complex syntactic hierarchy processing and third, it is not affected by any task-level factor, which suggest that it is a rather automatic process (Friederici et al. 2004). The late P600 component reflects, in the context of Generative Grammar, the integration of semantic information, which has been processed at 400ms after onset, with syntactic information, which explains why P600 can be elicited by both syntactic violations and Garden-Path sentences (Sprouse et al. 2012).

Besides the temporal order of the related ERPs, which suggest this order of events, Friederici and colleagues found a way to test the syntax-first hypothesis directly. This was done by a sentence which violates phrase structure rules and semantic expectations at the same time (Friederici et al. 2004).

(2) Das Buch wurde trotz *verpflanzt* von einem Verleger, den wenige empfahlen.

    The book was despite replanted by a publisher who few recommended.

The critical word *verpflanzt* violates both syntactic phrase structure and semantic expectations. According to Syntax-First theory, an ELAN effect and a P600 effect but no N400 effect is expected, because successful integration of the syntactic information should be required for semantic processing to emerge (Sprouse et al. 2012, Friederici et al. 2004). If the N400 response was also visible during processing such a sentence, this would mean that a successful build-up of syntactic information is not needed for semantic information being processed, which would contradict the syntax-first theory. Friederici and colleagues observed that during this experiment both ELAN and P600 were observable, but N400 was not (Friederici et al. 2004). This suggests that the assumption about a theory where syntax is processed before semantic information is plausible.

However, observations against this view are from brain lesion studies where patients with Broca's aphasia were able to understand sentences like *The boy ate the cake* because syntactic processing was not needed due to canonical word order. The fact that patients who suffer from problems with syntactic processing can understand this kind of sentences means that semantic processing should also be possible without a successful build-up of syntactic information. An example of non-canonical word order where processing of the syntactic structure is not needed either, and semantics alone can serve the understanding is the following example:

(3) Den Kuchen hat der Junge gegessen.

    The cake-Acc has the boy-Nom   eaten.

This sentence is thought to be understood without syntactic structure building, since it is unlikely that the cake ate the boy.

The Unification Model of parsing predicts that syntactic processing has no special role in sentence processing. Under the Unification Framework, words are stored in the lexicon as part of a structural frame that contains the syntactic environment for the particular word (Sprouse et al. 2012). Sentence processing then takes place as a single step on the syntactic, semantic and phonological level simultaneously. Assuming this architecture of processing, the major ERP components have to be interpreted differently from the generative view. Under this view, the different brain responses do not show different stages of sentence processing but rather different aspects of it. The ELAN effect then, is a brain response that occurs when there is an impossible unification due to an absent ability of connecting two nodes that can be combined between two structural frames. The LAN which also plays a role in this framework is elicited by a morpho-syntactic mismatch, after two syntactic frames have been combined. In the end, the P600 component, under this view, occurs if a sentence is difficult in being unified, which can explain why this component also occurs when a sentence is neither structurally ambiguous nor syntactically complex (Sprouse et al. 2012).

One issue with respect to violation paradigms in ERPs for syntactic processing is, that it is not possible to tell whether the activation pattern is due to syntactic processing or more likely to error detection (Kaan 2009).

Although ERPs show that there must be different mechanisms within the brain, which are responsible for language processing and syntax processing in particular, they do not tell us whether these brain responses are truly due to language processing or due to more general mechanisms like error detection or working memory nor are they informative about the possibility of these effects being not uniquely responsible for syntactic processing (Kaan 2009:123). Kaan therefore concluded that "to determine the relation between syntax and the brain, it may be more informative to examine to what extend different types of syntactic violations or syntactic processes elicit different types of brain responses. If indeed different brain responses are obtained for

different syntactic phenomena, we can assume at least a coarse relation between syntactic theory and brain processes" (Kaan 2009:123).

Relating different types of syntactic processing with brain responses is also of interest for the study of how recursive processes are related to the brain.

To examine this idea, Kaan (2009) discussed the relation between the brain and syntax by using three different syntactic operations among others: Local dependencies, anaphora and *wh*-movement.

3.1.1 Local dependencies

Syntactic local dependencies are characterized by being close to each other in hierarchical tree structure. An example taken from Kaan (2009) to illustrate this dependency is the following sentence:

(3) We admired John's sketch of the landscape/ *John's of the landscape.

The sentence marked with the asterisk represents a violation to phrase structure rules in English since the rule N→P doesn't exist. This kind of violation elicits two different ERP components, the ELAN/LAN component and the P600 component, which suggests that this type of violation is perceived very quickly, and that it is involved in two different processes, which are reflected by these two ERPs. (Kaan 2009:124) Another type of local dependency is agreement:

(4) The boy throws/*throw the ball.

It is possible to assume that agreement violations differ from phrase-structure violations insofar that agreement violations occur at a point, when a phrase-structure is already established. ERP responses are though very similar as they contain a LAN component and a P600 component. That in this condition a LAN and not an ELAN occurs could cohere with the assumption that agreement is processed after phrase-structure building (Kaan 2009:124).

3.1.2 Non-local dependencies

The next condition Kaan has investigated is anaphoras, which involve non-local dependencies. Regardless of whether sentences contained a violation of Binding Principle 1 or 2, the same ERP component had been observed, namely the ELAN and P600 component, which had also been observed during the other syntactic violations described above (Kaan 2009:126).

Since all these yet examined syntactic structures contained a violation paradigm to be visible, observing *wh*-movement provides a helpful syntactic structure for EEG studies, because it doesn't need to contain a violation to elicit an ERP. Therefore, this kind of syntactic operation is well suited to examine syntactic processing, since meta-linguistic repair processes can be excluded to disturb the outcome (Kaan 2009:127).

(5) Emily wondered *who* the performer had imitated __ for the audience's amusement.

Compare to the sentence without *wh*-phrase:

(6) Emily wondered whether the performer imitated *a pop star* for the audience's amusement.

The *wh*-phrase is the object of *imitated* although it doesn't appear in the expected position, which means that it has been moved to the position where it appears at spell-out. When processing this sentence, various processes occur. One of those processes is detecting that after the *who* in this sentence the following *the* violates phrase structure rules of English. This process is followed by the storage of the *wh*-phrase which cannot be integrated in the syntactic structure at this moment in working-memory, which is associated with a LAN response. The occurrence of this ERP component can be seen as a temporary violation, since it elicits a brain response which is normally achieved by phrase structure violation except that it occurs not as early as ELAN, which is perhaps due to the occurrence of a *wh*-element, which is in turn associated with syntactically more complex sentences. Next, the *wh*-phrase or some placeholder must be kept in working-memory until it can be

integrated in the syntactic structure and assign a theta-role, which had been observed to release a slow negative wave which is associated with working-memory demands. This negative wave chronologically starts to occur at the point, when it becomes clear that the *wh*-phrase cannot be integrated at this point. Finally, the *wh*-phrase has to be retrieved from working-memory, so that it can be inserted at the matching spot of the sentence where it can be integrated in syntactic and thematic structure. This operation is associated with the P600 brain response. Additionally, a LAN component has been reported to follow the gap, where the *wh*-phrase has been integrated (Kaan 2009:127).

Given this, it can be summarized for non-local dependencies that three ERP effects can be observed: First, a LAN for local syntactic violation, second, a P600 for general syntactic difficulty and third, a slow negative wave for maintenance in working-memory (Kaan 2009:127).

It seems that there are different brain responses with respect to different syntactic operations. Though not every syntactic operation has a unique brain response, three different responses can be observed for more general classifications of syntactic processing:

First, there is the ELAN/LAN component which is associated with local dependencies like build-up of phrase-structure, second, there is the P600 response, which is associated with non-local dependencies and reconstruction of canonical word order, and third, a negative wave could be observed in sentences involving movement.

3.2 LOCATING SYNTACTIC PROCESSING IN THE HUMAN BRAIN

Regarding syntactic processing, many researchers think of it as individual module which works independently from general cognition and other modules like memory, for instance. They propose an independent syntactic processing mechanism which is insensitive to other cognitive functions. Assuming this, a single brain area which supports syntactic mechanisms only would be necessary (Kaan et al. 2002:350). But recent studies reveal information about syntactic processing taking place in not only one area, but in a network with other brain areas.

3.2.1 Neuronal structures underlying syntactic processing

Neuroimaging studies for this purpose can be conducted with different conditions with respect to the language material. Kaan et al. (2002) conducted neuroimaging studies with complex versus simple sentences, sentences versus word lists, Jabberwocky (e.g. *The mumphy folofel fonged the apole trecori*) and syntactic prose and with syntactic violations to specify the brain areas involved in syntactic processing. By using sentences versus word lists they additionally aimed to show whether the activated brain areas during sentence processing were also active during single word processing which would suggest that they are not exclusively specialized for syntactic processing (Kaan et al. 2002).

In the simple versus complex sentence condition they used sentences like *The reporter who attacked the senator admitted the error* as simple sentences and sentences like *The reporter who the senator attacked admitted the error* as complex sentence because the latter sentence involves additional syntactic operations to be processed to reconstruct canonical word order. Areas which are additionally activated in the complex condition are assumed to be involved in higher syntactic processing. The participants had to decide whether a simple and a complex sentence had the same meaning, because to perform this task, it was assumed that the participants had to reconstruct the canonical word order, which should lead to the additional syntactic activation, which could show where complex syntactic processing takes place.

Brodmann areas:
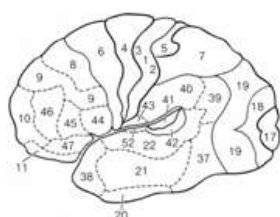
Left hemisphere   Right hemisphere
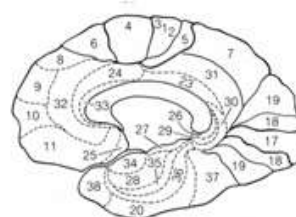
http://www.class.uidaho.edu/psyc372/lessons/lesson03/lesson3_brodmann_area.htm

By performing this task, in most studies an enhanced activation of Broca's area (left BA 44/45) can be observed. Sometimes this activation extends to BA 47, 6 and 9. Occasionally, additional activation is found in the left or bilateral superior and middle temporal gyri which belong to BA 21/22, in the left angular and supramarginal gyri which belong to BA 39/40 and in the cingulated gyrus, which belongs to BA 23,23,31,32. While processing both simple and complex sentences, activation could be observed in a wide range of brain areas. Left BA 44 and 45, which are assumed to be highly involved in complex syntactic processing (Friederici 2009) showed an enhanced activation during complex sentence processing. Kaan et al. argue that this activation has not necessarily to be involved only in a syntactic process but could also have to do something with memory load, because complex syntactic processing does not only differ from simple syntactic processing in terms of syntactically more complex structures but also in terms of activated working memory due to longer dependencies and reconstructing processes where information has to be retained (Kaan et al. 2002). The strongest support for this view comes from the finding that Broca's area also shows an enhanced activation when sentences with canonical word order that contain low frequency words are processed. This suggests that Broca's area is not alone specialized for syntactic processing, which does not mean that it hasn't any role in processing syntactic dependencies (Kaan et al. 2002).

Using neuroimaging and hemodynamic techniques, spatial distributions of local and nonlocal syntactic processing can be investigated by either comparing a sentence containing a syntactic violation to its grammatical counterpart or by comparing syntactic simple sentences to a list of unrelated words (Kaan et al. 2002).

Regarding local dependencies, activation differences can be found in the left, and sometimes additionally in the right hemisphere in temporal regions, in particular, the anterior temporal areas (Kaan 2009:125). It could be observed that Broca's area, which includes the left inferior frontal gyrus shows more activation for local dependencies like phrase-structure building and agreement, when a violation paradigm is built-in into the target sentence, or when the linear distance between the locally dependent elements increases which points out to the involvement of Broca's area in working-memory tasks. Likewise, parietal and subcortical areas also tended to be involved in local syntactic processing. Strongly overlapping activation pattern have been confirmed for phrase-structure processing and the processing of agreement with a higher activation of the caudate nucleus and the insula in phrase-

structure violations (Kaan 2009:125). Like it is assumed for general syntactic processing, also processing local dependencies involves not only one particular area, but rather a network consisting of spatial distributed brain areas (Kaan 2009). One issue about studying the processing of local dependencies is that it is likely to not provide much insight into how syntactic processing is processed in terms of computation, because local dependencies, notably if they are frequently used ones, are stored and not individually computed. That is why it is assumed to get more insight in the spatial distribution of syntactic computing by looking at non-local dependencies (Kaan 2009:125).

Examining non-local syntactic processing suggests that Broca's area is involved in retrieving not yet integrated structures from working-memory which also confirms its involvement in syntactic processing, and temporal brain areas of the left hemisphere of being involved in the processing of non-canonical word order and syntactic integration (Kaan 2009:128).

According to Kaan (2009), Makuuchi et al. (2009) showed that the activation of Broca's area and adjacent areas differs with respect to the kind of relations which have to be stored in working memory: The inferior part of the pars opercularis, which is a part of Broca's area, seems to be more active the more *wh*-relations are needed to be stored during sentence processing. The left inferior frontal sulcus, which is more anterior and superior to Broca's area, is more active when more words intervened between the subject and the clause's finite verb (Kaan 2009:129).

These two areas are connected with different parts of the superior temporal gyrus and could possibly be involved different aspects of syntactic processing.

When comparing sentences with syntactically unrelated words, Broca's area shows to be not significantly activated during such a task. This suggests that Broca's area is not necessarily involved in any kind of syntactic processing but only when processing load increases (Kaan et al. 2002:353).

Increased activation during processing sentences versus word lists was found in the anterior parts of the temporal lobe (BA 38), which was often observed bilaterally, another activation pattern is found in the superior and middle temporal gyri, which include BA 22 and 21. Working with Jabberwocky reveals an activation pattern in the posterior superior temporal sulcus (BA22, 41/42) and some activation was found in the anterior superior temporal sulcus (BA 38,22). Thus, the medial part of Broca's area was activated comparing Jabberwocky with normal sentences. Jabberwocky is

well suited for observing brain structures involved in syntactic processing, because it contains syntactic structures but no meaning which should mostly activate only parts of the brain which are involved in syntactic processing. The investigation by Kaan et al. suggest that Broca's area is not necessarily involved in syntactic processing, but comes to play a role when memory load increases. Thus, it is not the only brain area activated during syntactic processing. Activated brain areas include the BA 38 and the anterior parts of BA 21/22, which include Wernicke's area (Birbaumer et al. 2010).

The fact that parts of Broca's area are activated when working-memory load increases could also be traced back to the possibility that Broca's area is well suited for processing syntactic complex structures because of the close relation to working memory (see Fedor et al. 2009:301).

Friederici and her colleagues examined which kinds of violations lead to which kind of brain responses. They found that syntactic phrase structure violations do not seem to activate Broca's area (Friederici 2009:244). Broca's area seems to come into play when syntactically complex sentences like object-first constructions or *wh*-questions are processed. Here also, more complex sentences are associated with higher working-memory demands and object-first constructions need to be reconstructed, since they contain a non-canonical word order.

Friederici et al. also conclude from their fMRI studies that Broca's area is recruited for more complex syntactic structures while local phrase-structures tend to be processed by another brain region, namely the frontal operculum (Friederici 2009:245). These two brain regions can be functionally segregated as we will see when examining the brain structures underlying recursive and complex-hierarchy- processing.

Besides a functional segregation, Broca's area can also be segregated structurally. The part of the brain classically known as Broca's area consists of BA 44 and BA 45. Concerning their structure and their developmental features, one has to question whether it is justifiable to subsume these two areas under the heading Broca's area. Cytoarchitectonically, these two areas differ from each other, since BA 45 has a granular layer IV, which means that BA 45 is granular, whereas in BA 44 layer IV is poorly developed, which means that it is dysgranular (Fitch 2011). BA 47, which is also adjacent to BA 45, on the contrary, shows a granular cortex, as well, since it is part of the heteromodal component of the frontal lobe (Hagoort 2009:281). Furthermore, BA 44 and 45 show clearly different patterns during postnatal

development and also a difference in their patterns of lateral asymmetry. For BA 44, a significant left-over-right asymmetry could be shown whereas this is not the case for BA 45. However, BA 44 and BA 45 are, concerning cytoarchitectonic features, more similar to each other than BA 44 and BA 6 or BA 45 and BA 6, for instance (Hagoort 2009:282).

Studies concerning the receptor architecture indicate necessary divisions between BA 44 and BA 45 as well. A difference in receptor density can be observed concerning $5HT_2$ receptors for serotonin within BA 44. It can be said that there exist two different views of whether and how much these cytoarchitectonical features are relevant. The classical view assumes that these architectonic differences lead to functional differences (Hagoort 2009:283). According to this view the subsuming of these architectonically different areas can indeed be questioned. Another recent view comes from a computational perspective and assumes that cytoarchitectonically different brain areas can be very similar. According to this view, brain areas which support the same function are not necessarily so much determined by the heterogeneity or homogeneity of brain tissue, but rather by the way in which its functional characteristics are shaped through input (Hagoort 2009:284).

Furthermore, Hagoort concludes that from a computational perspective one cannot longer speak of Broca's area from a classical point of view but has to extend the complex of syntax involved brain areas, which he calls Broca complex. Besides BA 44 and BA 45, Broca's complex involves at least BA 47 and the ventral part of BA 6 in the frontal language network. These cytoarchitectonically different areas play a crucial role in language processing. The prefrontal cortex seems to be well suited perform post-lexical processing (Hagoort 2009).

By examining temporal and spatial properties of syntactic processing it can be assumed that the brain is not capable of all differences that syntacticians make, but some general aspects can indeed be distinguished and used to examine syntactic operation processing. The distinction between general syntactic aspects suggests that some of these aspects are hardwired to the brain (Kaan 2009:129).

3.2.2 Other functions of "syntactic" brain areas

Since the temporal and local structure of brain responses with respect to syntax is not unique to this domain, syntax is neither uniquely processed by the respective brain areas and temporal brain responses, it is interesting to mention processes with which syntactic operations share both brain areas and brain potentials.

Regarding ERPs, it has been observed that there are also involved in difficulties related to discourse processing, violations of musical structure, sequencing and mathematical rules. This suggests that this brain response is responsible for structural integration, in general, or for solving conflicts during processing (Kaan 2009).

Violations of musical chord sequences elicit LAN, which does nonlinguistic symbol manipulation as well (Kaan 2009).

The slow negative component which can be found in processing sentences containing *wh*-phrases can also be observed in tasks which involve retention of letters, colors, and locations with a varying distribution over the scalp with respect to the materials that have to be maintained (Kaan 2009:130).

Concerning spatial distribution, brain areas that are active during syntactic processing are not unique to it. Broca's area, for example, is involved in some non-syntactic and even non-linguistic functions like working-memory, inhibition, and resolving conflicts among representations (Kaan 2009). The anterior temporal lobe is, besides syntactic processing also involved in semantic tasks and discourse processing, whereas parietal areas, which are in involved in syntactic processing seem to be involved in attention, reading, working-memory and semantics, too. Syntactically active areas like the subcortical region mentioned above are also active in a variety of other tasks (Kaan 2009).

Furthermore, in an experimental study o find out about brain regions that process prosody, Mayer et al. (2002) found out that linguistic prosody is processed in the frontal operculum of the left hemisphere, where, according to Friederici et al., simple sentences are processed syntactically.

After having looked at the brain processes considered responsible for syntax in general, we can now go on to brain areas and processes that are considered to be involved in processing recursive structures. In this part of the chapter the aim is to

show the distribution of recursive processes in the brain. For this purpose, we will look at both linguistic and non-linguistic recursion.

3.3 RECURSIVE STRUCTURE PROCESSING

For the purpose of determining to what extend recursion can be looked at as the crucial part of human language, and human syntax in particular, one can observe brain structures underlying processing recursion in its different domains. The whole section mostly refers to Friederici et al., since topic of recursive processing and its relation to the brain, as far as I am aware, has only been explicitly observed by her and her colleagues so far.

Friederici et al. (2011) investigated brain structures involved in recursive processing by looking at recursive artificial grammar processing, natural language processing with respect to processing CP-embedded structures and processing complex hierarchy in two non-language domains, namely visuo-spatial processing of recursive structures and embedded mathematical formulae.

The linguistic structures, Friederici et al. worked with, were recursive in the respect that they involved center-embedded CPs. According to Friederici, the most important property, which qualifies a grammar for recursive structure processing, is self-embedding (Friederici et al. 2011:88).

In their experiments, Friederici et al. used a simple grammar, which they referred to as finite state grammar, for simple syntactic processing of the type $(AB)^n$, while on the one hand and on the other hand a phrase structure grammar of the type A^nB^n was used to mimic complex syntactic hierarchy. These types of grammar were not only used in the artificial grammar processing task, but also used to mimic this kind of processing in testing the other domains of recursion. The rules for the recursive structure A^nB^n is derived from these two rewriting rules:

    (1)   a. S→AB

                b. S→ ASB

A^nB^n then is derived for example like this:

(2) $S \rightarrow ASB \rightarrow AASBB \rightarrow A^{n-1}SB^{n-1} \rightarrow A^nB^n$

3.3.1 Linguistic structures

To examine the underlying brain structures of recursive structure processing, Friederici et al. conducted an experiment in which participants had to learn an artificial grammar containing recursion and an artificial grammar which, according to them, did not. They took a grammar which Gentner and colleagues (2006) used in an experiment to observe syntactic pattern learning in songbirds. Friederici et al. note that a disagreement or rather a accuracy respecting the term recursion had appeared concerning the A^nB^n grammar. They noted that this grammar in some situations had been taken as recursive and in some not (Friederici et al. 2011).

The experiment was conducted using two different artificial grammars, namely the simple and the complex one, which has been described above.

Assuming category A has the lexical items *ge bi di* and B *tu po ko* it would look like the following (Friederici et al. 2011):

(9) *"Phrase structure grammar":* **[be[bi[di bu]to]ko]**
(10) *"Finite state grammar":*   **[be ko] [bi to] [be ko]**

Furthermore, as already noted, Friederici notes, that the underlying structure of an A^nB^n grammar is responsible for it to be recursive or not. Insofar recursive structure is defined by its property of self-embedding, a grammar of the type A^nB^n would be sufficient (Friederici et al. 2011). A simply embedded grammar like [A[A[A[A B]B]B]B] goes, according to them, truly beyond a finite state grammar, but is not recursive, whereas an artificial grammar like [A_1[A_2[A_3 B_3]B_2]B_1] does fulfill the required properties of a recursive grammar, because it can't be processed by a counting mechanism like the former one that does not show any indices (Friederici et al. 2011, Corballis 2007).

In their experiment, participants were to learn the simple or the complex grammar. Brain activities were examined using correct and incorrect sentences according to the

two grammars in which the participant had to decide whether the heard sentences were grammatical or not. To avoid effects of learning by heart, sentences were used which did not appear during the learning session.

The two different grammars showed different activation patterns (Friederici et al. 2010:89). For the Finite State Grammar, syntactic violations lead to an increased activation of the frontal operculum (fOP), while processing the complex grammar, Broca's area was recruited stronger compared with the simple grammar (Friederici et al. 2011:89). Though, it is not clear, as mentioned above, whether the participants did reconstruct a hierarchical embedded structure or whether they used a simple counting strategy with which the goal to process this kind of grammar can also be achieved. But because of the knowledge that Broca's area is actually involved in complex grammar processing, it has been assumed that the participants did build up a hierarchical structure to process this grammar, since a strong involvement of Broca's area could be observed. But to be sure about this, Friederici et al. conducted an additional experiment, because as we have seen before, activation of Broca's area can also be due to working-memory load, since it has been shown that Broca's area is also involved in task which are not linguistic ones but require working-memory. The idea that stronger activation of Broca's area is due to working-memory demands is indeed reasonable because it goes with the assumption that the structure, that is referred to as finite state by Friederici et al. (2011), needs less working-memory involvement.

To test their assumption about the complex grammar, Friederici et al. designed another experiment with another complex PSG, but this time they built the sequences such that hierarchical processing for the A^nB^n structures was induced, because each subcategory had more than one member, to avoid item based learning. Instead of [A[A[A B]B]B], the new structure looked like that [A_1[A_2[A_3 B_3]B_2]B_1]. The critical relation between these depending elements was realized by distinctive phonological parameters, namely voiced – unvoiced counterparts. According to this pattern, a grammar would look like that:

(11)   **[be[gi[de to]ku]pu]**

(12)   **[be pu][gi ku][de to]**

Examining the underlying brain structures involved in processing the PSG compared with processing FSG showed that processing the more complex PSG strongly involved BA 44, which is part of Broca's area (Friederici et al. 2011:91). According to Friederici et al. (2011), these results supported the data obtained from the first experiment and attested the assumption that the processing of the PSG was processed by reconstructing hierarchy rather than by counting and additionally keeping track of n.

To differentiate between working-memory load and syntactic processing, which is, as noted above, both located in Broca's area and seems to interact there, Friederici et al. conducted another experiment. Here they did not work with artificial grammars but with natural language.

They used German, since it allows multiple embeddings, like the artificial grammar used in the previous experiment (Friederici et al. 2011:91).

For this purpose, Friederici et al. used subject-verb dependencies of the type $[S_1[S_2[S_3 \ V_3]V_2]V_1]$:

(13) The dog the cat the rat bit chased escaped.

To test the implication of working-memory load and syntactic processing independently from each other, Friederici et al. created a 2x2 factorial design with the factor syntactic hierarchy, which manifests itself in the number of embeddings and the factor verbal working-memory which manifests itself in the distance of the dependent elements, such that they got four conditions: Hierarchy & long distance, hierarchy & short distance, linear & long distance, linear & short distance. (Friederici et al. 2011) Linear in this sense, means that there exists only one dependency between two items, while hierarchical means more than one dependency that yields center-embedding.

(14a)   linear & long distance   (15a)   hierarchical & long distance

A_1 C C C C B_1 A_1 A_2 A_3 B_3 B_2 B_1

(16a)   linear & short distance   (17a)   hierarchical & short distance

A_1 C C B_1 C C A_1 A_2 B_2 B_1 C C

(Friederici 2011)
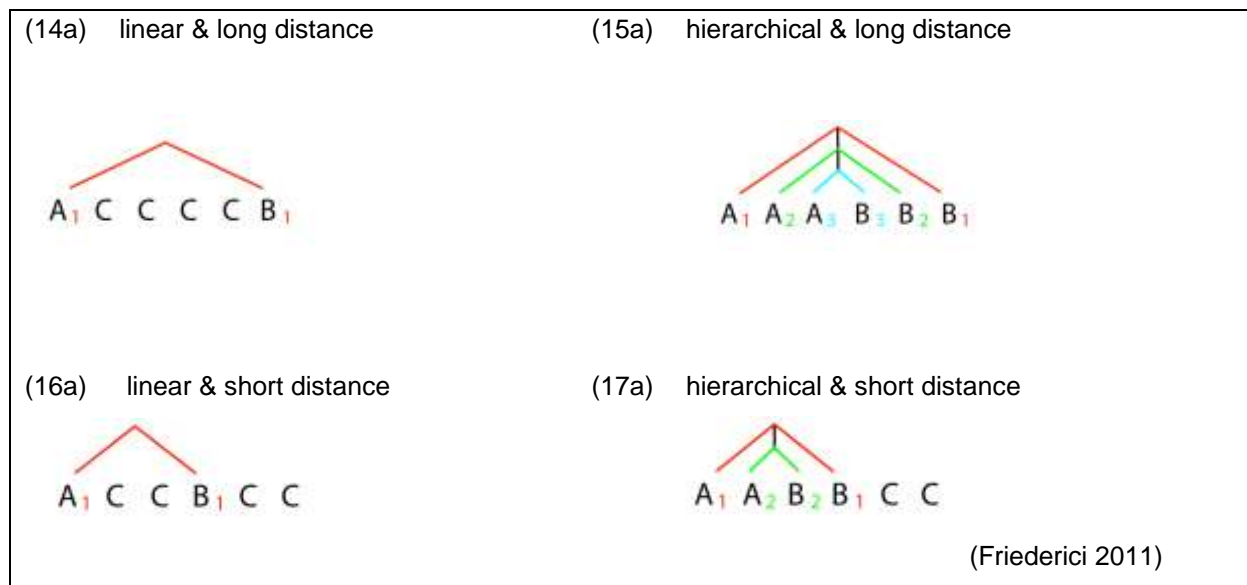
These structures correspond to the following sentences:

(14b) *hierarchy & long distance:*

…, dass [Maria, [die Hans,[der gut aussah], liebte], Johan geküsst hatte.

That   Maria   who Hans   who good looked   loved   Johan kissed   had

(15b) *hierarchy & short distance:*

…, dass [Maria,[die weinte], Johann geküsst hatte], und zwar gestern Abend.

That   Maria   who cried Johann   kissed   had   namely   yesterday evening

(16b) *linear & long distance:*

…, dass [Achim den großen Mann gestern am späten Abend gesehen hatte.]

Achim the-Acc tall   man   yesterday at   late   evening   seen   had

(17b) *linear & short dsitance:*

…, dass [Achim den großen Mann gesehen hatte und zwar gestern Abend.]

That Achim   the-Acc tall   man   seen   had   namely   yesterday evening

Friederici et al. 2011

Processing of these sentences showed that syntactic hierarchy, here defined by the number of embeddings, activated Broca's area in the inferior frontal gyrus (IFG) and

additionally the left superior temporal gyrus (STG) and the superior temporal sulci (STS). The additional activation of STG and STS indicates that these regions are also part of the language network. Examining Broca's area revealed that the effect of processing linguistic hierarchy is most active in BA 44. In contrast, working-memory load, here defined as distance between two related elements, activated the left inferior frontal sulcus, which is located dorsally to Broca's area. Furthermore, a functional connectivity analysis showed that these two indentified areas strongly interact during processing multiple embedded sentences (Friederici et al. 2011:93). By this experiment, processing of syntax and working-memory could be segregated into to subareas, which involve BA 44 for syntactic complex processing and IFS for working-memory load, which is in line with other studies, examining this issue (Makuuchi 2009). Thus, the data suggest a functional subdivision of the inferior frontal cortex, which makes it possible to process syntactically complex recursive structures by these computational different sub-components (Friederici et al. 2011:94).

3.3.2 Nonlinguistic structures

To test processing hierarchical relations in a non-language domain, Friederici et al. used mathematical formulae. It has been proposed that recursion as used in linguistic processing is also underlying mathematical structures (Friederici et al. 2009). It is assumed that people who are familiar with the respective rules can make grammaticality judgments about the correctness of those formulae. Therefore, experts in mathematics acted as participants in this experiment. Either linear or hierarchical structured formulae were presented and the participants had to judge whether they were correct or incorrect. To avoid brain activation of numeral processing, such as calculating, only formulae without numbers were used (Friederici et al. 2011:97).

(18) linear structure:	**{a+c, x * ʋ, φ ∧ ψ, x=a, u<y}**
(19) hierarchical structure:	**(a=c+u) ∧ (ʋ*x < u+y)**
	Friederici et al. 2011

Illustrating the syntactic structure of these formulae would look like this:

(20) linear structure:	**[a+c][x*y][φ ∧ ψ][x = a][u<y]**
(21) hirarchical structure :	**[[a=[c+u]∧[ʊ *x]<[u+y]]**

<div align="right">Friederici et al. 2011</div>

It has to be noted that mathematical structure varies from linguistic structure insofar as linguistic relations are asymmetrical whereas mathematical relation do not necessarily have to (Friederici et al. 2011:96). The formulae were presented visually during the experiment.

Activation patterns, associated with mathematical structure processing were found to be located in BA 47, BA 44/45 and in the parietal cortex. However, only a part of BA 44 was involved in the processing of hierarchical complex formulae, whereas the crucial part of processing these was located more anteriorly in BA 47, next to BA 45. As we have seen in the previous part of the chapter, BA 47 seems also to be involved in linguistic syntactic processing, since it belongs to the Broca's complex, but the crucial brain area for linguistic syntactic processing is assumed to be BA 44/45, such that there seems to be at least a slight difference between processing complex hierarchical formulae and complex hierarchical linguistic structures. Though, Broca's complex as a whole seems to be involved in both tasks, but activation of the different brain areas which are part of Broca's complex differ in its intensity with respect to the tasks including recursion (Friederici et al. 2011:97).

Another nonlinguistic domain has been examined with respect to recursive structures by using sequence structures in the form of visual stimuli. The type of underlying structure was again the same as in the artificial grammar processing experiment with category A and category B members. The membership of these elements was indicated by shape and texture, whereas all the stimuli were abstract to avoid item based learning. The dependency between these two categories was encoded by rotation of the respective shape:

For a whole brain analysis, the main effect of processing these hierarchical structures was found to occur in the left pre-central gyrus which corresponds to BA 6. Analyzing the region of interest (ROI), an increase of activation could also be found in BA 44. Together with the brain areas which are generally involved in visual

processing, BA 6 and BA 44, these brain areas constitute a processing network, which is responsible for the processing of recursive structures in the visuo-spatial domain.

This and some other studies dealing with this aspect of hierarchical processing seem to show that two parallel systems deal with hierarchical structures from the linguistic and non-linguistic domain. Interestingly, one domain, which is located the IFG and includes BA 44 and the posterior part of BA 45 seems to be responsible for recursion in natural language only, and the other domain, which is located at PFG and includes BA 47, the anterior part of BA 45 and BA 10, seems to be responsible for hierarchical structures in all other cognitive domains, with no further yet observable distinctions (Friederici et al. 2011:101).

In all experiments here referred to, an activation of BA 44 could be observed, leading to the assumption that BA 44, which is the posterior part of Broca's area, is involved in processing hierarchical structures in all domains, which is, as Kaan (2009) notes, possibly related to a higher working-memory load.

3.4 THE RELATION TO MODULARITY

A module is a hypothetical entity that is encapsulated and immune from other sources. According to Fodor (1983), modules have additionally to their immunity the following properties: They are localized, which means that they correspond to neural architecture. Furthermore, they are not only immune to information from other domains, but they also can be selectively impaired, and they are autonomous. A very important characteristic of modules is that they operate fast and thus can generate outputs very quickly. But they are also shallow, which means that they have simple outputs. Concerning biological development, modules are considered determined, in the sense that they develop in a characteristic way. Modules are domain specific and encapsulated and furthermore, modules are less accessible for higher function systems (Fodor 1983).

The current view, including Fodor himself, is that not all cognitive functions are modular, but rather that some functions are and others are not (Prinz 2006).

Language is often considered to form a module. Pinker for example states that the Faculty of Language is a module (Pinker 2005).

Besides, modularity can be distinguished into anatomical modularity and functional modularity, such that anatomical modularity predicts that modules correspond to the anatomical distribution of neural substrates whereas functional modularity refers to a functional distribution where a single module can correspond to different brain regions (Prinz 2006).

Concerning modularity, there seems at least to be a consensus about the fact that a module is a specialized entity or device.

Identifying the neuronal correlates of recursive processing, raises questions about the status of recursion in human cognition, which will be looked at more closely in the next chapter.

The question now is whether recursion is a module or not and whether linguistic recursion should be separated from recursion in other cognitive domains as the examples above. A crucial role within this issue, however, is played by working-memory.

3.5 How Is Working Memory Related To Processing Recursion In The Human Brain?

Concerning the closeness of the brain region responsible for working-memory and the region which is considered responsible for syntax and recursion in particular, and additionally, the debate about whether recursion only refers to center-embedded CPs, the question arises, how working memory and recursion are related to each other. Furthermore, the closeness of the processing of syntactic complex sentences and working-memory also raises the question of its relation. One option is that some of the activation in Broca's area is not due to syntactic processing, but rather to general working memory load, as already mentioned, while another possibility is that all of the activation in Broca's area during syntactic processing is specific to processing syntactic structures. According to Santi et al. (2007), the latter possibility nevertheless does not rule out working-memory load. Santi et al. conducted an experimental study to observe the relation between different syntactic operations and working-memory. To do so, they did both an fMRI-study and an aphasic-lesion study. They used Movement and Binding as the two different syntactic conditions to observe brain responses with respect to working-memory. In both conditions, working-

memory is required to process the sentence, but syntactically they are governed by distinct rules (Santi et al. 2007). The activation of Broca's area was shown to be stronger in a sentence with movement that causes a filler-gap dependency, than it was in sentences which did not contain such a dependency. According to Santi et al., this finding supports the view that there is a highly specialized region within Broca's area which is underlying syntactic Movement.

But Santi et al. also state that it is less clear, how this region is related to working-memory.   One possibility is that there is a working-memory specialized for Movement, another possibility, however, is that there is a working-memory within Broca's area that is specialized to syntactic processing, but not to Movement particularly, and the third possibility is that there is a working-memory within this region that has a more general cognitive character (Santi et al. 2007).

Santi et al. found that these two kinds of dependency showed activation in distinct brain areas, namely in the left inferior frontal gyrus and the left middle temporal gyrus, in which the former is considered a part of Broca's area.

The analysis of the fMRI data suggests that different brain regions were activated for Movement and Binding. While Binding activated BA 45/47 stronger, Movement showed a stronger activation within BA 44 (Santi et al. 2007). The finding that Binding also showed activation in the right hemisphere leads to the assumption that there is neither evidence for one syntactic working-memory, nor for a general working memory, but rather working-memory in different regions of the brain (Santi et al. 2007).

Since Movement causes a long-distance dependency, it could be indeed the case that the stronger activation of Broca's area is due to the long-distance dependency that causes a higher working-memory load. The finding that the left inferior frontal gyrus was active as a result of embedding-depth and the left inferior frontal sulcus was activated as a result of distance, which should cause working-memory load, speaks for Santi et al.'s finding that the activation is not due to general working-memory load, but rather specific to syntax. Since the region that is dedicated to processing embedding and the region dedicated to Movement happen to be the same, but e.g. Binding shows to activate another region, the question is, how Movement and embedding are related. The finding that working-memory activates the sulcus rather than the gyrus general working-memory to be the cause for the activation, is technically ruled out. Santi et al. mention that the shown specifity of BA

44 to Movement that was shown in this experimental study does not rule out other syntactic operations to take place there. Since this brain region is rather big, it would be possible that different processing modules are situated there (Santi et al. 2007). According to them, it would also be possible that there is both a general and a syntax specific working memory. This would mean that none of the above possibilities is correct. The region of interest within Broca's area seems to be specific to some syntactic operations, but not to Movement alone, since Friederici et al. also identified this region as being responsible for CP-embedding (Friederici et al. 2011). But since Binding seems to activate another area, this region doesn't seem to be responsible for syntactic processing in general (Santi et al. 2007).

Ullman (2004) argues that there are commonalities between language and non-language domains. He further assumes that the declarative-procedural model of language processing also can account for this. The DP-model relies on the differentiation between declarative memory, which is capable of facts and events, and the procedural memory which is capable of motor- and cognitive skills (Ullman 2004). In terms of modularity, procedural memory belongs to the implicit modules that lead quickly to an output, while declarative memory belongs to explicit processing that takes longer to get an output. Concerning linguistic abilities, declarative memory seems to be responsible for lexical processing while procedural memory seems to be responsible for computational aspects of grammar (Ullman 2004) by which lexical items are put together to form a grammatical utterance. Hence, procedural memory is capable of generative aspects of natural language.

The procedural memory consists of a network of brain structures, including basal ganglia and cerebellum, but also parts of Broca's area belong to the neural substrate of procedural memory (Ullman 2004).The basal ganglia are considered to be involved in implicit procedural learning and especially in learning of sequences as well as the maintenance in working-memory (Ullman 2004:238). The basal ganglia receive information from cortical areas in the frontal portion of the brain which is also associated with procedural memory, but also with declarative memory, especially Broca's area (Ullman 2004:238). According to Ullman, Broca's area in terms of procedural memory is particularly important for learning sequences containing abstract and hierarchical structures (Ullman 2001:240). Furthermore, there seems to be a close link between processing sequences and working-memory (Ullman 2004). The cerebellum also subserves procedural memory, especially in terms of motor

sequencing (Ullman 2004:242). The procedural abilities ascribed to Broca's area seem to stand in close relation to the declarative abilities ascribed to this brain area (Ullman 2004:240). The relation to non-linguistic cognitive domains can be seen in the fact that the two memory systems used in language, namely the procedural and declarative system, play a similar role in multiple other cognitive domains.

3.6 SUMMARY AND DISCUSSION

The findings from the studies dealing with recursive structures or respectively self-embedding sentences are compatible with the findings from experiments dealing with syntactic structures, in general, with respect to underlying brain structures.

Concerning the processing of hierarchical recursive structures in different domains, a domain specificity of Broca's area as a single unit could not have been observed. Instead, it seems like Broca's area receives its domain specificity in this respect from the interaction with other parts of the brain, which differs from domain to domain (Friederici et al. 2011:99).

Accordingly, Broca's area interacting with the posterior superior temporal cortex combines these parts of the brain into a network, which deals with hierarchically complex sentences is natural language, Broca's area in a network together with the pre-motor cortex, the pre SMA and parietal regions makes up a network for non-linguistic visual-spatial event sequences. Also in mathematics BA 44 partly supports processing hierarchical structures, but with a main effect observed in BA 47. Hence, it seems like BA 44 is part of the responsibility of recursive structure processing, although it needs to be involved in a network with other parts of the brain to build up the entire area of processing. This means that in language processing, Broca's area is part of another network than in other domains. Models of processing in the prefrontal cortex suggest a posterior-to-anterior gradient which means that more complex processing should take place in the anterior part of the prefrontal cortex. However, language processing undoubtedly belongs to complex human behavior, but is processed in the more posterior parts of the prefrontal cortex. So it seems like the finding that processing complex syntactic hierarchy takes place in these posterior brain portions is not compatible to this model of hierarchy in the prefrontal hierarchy. Friederici et al. propose one possibility which would make up for this, namely that

mathematical formulae need more cognitive control, since language is a largely automatic process. Moreover, the nodes of the mathematical structures contain logical operators which would make it also plausible that this requires more cognitive or rather computational control (Friederici et al. 2011:100). This proposal grants a special role to recursion in language, because of the finding which suggests that language though very complex is being processed in a region located more posterior than mathematically embedded structures. It seems to be plausible that there are two parallel cognitive systems dealing with recursive structures. One system which is responsible for all other recursive structures than language and which follows the posterior-to-anterior gradient and another one which is a single system uniquely responsible for language. At this point the question arises, if there are different cognitive systems for recursive structures other than syntactic recursion or if these are the same. This question is justified insofar that as we have seen in the first part of this chapter BA 44/45 are largely responsible for complex syntactic structures such as long distance movement and embedding and, however, in other linguistic domains which deal with recursion are not likely to show such structures.

Processing syntactic recursive hierarchies seems to involve some of the brain areas also seen to be involved in complex syntactic processing despite recursion, namely BA 44.

Since the brain areas concerning recursive structure processing are similar to those involved in processing syntactic complexities, the ERP response should be the P600 component. Possibly, also the negative wave, observed during processing sentences containing Movement, could also be observed during processing syntactic recursive hierarchies, because lexical items have to be stored and retrieved while reconstructing word order, too.

When looking at the brain areas that are responsible for the processing of center-embedded structures the question arises, in how far these can be representative for what is often titled "recursive processing". This question is important, since it is crucial for the understanding of what is recursive in syntax and why this is the case. According to the view that the brain areas that correspond to what is called complex syntactic processing represent what is recursive in syntax, sentences with only one CP are not recursive, since processing these does not activate the associated brain areas. This assumption, however, seems to be rather implausible, since these brain areas do not only correspond to center-embedded sentences, but to other syntactic

operations that have higher working-memory demands, as well. Although Friederici et al. showed that for center-embedding and long-distance dependencies different brain parts are required, this does not mean that the activity in these areas is not due to the higher working-memory load, but suggests that different kinds of working-memory, corresponding to different kinds of syntactic operations, are available, like Santi et al. assumed (Santi et al. 2007). Ullman (2004), further suggests that linguistic and non-linguistic material could require the same brain areas, such that the particular brain areas may represent certain kinds of working-memory load that is perhaps not specific to language, but to something like complex hierarchy in general. If this is the case, it is questionable, which role the fact that the gradient, which Friederici et al. (2011) observed, does not hold for linguistic complexity, plays within this matter. The fact that simple sentences do not show this activity though being recursive through Merge and their general hierarchical representation and general complexity, could in turn be explained by the assumption that increased working-memory load plays a crucial role, as well. When assuming that working-memory plays primarily a role, a further question is how this could be explained in terms of modularity. Given the assumption that every natural language sentence is recursive, there is not necessarily need for a recursive module within syntax, since syntax itself would be this recursive module. Nevertheless, a recursive module could exist somehow, since syntax is not the only domain in language that makes use of recursive rules. Moreover, the use of recursive rules is not only evident in language, but also, as we have already seen in this chapter, it makes use of in processing mathematical formulae and processing visual sequences. However, these are by far not the only non-linguistic cognitive domains that show to use recursive computations. Recursion seems to play a crucial role throughout human thinking, which is a topic of the next chapter. Furthermore, the next chapter deals with recursion not only in human cognition, but also with the potential ability in some non-human species to process recursive structures.

CHAPTER 4

RECURSION AND COGNITION:

RECURSIVE STRUCTURE PROCESSING IN HUMANS AND NON-HUMAN SPECIES

In this chapter, recursion is considered in other cognitive domains than language. The aim of this chapter is to show, in which cognitive domains recursion is present, to compare it to recursion in natural language and be able to draw some possible conclusions from it.

Further, this chapter concerns probable abilities of recursive structure processing in some non-human species to determine further, what makes human cognition unique with respect to language.

4.1 EVIDENCE FOR RECURSION IN HUMAN THINKING

Recursion in cognition does not only require the principles that recursion as a formal issue does, but also needs some additional abilities in the cognitive domain that make an individual able to think recursively and use this ability in several fields of cognition. Recursion, from a cognitive point of view, has certain demands on cognition that have to be fulfilled to be able to think recursively. One aspect is being able to think in an abstract way. Another requirement is being able to process hierarchical structures, which is all possibly related to working-memory, as we have seen in the previous chapter.

4.1.1 Memory and mental time travel

Humans can easily remember past events, imagine possible future events and also think of fictional events. All these abilities are possible for human-beings, because they are capable of recursive thinking (Corballis 2011). Thomas Suddendorf called this cognitive ability *mental time travel* (Corballis 2011). Another example for recursive thinking like mental time travel is possible-world-semantics (Lewis 1986). Both thinking about past events and thinking about future events and fictional ones requires constructive elements. The memory device for thinking of episodes, whether past, future or fictional, is the so called *episodic memory*, which belongs, together with *semantic memory* to the *explicit memory* (e.g. Eysenck et al. 2010). The semantic memory stores knowledge of facts, like names of cities and persons or mathematical formulae and things like that. Contrary to explicit memory stands *implicit memory*, which consists of *a procedural memory* device, which includes actions like walking or riding a bike (Eysenck et al. 2010). Retrieval from implicit memory happens unconsciously and fast, while retrieval from explicit memory is conscious and takes more time. Applying to the use of language, one can say, that the use of the grammar, or rather I-language, every speaker of language has in his mind, namely intentions about what is grammatical in a language, is stored in procedural or implicit memory (Corballis 2011). A speaker without any knowledge about how his mother tongue works can judge whether a linguistic utterance is grammatical or not, without ever having heard it before. The lexical items of a language, namely words, are stored within semantic memory, like facts are (Corballis 2011), and have to be learned.

It has been observed that episodic memory is not present in infants before an age of four or five years. It is suggested that with approximately four years the concept of self begins to emerge. This is the beginning of memory as a recursive phenomenon, where previous experience is inserted into present consciousness (Corballis 2011:83).

The psychologist Endel Tulving distinguishes between *noetic* and *autonoetic*, in that autonoetic is what can be paraphrased with remembering or self-knowing and refers to episodes from one's own life, and noetic which means knowing without self-reference, like knowing that the boiling point of water is 100° Celsius, as Corballis pointed it out (Corballis 2011:84). Mental time travel is connected to symbolic

representation in the form of displaced reference, for instance, where, a person points in a direction to point at an object that has been in this place before, but is no longer available at the time of pointing. Experiments with displaced reference have been conducted with some animals, for example, chimpanzees and also with birds. Here, birds do better than chimpanzees (Corballis 2011). In one study, 12-month-old infants were compared to chimpanzees. In the setting that was shown to both infants and chimpanzees, a person placed desired objects on one platform and undesired objects on another platform. Then, the desired object was hidden under the platform, so that it could not be seen by the participants. Both the majority of infants and chimpanzees pointed to the platform where the desired object was hidden. In another condition, the platforms were left empty and it was observed that the human infants unlike the chimpanzees still pointed to the platform where the desired object had been before (Corballis 2011).

Episodic memory, then, is recursive, since past episodes can be inserted into present awareness. According to Corballis (2011), this is comparable to embedding of sentences within sentences or phrases within phrases. Also, in terms of episodic memory, embeddings of higher degree than one can be accomplished, in that one imagines that he imagined yesterday an event that took place in the past, before yesterday, or that someone remembers that he imagined yesterday, what would happen next week. Further, Corballis suggests that this kind of recursive thinking has set the stage for the recursive structure of language (Corballis 2011:85).

Regarding the brain structures that underlie mental time travel, in fMRI studies can be seen that both remembering past events and imaging possible future events activates the same brain regions (Corballis 2011).

4.1.2 Theory of Mind

Theory of Mind is, roughly speaking, the ability to read mental states of others, namely what they know, think or feel like. In human communication, it is striking, not only to infer from what a person actually says, but also from what the listener knows that the speaker thinks or knows. This is, like mental time travel, a recursive cognitive ability. It is recursive, in it requires the insertion of a belief into a belief, namely of what you believe that another person believes. While most animals can detect

emotions of their fellows, for example, mothers that can detect physical desires of their offspring, inferring mental states goes beyond this ability (Corballis 2011:134). Not only can humans understand what another individual knows or believes, but also what another individual *sees* or rather not sees, when looking from another place. More complex than knowing what another person knows is what another person believes about a certain situation. To test this ability, known as false believe, different test conditions are being used, like the *Anne-and-Sally-Test* (Wimmer et al. 1983)*,* as certainly the most famous example. In this condition, the participant watches how two other persons are together in the same room and one person (Anne) has an object, a ball, for example, and puts it into a basket. After having done this, she leaves the room. While Anne is not present, Sally takes the ball from the basket and puts it into the cupboard. Then, Anne comes back. At this point, the presentation stops and the participant is asked, what he believes, where Anne will look for the ball. Participants, who understand the theory about the false belief, are considered to say that she will look in the basket where she left the ball and people, who do not understand the false belief, will say, that she is looking in the cupboard, where the ball actually is located. This is, because they don't understand that Anne, who was not present while the ball had been dislocated, has other knowledge than they do themselves and therefore are not capable of the concept of Theory of Mind, which requires the cognitive ability of processing recursive structures (Perner 1983). It had been assumed that children by the age of 3-4 years acquire the ability to solve these tasks, since they give the right answer while younger children fail. But these tests that are conducted under the conditions that not yet speaking infants are taken into account, most participants of lower age pass the test. These tests are conducted such that the participants see the scene with Anne and Sally on a monitor and it is recorded, where they look, after Anne comes into the room again. Recently conducted experiments with seven-month-olds revealed that even they are capable of the thoughts of others. (Kovács et al. 2010) The babies' behavior could be observed, because in this case Theory of Mind had been tested non-linguistically, meaning that no language had been involved. Instead, the ability was tested based on the babies' eye-movements. This study revealed crucial assumptions about the cognitive abilities of babies and young infants, especially for the evidence of recursive thinking, leading away from Piaget's assumption that children have only the cognitive abilities about things they

can express verbally, such that linguistic expressions provided an insight into children's way of thinking (e.g. Gerrig et al. 2008).

According to what Kovács et al. found in their study, recursive thinking seems to be evident already in infants and babies.

Theory of Mind is thought to have evolved, because of humans' complex social lives, in terms of cooperation and social intelligence (Corballis 2011).

The given examples of Theory of Mind are recursive in the sense that thoughts, or rather beliefs, are embedded into each other which involves embedding something like a constituent in another constituent of the same type. Roughly speaking, Theory of Mind is about a belief about a belief. The embedding of thoughts into each other can be illustrated by linguistic utterances for such believes:

> (1) I believe that you believe that the sky is blue

These beliefs can have different degrees of embedding, as the following examples shows:

> (2)   a. I believe that you believe that I believe that the sky is blue
>   b. I believe that you believe that I believe that you believe that the sky is blue

The embedding of beliefs into each other can go on infinitely. However, these examples of Theory of Mind are, even in their linguistic representation, not center-embedded, but nevertheless considered recursive, which as I claim, shows, that center-embedding, is not a crucial part of recursion in human cognition.

Concerning Theory of Mind, the question gets evident in how far Theory of Mind depends on language.

4.1.3 Action planning

Action planning also requires the cognitive ability to process hierarchical dependencies and furthermore is considered to be part of the evolution of syntax in human language (Greenblatt 2011).

When planning an action, above all complex actions that require multiple steps of planning, the output from the previous step has to be used as the input for the next step until the actual action is executed. Action planning means to divide a big problem, namely the whole action that is necessary to achieve the goal, into smaller problems that can be processed in stages.

Furthermore, action planning also requires a certain degree of working-memory capacity to be able to keep track of the first level of the process of action planning.

Action planning is considered to have played a role in the evolution of syntax, which means that it also plays a role in linguistic recursion, or rather the ability to process such structures (Greenblatt 2011).

4.1.4 Tool manufacturing

The cognitive ability of humans to combine different objects in a recursive way is also considered to have lead to the fact that humans have the most complex tools of all living kinds. Other animals, like chimpanzees also use tools, which consist of combined objects, but human beings are the only species that has ever used a tool to make another tool (Corballis 2011), which usage of recursive means.

According to Corballis (2011), John F. Hoffecker, sees the origin of recursion in combinatorial tools.

But when looking at the manufacture of tools, it appears that tools differ from culture to culture, while the principles of language don't (Corballis 2011:204).

Making and using tools is recursive because two single items are combined in a way that a bigger single item is created. The new object is also seen as a whole and not as something that has been created by two other items. For example, when a stick is combined with another one, the new object is not two short sticks but a long stick. Even better suited two illustrate this, is a tool which does not look anymore like the parts it had been constructed from. Take a saw. It is combined from jagged metal and wood, but the whole item is not taken as wood and metal, but as the whole new object, namely the saw. The process of combining as well as the structure of combined tools remind of Merge in syntax.

As described so far, tool making seems to be different from tool use in the sense that tool making requires the kind of combination that is also used in syntax.

Tool use is recursive, since it needs the cognitive abilities that allow processing hierarchical structures, because tool use requires hierarchical structured behavior in two senses: First, when a tool is used the user needs to plan what he wants to achieve by using this tool as he would need even without any tool, and second, the user needs to be aware of what the tool is good for when he wants to be able to use it for certain purposes and not only for such ones that he discovered by chance. Concerning tool making, the assumption that it shows recursive properties by its required method of combination and its comparison to syntax in natural language leads to the assumption that Merge in syntax really is the mechanism that makes language recursive. This in turn would also mean that not only sentences with CP-embedding but also simple sentences are recursive since they all contain the syntactic operation Merge.

4.1.5 The need for recursion in natural language

If recursion is crucial for language and is furthermore the property that sets apart a complex grammar from a finite state grammar and thus distinguishes human language from any other communicative system, it supposedly exists among all human languages. Since recursion is thought to be a human universal, it should be a language principle and thus exist in every natural human language. A principle, however, does not have to be represented in every language by the same method, but rather as a parameter that differs between languages. However, several years ago, Daniel Everett, who lived among an indigenous people, namely the Pirahã, challenged this assumption by arguing that the members of this people do show certain constraints thought to be due to their cultural environment: Everett claimed that members of the Pirahã lack cognitive abilities, or rather show constraints on them what he considered to be due to cultural constraints (e.g. Corballis 2011). Besides non-linguistic abilities, like living in the here and now and having no folklore and lacking the ability to imagine these, also some linguistic abilities are thought to be included, most prominently recursion.

The non-linguistic cognitive constraints were also considered to be due to absence of certain linguistic abilities, following the Sapir-Whorf hypothesis (Corballis 2011). Thus, Everett supports the view that cognitive abilities result from language, which

means that if a linguistic item, or structure does not exist in a particular language, speaker of this language do not develop the cognitive ability that, from this viewpoint, results from the linguistic structure (Everett 2005).

Everett has claimed, for example, that the Pirahã are not able to distinguish between different numbers of items, since they do not appear to have any more words for quantity than *one* and *several*. Furthermore, Everett claims that the language of the Pirahã lacks recursion, since he believes that this language does not have any CPs and thus shows strict parataxis, or rather any embedding of multiple CPs. As evidence for this, Everett takes examples like this:

(1)   *ti ga´ i -sai ko´ ʼoɪ´ hi kaha´ p -iɪ´*
       I say -nominative namehe leave -intention
       "I said that Ko´ ʼoɪ´ intends to leave."
       (lit. "My saying Ko´ ʼoɪ´ intend-leaves.")

<div align="right">(Everett 2005)</div>

Everett claims that clausal complements here are expressed without embedding and that verbs that are analog to verbs like "think", "believe" and so forth, which are followed by embedding, are expressed in Pirahã without embedding (Everett 2005).

But even if CP-embedding does not exist in Pirahã, it is not plausible that this language lacks recursion. Thus, it is more likely that recursion is indeed a human universal and thus also Pirahã does show recursive structures. This argument is based on several pieces of evidence, or at least indications, which are both based on linguistic and general cognitive argumentation: If there was a language without recursion, this would mean that something within the mind and thus in the brain of the Pirahã is crucially different from other human beings, since all languages are considered to develop according to the same principles and that only the parameters differ from language to language. Only if recursion indeed was a cultural phenomenon, it would be plausible that there exist cultures, which lack this cognitive mechanism. But the far I am aware, this is rather unlikely, at least because of the fact that it seems to be a hallmark of human cognition in multiple domains.

If the members of this people are able to think recursive, which is reasonable, they would probably use it in language, since the general phenomenon of natural language is considered to work equally in every human culture.

The only question, to look at, is whether recursion really is a human cognitive universal that naturally is present in human cross-culturally or whether it depends on the cultural environment.

Since Merge is responsible for linguistic constituents to be combined within language processing and thus seems to be involved into recursive processing, the existence of a language without recursion would mean a language without Merge. And this would not only mean that Pirahã is lacking something that is considered universal in human language and thinking, but also that their language is not what is considered as natural language, since in that case it would not follow its principles. I claim that this is much unlikely.

Sakel et al. argue that cognitive complex structures in Pirahã are expressed via verb constructions. According to them, in Pirahã, there are several suffixes that are attached to the verb and have adverbial character, meaning things like *maybe, definitely* and so forth. These adverbial suffixes are held to express what in languages like English is expressed through an additional CP and Verbs like *I think, I doubt* and so forth (Sakel et al. 2009).

It could be the case that instead of an overt structure showing complementizers that introduce the new CP, this construction in Pirahã is covert. Additionally the constituent that displays the Verb from the first CP is attached to the main verb.

When assuming that also Merge is an operation that creates recursion in syntax, then there is good reason that Pirahã is recursive.

Even if the structure of Pirahã does not show any recursive structure, expressing recursive thinking seems to be possible.

Uli Sauerland, however, claimed that embedding also exists in Pirahã, namely in the form that the suffix *–sai* is pronounced differently, depending on the context (Sauerland 2010). According to Sauerland, the lower pitched –sai is a conditional marker, while the higher pitched –sai is considered to mark nominal clauses (Sauerland 2010).

In a paper from 2009, Nevins et al. take Everett's claims and show, how these can be falsified, especially, because Everett himself, in a paper from 2009 invalidates his earlier claims. However, he does this in favor to show that Pirahã still is not recursive and doesn't exhibit any embedding (Nevins et al. 2009, Everett 2005).

Nevins et al. 2009 take different syntactic conditions from Pirahã syntax, which they argue to function differently from what Everett had claimed. To take only one

example, they looked at the suffix –*sai*. The starting point for the argumentation that –*sai* yields recursion is that many clauses in Pirahã that would be analyzed as containing embedding in English, show this suffix. They further notice that Everett in his paper from 2005 claims that clauses containing this suffix are nominalized and –sai represents the nominalizer (Nevins et al. 2009:673). Everett (2005) sees this nominalizer as argument against embedding in Pirahã. His first argument comes from word order: Since Pirahã is considered an SOV language, and a –sai clause is nominalized and thus can serve as a verb's complement, it should precede the verb in an SOV language as, according to Everett, other nominal complements do. However, the fact that a nominal complement containing –sai follows the verb is an argument for Everett that Pirahã indeed is non-recursive (Nevins et al. 2009:673). The second argument against embedding in Pirahã using –sai, comes from clitic agreement (Nevins et al. 2009). Everett (2005) claims that clauses with –sai, since they are nominal, should trigger clitic agreement like other nominal complements, but since they don't, Everett considers them to be independent utterances, which he takes as an argument against embedded, recursive structures in Pirahã. However, Nevins et al. (2009) note that in a later paper from 2009, Everett argues that –sai is no nominalizer, but instead he claims that it marks old information and is, in contrast to what he has argued before, compatible with verbal inflection (Nevins et al. 2009:673). Nevins et al. (2009) argue that the revise of the assumption that –sai clauses are nominal, makes his arguments that are bound to this assumption, not holding.

Nevertheless, it has to be noted that Everett's as well as Nevins et al.'s explanations concern multiple CP-embedding and do not concern the general property of language to embed constituents within each other. However, when assuming that Merge is recursion and that this operation forms embedded structures, and thus the embedding of an NP within an NP or the embedding of an NP within and VP is the same as embedding CPs within each other, Pirahã of course is recursive, and of course exhibits embedded structures as well. Assuming that Pirahã holds the same generativity as other languages, which would be only natural, and thus contains a mechanism of concatenation like Merge, then the syntax of this language should be represented within the speaker's mind the way it is assumed for other languages, namely via embedded representations, and thus the embedding of *all* constituents within each other should be possible. Even if CP-embeddings were perhaps rather

rare or even almost never used in Pirahã, this language would be recursive, anyhow. I claim that there isn't any reason at all to assume that Pirahã is not recursive or that it doesn't show embedded structures as long as it is generative, such that its speakers can produce and understand never heard utterances.

4.2 ANIMAL COGNITION

After having examined the ability of processing syntax and particularly hierarchical structures in humans, and having looked at evidence for recursion in non-linguistic domains, the interesting point now is, whether humans are the only species which is capable of recursion, or whether the cognition of animals covers the ability to handle recursion and whether some of them also use it in communication.

To investigate this issue, the abilities of animals both in the field of general cognition as well as in the field of communication are considered throughout this chapter. Looking at possible recursive abilities in animals shall help to find out about the relation between recursion, cognition and syntax in humans.

For this purpose the neuronal differences between humans and non-human animals related to recursive processing and some possible genetic influences on the recursive human language ability are also taken into consideration to shed some light on the question of the role of recursion human cognition and the syntax of natural language.

4.2.1 Animal cognition with respect to recursion

Many vertebrates have cognitive abilities in the same cognitive fields as humans do. These cognitive abilities are also considered critical for language in humans.

Concerning categorization and learning, some animals are capable of generalizing from past experience. In one experiment, pigeons were tested for this, and it was observed that they are able, when trained on photographs, to learn concepts like "tree" and apply it on other "individuals" of this kind. This means that they can recognize pictures of other trees which they have never seen before and also silhouettes of trees as well as concealed trees. This paradigm works even well with

kinds, pigeons would never see in their natural environment, like underwater environments or abstract objects, like shapes of letters. The application on non-natural environments suggests that the ability of pigeons to perform these tasks is at least not purely innate, but learned to a certain extent (Fitch 2010:150). According to Fitch (2010), this ability can be seen as some precursor for language in non-human species, since it requires reference of the same type as it is required in language learning and processing. This ability is shared among all vertebrates (Fitch 2010).

Regarding memory, it has been shown that apes and monkeys are able to remember under which of several cups, food has been hidden and pigeons are able to remember more than hundred scenes for the time of at least a year (Fitch 2010). And it also had been recently shown that ravens have a well developed long-term memory, since they are able to recognize other ravens for a long period. Evidence for this is the fact that they reacted on befriended conspecifics friendly and on enemies not friendly, which suggests that these animals have an episodic memory which enables them to remember individuals from their past (Boeckle et al. 2012).

There is also evidence that animals are able to plan future behavior, which is in humans associated with recursive structure processing.

Also, animals have the ability to plan the future, which implies that they have an understanding of time in a more complex way than instinctively knowing the time of the day or which season it is. For example are they able to predict where a rotating clock hand must be after it has disappeared (Fitch 2010:150). In nature, hummingbirds remember where nectar-rich flowers are located and also keep track of how long it had been since they got there the last time. There are also food-hoarding birds that have not well enough olfaction and thus need to remember the places, they hid their food. To get to the food again, before it has rotten, they accordingly need a sense of time, which tells them how long it has been, since they cached the food. These data show that animals, contrary to what Corballis (2011) postulates, must have some kind of mental time-travel, like humans do (Fitch 2010:151).

In the cognitive field of numbers, three types of concept about these can be distinguished. The first concept has the name "small exact", the second "large approximate" and the third "large exact". While both humans and animals have the capacities for the first and the second type of numeral concepts, humans can as well handle the third type. Nonetheless, animals are capable of numerals and can reliably

distinguish between different small numbers. Rhesus macaques also have an understanding of basic arithmetic (Fitch 2010:132). The cognitive difference between humans and non-humans then, seems to rely on human's ability to recursively produce any number in an accurate way (Fitch 2010). Non-human primates actually learn numbers in quite different ways: While apes can only learn numbers by explicit instruction, which means that they have to learn them piece by piece, human children learn numbers by instruction approximately only the first four years of their lives. From this age on, they learn them automatically through the underlying successor function (Izard et al. 2008). This indicates that humans but not non-human primates understand the rules that underlie the concept of numbers, which is, as we have seen in Chapter 1, recursive.

Cross-modal matching is a cognitive ability that was long time claimed to be uniquely human, but it has been found that apes can match felt objects to their visual counterparts (Fitch 2010), which means that they are able to transfer knowledge to another modality, which in turn requires a certain degree of abstractness.

And concerning another cognitive ability which is closely tied to recursive processing, namely serial order, animals are not able only to manage tasks with serial order, but also when processing hierarchical orders is necessary (Fitch 2010:153).

Thus, Fitch claims that some of the data suggests that "some aspects of language are built upon ancient cognitive capabilities, widely shared with animals" (Fitch 2010:153).

Animals also show cognitive abilities more specialized fields like social cognition and tool making, which are held as possible primate precursors of human language (Fitch 2010). This suggests that it could also have been present in pre-linguistic hominids, and also many authors have claimed that tool use in pre-linguistic hominids has been a crucial factor for the emergence of language (Fitch 2010:153). Chimpanzees have established at least two kinds of tool use, namely leaf sponging to gain drinking water and insect fishing, using a modified stick to get insects from a place which would be out of reach without this tool. The stick has to be shaped such that it has the right width and length to fit into the hole, where the insects are suited. This requires the cognitive ability to plan behavior in order to reach a certain goal. Even if a chimpanzee has discovered this behavior by trial and error, reproducing it requires action planning, because it is unlikely that they get to their goal by trial and error every time they do it. And even if another chimpanzee uses this method because he

is imitating another individual's behavior, something like action planning is necessary, because this behavior is rather complex and involves multiple steps. Furthermore, chimpanzees are able to use stones to crack nuts by using second stone as underlay (Fitch 2010). Although this ability seems to be less complex and more likely to happen accidently, some things show that it is more complex than that. First, the chimpanzees have to take the stones from the forest, where they find them to the place where they want to crack nuts, which makes it rather unlikely to happen accidently and second, the transportation of the rocks requires spatial orientation and planning behavior (Fitch 2010).

These behaviors in animals suggest first, that they are capable of specifying and executing sub-goals to reach a goal, which has been planned to be reached and second, it shows, because of the complexity of the method, that these animals get a causal model of the task they perform (Fitch 2010). This indicates that they are capable of managing some kind of hierarchical structures in order to reach a goal and thus, it is possible that also in our ancestors these abilities were present without language (Fitch 2010:156).

Besides this knowledge about physical objects in their environment, which they seem to be able to use for specific goals, many animals also have the ability to live in complex social groups. This so called social intelligence might also have been a crucial predisposal for language development in humans. Social animals need to fulfill certain properties, like identifying the individuals that belong to their group, and remembering interaction which have taken place both between itself and other group-members and between other group members. And further such an animal has to be able to abstract the behavior of other group members at such a level that it can infer how to behave in the future, which demands some processing at an abstract and recursive level, as well (Fitch 2010). Furthermore, primates do have things like coalitionary behavior within and also sometimes in non-kin groups, which means that several subdominants gang together to be able to defeat one dominant individual and according to this ability, they also have conciliation after fights. This complex behavior has been considered as not being trivial, since information has to be combined an integrated into own behavior (Fitch 2010). These cognitive abilities can be considered as evolutionary relevant, since they can have major effects on reproduction, which can have lead to achieving the emergence of language in

humans. According to Fitch, social cognition in primates is directly relevant to pragmatic inference (Fitch 2010:157).

Concerning social intelligence, many animals are capable of social learning by observation in the form of enhancement or even imitation. Marmosets, for example, seem not only to be capable of social learning, but also of imitative learning. But they seem to show even more sensitivity to social learning than that: Dell'mour et al. (2009) also observed social learning behavior in marmosets and in the course of this, paid particular attention in the two questions, (1) how social learning affects task acquisition in infant animals and (2) whether the mother augments the behavior by enhancing the infant's behavior (Dell'mour et al. 2009:503). The two tasks, the marmosets had to solve, involved killing a big insect on the one hand, and getting artificially embedded food from a box on the other hand (Dell'mour et al. 2009:504). Dell'mour et al. aimed to observe the marmosets' behavior under two conditions: First, they let the mother and the infant marmoset being together at the scene, where the mother solved the task and the infant observed her behavior and second, they let the infant be at the scene alone, with the mother watching from behind a wire-mesh fence. They observed that the mother's behavior seemed to show signs of active provision of information to the offspring, which, very interestingly, also showed communication which at the first sight reminds of natural pedagogy in humans. Indeed, the communicative act seemed to refer to the infant solving the task. Dell'mour et al. recorded the vocalizations of all subjects during the experiment and analyzed these afterwards with respect to the interaction between mother and infant. The recordings also included tests with the mother in presence of their offspring as well as without them. According to Dell'mour et al.'s findings, the mother's vocalizations differed depending on the presence as well as on the age of the offspring (Dellmour et al. 2009:506). In the presence of 11-15-week-old infants, she always emitted food calls after opening a can, if the infant was not already manipulating it. She did not show this behavior when the infant did already manipulate the *same* or *another* can. During trials with infants aged 19-23 weeks the mother did not emit any food calls at all, regardless of whether the infant manipulated the can or not. Additional observing of the mother alone in the trail situation revealed that she did not emit any call when being without an infant, either (Dellm'mour et al. 2009:507).

Another interesting observation was that when the infants obtained the food the parents did not directly take it from them, which also strongly reminds of teaching the offspring a certain behavior (Dell'mour et al. 2009:504). When the accompanying infants were 11-15 weeks old, the mother left food-containing cans that she had opened unattended by moving away from it. She hardly left cans unattended when she was in the cage with the older infants and she never left them alone before having emptied them when she was alone. Furthermore, the mother behaved also differently according to the age of the infants with respect to the food from the cans. When being together with the younger infants, the mother gave some of the mealworms directly to the children and let them obtain some of them by leaving the can after having opened it. In contrast when being with the older infants, she did not give any of the mealworms to her offspring and showed signs of aggression when they came close to her when she had some of the food (Dellm'mour et al. 2009:507). Additionally to this behavior, Dell'mour et al. could also observe that the infant observers in contrast to the non-observers could solve the task faster, whereas the behavior in juvenile marmosets did not depend on the observer/non-observer condition (Dell'mour et al. 2009:508). These observations suggest that marmosets are not only able to learn from a conspecific's behavior, they are also able to imitate the observed actions and furthermore learning by observation is an important part of raising their offspring with the mother teaching them. Although marmosets show a special sensitivity to social learning, they are not the only non-human species which learns by observation. Even non-social red-footed tortoise which do not live in permanent social groups and also are not parental care givers, are capable of learning by observation. This was observed in an experimental study using a detour task, where the non-observing tortoise was not able to solve the task, but the observing tortoise was (Wilkinson et al. 2010).

Many non-human species show a lot of cognitive abilities which are rather impressive. But since primates and also other non-human animals seem to provide cognitive abilities, which have led to language development in humans, the question arises, why only humans were set ready for language. For this purpose we shall look at the communication systems of some animals to get an idea of what distinguishes them from human language.

4.2.2 The general difference between animal communication and human language

Although all animals communicate, not every communication system is language: There are crucial differences between human communication and animal communicative systems, which are topic of this part of the chapter. Communication is not only available in cognitively higher developed beings, but also present even in one celled organisms. One celled amoeba, for example, use chemical substances to attract other amoeba in order to reproduce sexually (Fitch 2010). Different species, including birds, squirrels, dogs, spiders and chimpanzees, use communicative signals to warn members of their own species, to attract mates, or to inform about food that has been found. These communicative signals do not necessarily involve verbal behavior, but can also contain signals like using urine to mark territory, or the vibrating pattern of male spiders on the net of a female to attract her (Fitch 2010:173). Animal communication, in contrast to language, only refers to the here and now, whereas language can refer both to past and future events as well as possible worlds (see Lewis 1986, Corballis 2011). Humans also make use of these non-linguistic communication signals: Although it is in many cases verbal, it is not language. Take for example laughter: It conveys the communicative message that the producer of this verbal behavior is happy, but does not involve language, since it does not involve any arbitrary signal, nor does it use any form of syntactic structure (Fitch 2010). And furthermore, a communicative signal like laughter always has the same meaning, no matter, which exact structure it has, if there is an observable structure at all. Of course, different kinds of laughter can indicate different state of minds, but this has to do more with the tone of the laughter than with its structure (Fitch 2010). Another example of this kind of non-linguistic communication is crying: It transfers the message that the producer is sad, but does not involve language (Corballis 2011).

A crucial point about this non-linguistic communication is the fact that it is not intentional like language. Language is intentional, since the individual that produces language can decide whether or not he or she will utter a sentence. Other than language, non-linguistic communication does not depend on the will of an individual. Of course cultural "rules" have influence on this behavior such that emotions like laughing and crying can be hold back, but this is at any rate more difficult than holding back a linguistic utterance (Corballis 2011). Furthermore, non-linguistic

communication, like emotions in humans, is innate and can be both produced and comprehended from birth on. Although human emotions, as well as most non-human communication, are innate, some animal species are vocal learners like humans (Fitch 2010). In how far other linguistic properties, particularly syntax, are available to some a non-human species, is topic of the following part of this chapter.

4.3 SYNTAX AND RECURSION IN DIFFERENT NON-HUMAN SPECIES

Since it seems not parsimonious that syntax appeared suddenly and in toto as a mutation in one human individual, it is a possible assumption that a precursor of syntax exists in now living non-human species. Species that come into question are vocal learners which include marine mammals, bats elephants and songbirds, which of songbirds are looked at closer and compared to the abilities of non-human primates with respect to producing syntactic structures in communication, since they are the closest relatives to humans.

4.3.1 Birds

Regarding birds, there is a difference between vocal learning birds and those who do not learn their song, but have it innate. We are now looking at vocal learning birds, which are considered to show some similarities to syntax in humans.

The vocal learning of songbirds is experience-dependent, and requires the ability of coordinating fast and precisely complex sequential movements of lingual, vocal and respiratory muscles in order to create the appropriate sounds (Hilliard et al. 2009). Here again, this ability is related to syntax in the way that syntax also requires fast sequential processing, both in production and comprehension.

Birdsong shows some parallels to human speech: Within the number of vocal learning birds, which include not only songbirds, but also hummingbirds and parrots, songbirds are the easiest to investigate in laboratories, and thus most is known about their song learning and the underlying neuronal substrates (Hilliard et al. 2009:163). Like speech, songs can be divided into smaller units. The smallest units are notes, which can be combined to syllables, which in groups of two or more can yield a

phrase. A motif is a sequence of notes and/or syllables which are repeated in a specific order. Motifs or phrases put together with an interval of silence between them build up a song. Syntax in birdsongs is constituted by the temporal order of the above mentioned features (Hilliard et al. 2009).

Learning speech and song shares some key features, like listening and social interaction. Moreover, a critical period also exists for birds, where they have to learn their songs. Another key feature is that songbirds go through a period which is analog to human babbling phase, where young birds utter sounds that are not understandable to adult birds and by which the young birds try out their phonological repertoire. It had been shown that songbirds which had been kept away from their tutors during the critical period of song learning never were able to learn their songs appropriate, in they lacked precision (Hilliard et al. 2009).

Except babbling phase, other phases during speech and song development are very similar. Before babbling, the acquisition begins with only listening to adults both in songbirds and humans, while the adult's speech/song is memorized. After this, in a phase called sensorimotor learning, also known as babbling, helps the young to practice and refine their own vocalizations in order to mimic adult sounds. What distinguishes some songbirds, for example mocking birds, is the ability to learn new songs throughout life (Hilliard et al. 2009:163). Concerning this, it is interesting that FOXP2, a gene that is related to language ability in humans, is expressed in the brain of vocal learning birds but not in the brain of pigeons which are not vocal learners (Haesler et al. 2004).

Besides parallels in acquisition, the neuronal structures underlying speech and song also show parallels. Except the cortical areas known as Broca's area and Wernicke's area, which are uniquely human, songbirds show a circuit, including basal ganglia, cerebellum, thalamus and the cortical-like pallium, which interestingly are interconnected only in male songbirds. The song circuit of songbirds functions in a rather analogical way. First, auditory input enters the song circuit at the so-called high vocal center (HVC). These neurons contribute to two pathways, namely the vocal motor pathway and the anterior forebrain pathway. The circuit in songbirds is analog to human association cortex. What is important in this case, is the assumption that the pathway, which is relevant to song modification in vocal learning birds, like zebra finches, is responsible for planning and execution of complex sequential movements in humans (Hilliard et al. 2009:164). The brain of songbirds differs from the brains of

non-singing birds in so far that songbirds have a network of interconnected forebrain nuclei that form an interface between the auditory input and the vocal output, while other birds don't have such a circuit. They indeed also have field L and they are also able to produce vocalizations using their syrinx, but are lacking the specific network (Bolhuis et al. 2006:351).

Lesion studies in both young and adult songbirds have provided an insight into the function of the songbird's brain. It has been found that a distinction between two pathways exists, namely the caudal pathway and the rostral pathway. The former is thought to be involved in song production while the latter is considered to be involved in song learning (Bolhuis et al. 2006:352).

Songbirds provide an example of non-human vocal learners which have a syntax that is structural rather complex and which also express FOXP2 in the brain.

The structure of songs in mockingbirds is even hierarchical showing hierarchical structures of phrases which constitute of syllables. This hierarchy provides a parallel to phonological and syntactic phrases in humans (Hilliard et al. 2009).

Nevertheless, the syntax in songs of these avian animals are considered meaningless. The meaning of such a song is restricted to a simple meaning like uttering to be a male of a certain species which is ready to mate (Fitch 2010:183).

4.3.2 Monkeys and apes

Primates are able not only to utter single calls but also sequences of calls. Though, they are not capable of processing complex structures like songbirds and whales are. But strikingly is that while the complex structures produced by songbirds and whales are syntactic meaningless, primates seem to be able to interpret calls, which are socially created by two or more vocalizers, in a cognitive complex way, which involves important aspects of syntax (Fitch 2010:185). Evidence for meaningful call sequences in primates comes from Klaus Zuberbühler who worked with the alarm calls of several species of African forest monkeys. These monkeys typically use an alarm call which is preceded by a low-pitched "boom" when the danger is not as immediately. In more dangerous situations the alarm call is produced without the preceding "boom". Zuberbühler used playbacks of these calls in another closely related species and observed that these monkeys seemed to understand the boom-

sound as modifier to the alarm call. The important thing here is that the monkeys which listened to the playback did not react to the boom-sound in own alarm calls, which can rule out the possibility that the low-pitched boom only has a calming effect on these monkeys. Furthermore, these monkeys have distinct calls for distinct predators (Fitch 2010:185). Zuberbühler argues that the modifying "boom" can be compared to linguistic combination in a compound of two words, which change meaning when they are put together, like *hot* and *dog* in the compound *hotdog*. The difference to human language, nevertheless, is that the alarm calls in monkeys are innate and do not contain rules that are learned and applied to certain calls (Fitch 2010). But nevertheless, this can be designated as some kind of learned syntax which has been suggested to have occurred in pre-grammatical hominids, too (Fitch 2010).

Fitch (2010) in contrast, claims that the alarm calls of African forest monkeys do not provide any evidence for precursors of syntax in the last common ancestor, since this kind of behavior which combined simplexes into complex sequences is only known to occur in this particular species (Fitch 2010:185).

4.4 NEURONAL DIFFERENCES BETWEEN HUMANS AND NON-HUMANS WITH RESPECT TO RECURSIVE STRUCTURE PROCESSING

Besides the two classical language areas within the brain, of which Broca's area seems to be highly involved in syntactic processing, the cerebellum and basal ganglia are also an important neuronal component of the human language network. Since cerebellum and basal ganglia seem to play a role in the processing of songs in songbirds, it seems to be interesting to look at possible neuronal differences between humans and non-human which possibly help to explain the cognitive difference between those which can account for the existing language faculty in humans being absent in non-human animals.

The large part of the brain, which goes beyond Broca's and Wernicke's area, and sustains language in humans, does not exist in apes (Fedor et al. 2009:26). Locations as well as the size and number of certain regions in the brain differ among species, also in dependency to overall brain size and body size. Evolution of the vertebrate brain shows an increase of the size of cortical regions and also of cortical

circuits (Fedor et al. 2009). Notably, cortical layers II and IIIb and IIIc of the chimp differ from these cortical regions in humans respectively. Furthermore, analyses of the macaque monkey brain show that in these animals the prefrontal cortex is not primarily connected with temporal regions like in human brains and the relative size of the homolog to human BA 44 is smaller in macaques. And also this brain region, which is dysgranular in humans, is agranular in macaque monkeys and thus is cytoarchitectonically more comparable to human BA 6. The macaque BA 44 is involved in using orofacial musculature, whereas human BA 44 is used for processing grammatical structures. In turn, orofacial movements in humans are controlled by BA 6 (Friederici 2009).

Differences between non-human primates and humans, concerning language, can be found in both macroscopic differences and microscopic differences in the brain as well. The microscopic differences could involve differences in neurotransmitter systems due to cytoarchitectonically different conditions. Moreover, the evolution of the "syntactic brain" in humans is considered in Chapter 5. Now, we take a look at some possible genetic influences on human language ability.

4.5 GENETIC INFLUENCES ON THE HUMAN ABILITY TO PROCESS SYNTAX

4.5.1 The FOXP2 gene

FOXP2 (Forkhead box protein P2) is a protein that is encoded by the FOXP2 gene and is located on chromosome 7 in humans. It contains a forkhead box protein DNA-binding domain which makes it a member of the forkhead box (FOX) group of transcription factors, which in general are involved in the regulation of gene expression (Vargha-Khadem et al. 2005). These proteins are critical for proliferation, cell growth and cell differentiation. Many of the members of this group are also involved in embryonic development. They have a monomeric binding domain consisting of 80 to 100 amino acids. This binding domain has hardly changed during evolution. Many different types of FOX proteins have already been found, which FOXP2 belongs to (Vargha-Khadem et al. 2005).

The FOXP2 gene is the most famous gene that has been considered of being involved in language ability. The gene has been discovered to be critical for language

acquisition for the first time in a family where some of the members showed an inability to use language appropriately. It was shown that the family members, who suffered from this condition, had a deletion at one end of this gene. At the time, this was found, the gene was considered to be "the language gene". All affected members of this family show a language disorder. This language disorder is not particularly syntactic, but has a morphosyntactic component. Mainly this condition is a speech disorder, which manifests itself in verbal dyspraxia due to deficits in sequencing of orofacial movements, which are required in speech (Hilliard et al. 2009:165). For the purpose of looking at what influences syntactic abilities this orofacial deficit also seems to be relevant, since syntax consists of the capacity to generate complex sequenced movements (Hilliard et al. 2009:166). Since the deletion at this gene also occurred in an individual not relates to this particular family, it was suggested that it might be crucial for the use and acquisition of language (Hilliard 2009). Concerning the brain, affected individuals show bilateral abnormalities in the basal ganglia and cerebellum. Furthermore, they also show abnormalities in cortical areas including Broca's area. Also, altered amounts of grey matter can be observed, which is accompanied by underactivation during tasks involving verbal fluency. These findings suggest that FOXP2 in humans is involved in brain development and a mutation of this gene leads to a malformation of brain structures that are at least crucial for the control of orofacial musculature (Hilliard et al. 2009). Homologues of this transcription factor have been found in many mammals and also in songbirds.

Chimpanzees, mice and zebra finches have a version of the FOXP2 gene, which differs only in a few amino acids from the human version (Hilliard 2009). The version, zebra finches have, differs in seven amino acids, the version of mice in three amino acids and the version of chimpanzees and rhesus monkeys only differs in one amino acid.

Studies conducted with mice and songbirds, which have an induced knock-down of the FOXP2 gene, indicate that this gene is important for modulating plasticity of neural circuits (Hilliard 2009). In mice and songbirds, this protein is also expressed in the cortex, which corresponds to the pallium in songbirds. Additionally it is also expressed in these mammals in the striatum and the thalamus during development, which is consistent with the role of forming these structures in humans (Hilliard et al. 2009). Studies with songbirds, which got injected a virus that causes a knock-down of

the FOXP2 gene, suggest that this gene is crucial for the development of speech, since their song lacked precision in adulthood in these individuals, which is consistent with the finding that humans with SLI show an abnormality in syllable structure (Hilliard et al. 2009).

In mice it had been observed deficits in motor skill learning had been observed. These knock-down mice furthermore showed an abnormal development of synapses in the dorsal striatum implicated in motor skill learning (Hilliard et al.2009:168).

Both the findings from studies with mice and from studies with songbirds suggest that the FOXP2 gene is playing a developmental role of motor skill learning.

The FOXP2 gene does not influence the brain growth and thus the ability to learn the motor skills for language ability directly, since it belongs to the group of transcription factors. Instead, networks consisting of signaling molecules, receptors and regularity factors, like FOXP2, which interact in these networks, seem to be crucial for the specification of behavior and cognition. The human version of FOXP2 affects the target genes it influences differently than the chimpanzee version does for example in this species. The FOXP2 gene is considered to down-regulate the expression of other genes, which of CNTNAP2 is known as critical for language.

4.5.2 CNTNAP2

The CNTNAP2 gene (contactin-associated protein-like 2) is a gene which also is considered to be involved in the human ability to acquire language. It is related to the FOXP2 gene, by which it gets regulated. It encodes a neurexin protein, called CASPR2, which is directly repressed by FOXP2 (Hilliard 2009). This assumption is supported by the observation that the expression pattern of CNTNAP2 and FOXP2 are opposite, in that where FOXP2 levels are high, CNTNAP2 levels are low and vice versa. (Hilliard et al. 2009) Neurexins are presynaptic proteins which are involved in gluing together neurons and synapses. In the brain, together with postsynaptic neuroligins, this protein is thought to be important for synaptogenesis (Abrahams et al. 2008). The expression of CNTNAP2 during development is enriched in cortical areas, which is involved in the ability to be able to process language, while in rodents the expression of this gene in cortical areas is diffuse. (Hilliard et al. 2009) The assumption that FOXP2 is not directly involved in language is supported by findings

of language impairment caused related to CNTNAP, but not related to FOXP2 (Hilliard et al. 2009:171).

The differences in learning motor abilities are possible not only to be critical for the learning of motor skills themselves, but can also be related in a broader sense to the ability of processing sequences like syntax involves. When identifying the brain regions where FOXP2 is active and which regions are impaired in SLI and how they are, it possibly could be investigated in how far working-memory with respect to processing structural relations plays a role. Furthermore, sequence learning can also be associated with syntax learning or rather learning the underlying rules of syntax, since learning these rules depends on processing the structures the child hears during language acquisition, as it also is the case in other vocal learning species. A generalization via induction has to be made in order to learn and apply the rules. If a human individual is not able to process the sequences he hears, it seems difficult to make an inductive conclusion about them. Since people with SLI seem not be impaired in syntax per se, but in the field of morphosyntax, it seems to be necessary to observe the particular brain regions that are considered to be a target of FOXP2 or CNTNAP2 expression and set them in relation to the function they are thought to serve in the language network. Another possibility would be that people with SLI not only suffer from orofacial deficits but also from deficits in either language planning or a deficit in the step that lies between planning and articulation, which seems also to be related to syntax in a broader sense, but nevertheless, it is important for the question why humans are ready to process language and syntactic structures, in particular, but animals are not or merely in a downgraded way. The next chapter deals with the syntax-like abilities of some animals, which could have been precursors of human syntax.

4.6 LINEAR AND HIERARCHICAL PROCESSING IN NON-HUMANS

Some animals show cognitively complex behavior or even make the use of complex sequences in communication, which, in the case of songbirds, has to be acquired by imitation and learning. This chapter deals with the question whether non-human animals are able to handle hierarchical structures.

To compare these findings with non-human abilities of hierarchical syntax processing, we will look at experiments with artificial grammar learning in apes, monkeys and songbirds.

Concerning sequential learning, which shows similarities to human syntax, experiments have been conducted by Conway and Christiansen (2001). They focused on three areas, namely learning of arbitrary, fixed sequences, statistical learning and learning of hierarchical structures.

Gentner et al. (2006) did an experiment with songbirds, namely European starlings, where they exposed these birds to grammatical forms of sounds. They distinguished between context free grammar and finite state grammar, like Friederici et al. (2011) used, in which the finite state grammar was considered to be paraphrased by a linear structure while a context free grammar needs more computational power, since it contains embedded structures. These structures were of the same type as the structure provided in the experiments concerning hierarchical processing by humans, namely a finite state grammar of the type A^nB^n and a context free grammar of the type $(AB)^n$. Gentner et al. observed that the starlings were not only able to process the linear finite state grammar but also the more complex context free grammar (Gentner et al. 2006). Corballis argued that the ability of starlings to process this type of grammar could have depended on the fact that they did not have to process a grammar of the type $[A_1[A_2[A_3 B_3]B_2]B_1]$, but only the easier type $[A[A[A B]B]B]$, which was claimed to be able to process by a simple counting mechanism (Corballis 2007).

Using sequential structures, studies concerning syntax-like processing have also been done with non-human primates by Conway et al. (2001). The ability to learn and encode sequential structures is critical to language acquisition and human communication. But not only humans are considered to be capable of processing sequences. Conway et al. observed in how far non-human primates are able to process both linear and hierarchical sequences. They tested humans and apes as well as monkeys and apes. Concerning linear sequences, primates seem to be able of encoding, storing and recalling these. Humans and chimpanzees showed evidence of planning their movements before planning while monkeys did not. Regarding hierarchical sequences, limitations seem to be evident in non-human primates. Reasons for this, other than the inability of non-human primates to process these structures could be, first that human children have more previously acquired experience with such structures and second, it could also be possible that the

experiments have not been sensitive to the hierarchical ability of apes and monkeys (Conway et al. 2001). However, this inability of non-human primates can also be the step which distinguishes humans from non-human primates and accounts for the absence of language in these species.

4.7 SUMMARY AND DISCUSSION

The collected data lead to the assumption that some of the cognitive abilities needed for processing syntax in humans, is also to a certain extend available in some non-human animals, including monkeys, apes and different avian species.

It is possible that some of these abilities can be seen as precursors of human syntax, and those which cannot be seen as precursors, nonetheless can provide an insight in how syntax could have evolved. One example is the possibility of learned syntax as a precursor of real syntax: While some animals have the ability to process these structures and also show some syntax-like elements in their communication, like compounded call in one monkey species, it is no learned system but rather an innate one.

One interesting thing here is the relation between FOXP2, processing complex sequences and vocal learning. While songbirds, which express a variant of FOXP2, which is distinct in 6 amino acids, in the brain, like humans, and are vocal learners, apes have a variant of FOXP2 that distinguishes from the human form in only one amino acid, and are no vocal learners. The interesting point is that birdsong, although structural complex only conveys simple meanings, what makes the syntactic structures rather meaningless, while apes have no structural complex structures in their communication, but show complex social interactions. This implies the possibility that FOXP2 influences not only motor learning, which is evident, since songbirds and humans are both vocal learners, but also the ability of structural complexity, while cognitive complexity, which manifests itself otherwise than in overt structures, is controlled by some other factors, which are more narrowly related in humans and apes than in humans and songbirds.

Comparing brain tissue from humans and monkeys with each other reveals that the homologues of the brain areas involved in complex syntactic processing in humans, namely BA 44 and BA 45 show the cytoarchitectonic properties of human frontal

operculum which is rather capable of simpler structures in humans and thus seems to be phylogenetic older than BA 44/45.

Humans are able to process complex hierarchical structures both in the linguistic and non-linguistic domain.

Even if some animals seem to be able to handle a "human ability", like apes seem to be able to handle the concept of numbers in some way, it is still possible that the "animal form" of this ability relies on an entirely different system. Regarding syntax in some vocal learning animals, this could mean that these indeed have the ability to produce syntactic complex structures, which can also be indeed related to the FOXP2 gene, but it is possible that these abilities in animals rely on another system than in humans, which then in humans indeed is a uniquely human system.

Concerning Merge, working memory is also required, such that even a simple sentence, cannot be processed due to lacking working-memory capacity. Working memory is required, since Merge combines binary, and thus previously combined structures have to be kept in mind until the next constituents are combined and so forth.

At least one crucial difference between humans and other vertebrates and even mammals that could have lead to the fact that any other species despite humans has language, seems to rely on a difference in working-memory capacity. When looking at chimpanzees, despite their inability to articulate language sounds, they are able to learn words by intensive training and even are able to combine words in a Merge-like fashion (e.g. Corballis 2011). However, there are at least two factors that distinguish these abilities in chimpanzees from linguistic abilities in humans: First, imitation linguistic sounds or signs and thus words in humans occurs automatically, while in chimpanzees it does not, such that chimpanzees have to learn it by intensive training, which is not the case in humans. And second, humans can Merge infinitely, at least in theory, while chimpanzees only master two-word-utterances (e.g. Corballis 2011). This infinity seems to be related to working-memory and thus explains the possibility of CP-embedding in humans. This of course doesn't mean that chimpanzees have the ability of recursion, since it seems to be a crucial factor of Merge to be able to go on ad infinitum, which is obviously not the case in any non-human primate.

In contrast, some animals show better developed skills in other cognitive domains, where working-memory is also required. This could be related to the possibility of different kinds of working-memory, for syntax and other cognitive domains.

The role that recursion might have played in the evolution is the topic of the next chapter and will be observed more closely there.

CHAPTER 5

RECURSION AND THE EVOLUTION OF LANGUAGE

5.1 EVOLUTION – A BRIEF PRIMER

After the concept of evolution had been discovered by Lamarck in the beginning 19th century, Darwin, a couple of years later, postulated a concept on how evolution works, namely through *natural selection* (Darwin 1859): Individuals from a certain species that fit better in their environment are more likely to survive and reproduce. Within this concept, three logical consequences can be drawn from the way how living things are and what they do: The first consequence is the one of variation, which means that individual organisms differ from each other, the second consequence is inheritance, namely that organisms resemble their parents and finally, differential survival, which means that not all individuals from a species, that are born, survive and breed (Fitch 2010).

Natural selection itself can be split up into at least three subcategories, which are sexual selection, kin selection and group selection (Fitch 2010:39).

Natural selection can be understood as a way of natural selection which doesn't manifest itself directly through the survival of an individual, but more indirectly through the competition between males to get a mate for the purpose of reproducing (Fitch 2010). The second subcategory of natural selection, namely kin selection, manifests itself in what is called altruistic behavior: An individual sacrifices its life or its time to help other individuals from its species. The purpose of this behavior is to help the own genes (Fitch 2010).

Fitch suggests that kin selection of the type kin communication played a critical role in language evolution by driving humans' propensity to share knowledge (Fitch 2010:42).

Within the theory of evolution there has been some controversy, which is also playing a role in the field of language evolution. In the field of theories about how evolution processed, broadly speaking, a distinction can be made between gradualism and discontinuity. In the theory of gradualism, evolution moves in small steps acting on continuous variation in a population (Fitch 2010). Discontinuity on the other side, which can be caused by mutation, for instance, means a sudden change in one individual of a species, which is because of this mutation better suited for its environment. But the change in one individual is not sufficient to fit into the term of evolution. Evolution appears when the individual mates and its offspring make an entirely new species, because evolution occurs in populations rather than in individuals. This concept of sudden change is also called *saltation* (Fitch 2010).

These two series do not have to be in conflict with each other, since both variants of variation can appear, on the one hand gradual speciation and discrete mutation, which explain evolutionary change at two distinct levels. But although the cause of evolution can appear sudden, population change will always be gradual, since the birth of a novel mutant is not the birth of a new species (Fitch 2010).

In the case of language evolution, this displays an interesting question of whether the emergence of language in humans is caused by gradual evolution or by a mutation in an individual which again caused the emergence of language in a new species (Fitch 2010).

Another distinction with respect to how a new mechanism evolved can be captured by the two terms *adaptation* and *exaptation*. Adaptation means that a mechanism has directly evolved for the purpose it serves, while exaptation means that a mechanism originally evolved for another purpose than it does actually serve at the time of interest. This means that a function shift has taken place. A former name for the concept of exaptation has been preadaptation, but the term exaptation refers both to the process of function shift and to the end product of this process (Fitch 2010). An exaptation thus, is an evolutionary trait that fulfills another role than it had originally evolved for (Gould et al. 1982). More narrowly, an exaptation only stays an exaptation during the time of the function shift. Because of this, according to Fitch,

exaptation only refers to the assumption of a new function, since otherwise, most adaptive traits would be exaptations (Fitch 2010:64).

Particularly for language, the evolution of behavior is of special interest. This evolutionary direction bears the problem, as language does equally well, that no fossils or something equivalent exists. What is important about behavioral development in a species is that it not only drives evolution but can also inhibit evolution due to a certain behavior that made a morphological evolution unnecessary (Fitch 2010:71). The only fossils that can help determining this, are founds of tools and other artifacts, which help to infer about the cognitive abilities of their inventors. This method, called cognitive archeology (Sacket 1977), of course, only gives indirect insight to the cognitive abilities of our ancestors.

In the field of the evolution of behavior, four terms are of special relevance. The first term deals with the question of mechanism. This means for instance, that a songbird sings because "it has a vocal organ which produces complex song, because it has specific neural mechanisms devoted to controlling that song, and because hormone levels at certain times of the year activate these mechanisms" (Fitch 2010:69). On the other hand there is the question of function: Birds sing to attract mates or to defend territories and of course, not to forget, because their ancestors sang (Fitch 2010). Another distinction can be made in the case of the two terms ontogenetic and phylogenetic. Ontogenetic questions refer to the matter of how an individual being *develops* and learns behavior. The matter of the phylogenetic level is how a species as a whole *evolved*.

Concerning the role that recursion plays within the issue of language evolution, language evolution has to be observed within the framework of evolutionary theories, which is the topic of the next part.

5.2 LANGUAGE AND EVOLUTION - LANGUAGE WITHIN THE FRAMEWORK OF EVOLUTIONARY THEORIES

Putting language into the framework of evolutionary theory, the first question that arises is whether language was an adaptation or an exaptation. Thus, one question to address is whether language evolved for the purpose of communication, or whether it actually evolved for other purposes. Here, it is important to note, that it isn't

helpful to regard language as a whole, but the different abilities that make up language, or better saying what made us ready to develop language, namely the language faculty. Here, the main focus will lie on the abilities, necessary for the evolution of syntax, which is especially recursion. The second question of interest is, whether the abilities that lead to the language faculty emerged continuously or due to a mutation in one individual.

Concerning language evolution, it is not only important to look at the question, how language evolved, but also which factor or factors caused language to emerge (Bickerton 2005). Concerning this issue, some theories focus on tool-making or co-operation in hunting to be the cause of language emerging in humans, while other theories, for example, focus on social interaction to be the crucial factor. Another theory focuses the avoidance of inbreeding as being the original factor that has lead to the onset of language-like utterances. Since the depression of inbreeding is a crucial factor in evolution, but genetic relatedness cannot be observed directly (Lieberman 2000), many species have mechanisms that support this avoidance. In fact, language-like utterance as such a mechanism in humans seems rather plausible, since humans don't have a well trained olfactory system, which would make it possible to recognize family members without having seen them before through olfaction. In this case, recognizing never seen members through language-like utterances, which differ from group to group, could possibly have served the avoidance of inbreeding in pre-historic humans.

Bickerton, however, comes to the conclusion that, since animals with advanced social intelligence and animals that hunt co-operatively exist, these factors cannot have been that crucial for language to evolve in humans but not in any other animal. Instead, he claims that there must have been some selective pressure on humans that did not occur in any other species (Bickerton 2005:515).

5.2.1 The evolution of syntax

One of the most central issues in language evolution is, besides the evolution of symbolic units, the evolution of syntax, since these two capacities are, according to Bickerton, the only real novelties in human communication (Bickerton 2005:511). Furthermore, Bickerton claims that it is not much likely that these two abilities

emerged in humans neither simultaneous, nor for the same reason and possibly under different selection pressures (Bickerton 2005).

Symbolic units are considered to have evolved earlier, since they form a prerequisite for syntax to emerge (Bickerton 2005). Bickerton also mentions that Chomsky has made a differentiation between the conceptual and the computational aspect of language, where, with respect to the evolution of language, the emergence of symbolism belongs to the conceptual aspects of language, while the emergence of syntax rather belongs to the computational aspect of language (Bickerton 2005:511). An evolutionary theory, furthermore, must be able to explain why syntax only emerged in humans, but did not, not even rudimentary, in any other species (Bickerton 2005:519).

The evolutionary theory of exaptation seems to be important in the case of syntax evolution. There is some consensus about that syntax emerged through exaptation of nonlinguistic capacities (e.g. Corballis 2011, Bickerton 2005). As mentioned in the previous section, an exaptation is an adaptation that has gone to fixation in some specific environment and then turns out to be useful in another one and then serves for this ability. It has been suggested that the more complex a certain phenomenon is the greater is the possibility that it can be explained by exaptation having taken part in it (Számadó et al. 2009). When being involved in this new function the exaptation gets more refined through genetic evolution by natural selection. Számadó et al. suggest that functionally different exapted modules played an important role in the evolution of language, and particularly syntax.

A possible setting for this is that the ability of tool manufacturing precedes the emergence of language. It is possible that hierarchies were first processed by humans in the field of tool making and then language began to evolve, where the hierarchical abilities of tool making were refined, which in turn reflected on the manufacturing and use of tools, which was refined by the hierarchical abilities learned through language use (Számadó et al. 2009:223). The cognitive phenotype of being able to process hierarchical structures could be a possible cognitive subtype of the suite of complex cognitive function, humans a capable of. Furthermore, Számadó and colleagues propose that language functions like syntax are the product of a synergy between distinct cognitive abilities and to find out which these synergies are leads to solving the puzzle of how syntax evolved (Számadó et al. 2009).

Since humans are social beings and language is inter alia a social phenomenon, which is also a rather complex one, looking at a coevolution of genes and social transmission in the regard of syntax is necessary (see Dunbar 1996).

There has been the suggestion that language emerged in humans because of a single mutation in one individual as a lucky accident, which has been considered to be implausible by most biologists (Számadó et al 2009). Instead the assumption that it had been possible for language to evolve in humans is due to many changes which occurred in genetics and thus also in neurology. The emergence of cultural conditions in human language evolution makes it more complex than other evolutionary processes which occurred without cultural influence, which is another parameter to be paid attention to. It had been proposed in recent years that it is possible that "a Darwinian variant of something like a Lamarckian process might have been involved" in language evolution (Számadó et al. 2009:223). This means that there might has been something like "learned syntax" in the first place, which then evolved with means of extracting rules, which led to a more complex language which in turn led to the usage of induction to learn the more complex language via its rules. This could have led to a scenario where beings, who were capable of not only handling hierarchical structures, which made it possible to understand the language, but were also capable of imitation, motor-learning and more importantly of the language faculty in the form of universal grammar, were best adapted to this environment and thus the fittest. Then, by natural selection, the fittest survives and transmits his abilities genetically to his offspring. Cultural transmission plays a role with means to the surroundings and situations where language can be used and later becomes necessary. This scenario also supports the view that the bare understanding of hierarchical dependencies and the ability to produce an infinite number of utterances by finite means are closely related.

Besides tool use and manufacturing, action planning has recently been considered important for the evolution of language, too. In a paper, published in 2011, Richard E. Greenblatt emphasizes the role of action planning in syntax evolution, as already mebtioned in Chapter 4.. He suggests the possibility that action planning could be the link between linguistic and non-linguistic cognition and further, that tool-use and linguistic abilities coevolved from simpler motor cognition (Greenblatt 2011).

Summarizing these ideas about syntax evolution in humans the interaction of genetic evolution and cultural transmission, as Számadó et al point it out, "can have a

profound effect on the nature of genetic contribution to the acquisition and neural processing of syntax" (Számadó et al. 2009:229).

These findings about which cognitive abilities were present in humans when they began to acquire syntactic language, and what could have been precursors of syntactic language, like learned syntax or pre-syntactic proto-language, can help to find out, to what extend animal communication or the ability of animals to perform tasks that require hierarchical thinking, are linked to human cognition and language ability. The ability of animals to process complex structures like the singing of vocal learning birds, in turn can provide an insight in what can be possible precursors of human syntax.

5.2.2 Possible precursors of syntactic language: Evidence from Pidgin-speakers, pre-grammatical children and agrammatic aphasics

Pidgin speakers, pre-grammatical children and patients with Broca's aphasia do at least a little insight in what precursors of syntax could have looked like:

> a) Pidgin: *and then, ey, Japan go school see?*
> b) Child language: *Baby ball.*
> c) Aphasic patient:
> *I had stroke…blood pressure…low pressure…period…*

(Examples taken from Givón 2009)

Pidgin speakers, pre-grammatical children and agrammatic aphasics, who all produce pre-grammatical language, are able to produce and comprehend a coherent linguistic discourse which also is multi-propositional. In contrast to "syntactic" language, this discourse is slower and has higher error rates. While grammar is processed with a high speed and mostly subconscious, pre-grammatical communication is slower, which can be associated with its mostly conscious processing. Furthermore, morphology is absent in pre-grammatical speech, construction are rather simple, conjoined and non-hierarchic than complex,

embedded and hierarchical and word order follows pragmatic rules. Pauses while speaking are longer, which also points to more conscious processing. Besides this, mental effort is less in grammatical speech, due to automatic processing, while context dependence is higher in pre-grammatical speech (Givón 2009).

5.4 THE EVOLUTION OF THE SYNTACTIC BRAIN

When looking at what makes humans ready to process language, the remaining question is what in the brain is distinct from other vertebrates, other mammals and other primates, in particular, and how the cognitive abilities in humans evolved after the split-up from the last common ancestor with chimpanzees. A solid point of reference, according to Fitch is to look at the differences between human brains and the brains of primates, concerning brain anatomy and brain function, as well. By doing this, for the purpose of identifying which traits are uniquely human, it is sought for *human autapomorphies*. This term refers to the traits which differentiate humans from the last common ancestor with chimpanzees (Fitch 2011:1). But despite neurobiological features that set humans apart from chimpanzees, there is much more to find that humans have in common with chimpanzees, so called *synaptomorphies*. Synaptomorphies are traits that a species shares with a relative species, by common descent (Fitch 2011:2). Synaptomorphies with humans are not only found among chimpanzees, but also with other vertebrates, humans share all aspects of neurotransmitter chemistry, neuronal morphology, brain stem circuitry, and also many aspects of neural processing. (Fitch 2011) With other mammals the similarities are even bigger: All mammals have a six-layer neocortex. And eventually with chimpanzees, humans share all known aspects of neuroanatomy, despite size (Fitch 2011).

Fitch (2011) points out two different theories on the evolution of the syntax specific regions, namely BA 44, BA 45, BA 6 and the frontal operculum. Both theories use the functional differences between these areas, which are due to differences of granularity and affect connectivity of these areas respectively. The first theory focuses mostly on BA 45 and thus assumes the origins within premotor functions of this area. This theory assumes that the underlying computations of syntax in natural language are related to motor control and motor planning with relations of the

hierarchical nature of syntax to the hierarchical nature of motor planning (Fitch 2011:7).

Here, analogously to the finding that less complex sentences lead to a stronger activation within BA 6 and the deep fOP, while complex sentences activate BA 44 and BA 45 stronger, the assumption is that the premotor functions of the deep fOP served as a precursor for linguistic computations. BA 6 and the deep fOP, being agranular, lead through a gradual granularization of gray matter and strengthened pre-existing connections to other regions of the cortex (Fitch 2011).

The other theory concerns binocular vision, which is shown to exist in chimpanzees and macaques. Furthermore, these also have trichromacy, which is the property of possessing three independent channels for conveying color information (Fitch 2011:7).

This leads to an increased importance of the visual system relative to the olfactory and sound system. Thereby, these species have heightened awareness of the gaze of others which plays an important role in social behaviour and understanding (Fitch 2011). Movement of the eyes is a motor function while controlling this function requires intracortical communication. Fitch assumes that when a species depends on the visual system and this is combined with strong social pressure, then this might lead to a computation of eye movements that have a more abstract component than limb or hand movement. Fitch (2011) furthermore suggests that, since in the macaque one portion of BA 45 is closely linked to eye movements, while social cognition requires intracortical connectivity, the amodal computations of language had a pre-adaptation in the visual and social aspects of gaze, which, according to this hypothesis, are subserved by a portion of BA 45 (Fitch 2011).

Fitch notes that these two different theories could be complementary, such that the abilities that evolved from BA 6 and the fOP, and the abilities that evolved from BA 45 represent a kind of fusion, as Fitch puts it, in BA 44, which anatomically lies between the former and the latter area. This would have lead to a more abstract computational process than only hierarchical motor planning, namely "an operator that can combine and unify pre-existing conceptual units" (Fitch 201:7), called Merge. Fitch, furthermore, characterizes the features that such an operator must have, like follows (Fitch 2011:8):

> Whether during comprehension or in production, such an operator must quickly retrieve items from memory (e.g., retrieve the phonological form of words from the lexicon), combine them in a context–relevant fashion (e.g., using background information and current context) into flexible, temporary, goal-relevant structures that can be parsed semantically (in comprehension) or produced motorically via some serialization process (during production). As emphasized by Hagoort, such an overarching computation is consistent with both the neuroanatomy of Broca's area, as discussed above, and a wide variety of brain imaging results focused on language comprehension.

The next part of this chapter focuses on the ability that makes humans able to process recursive structures: Different theories on what is responsible for this ability are looked at more closely and then, recursion within the theory of language evolution is considered.

5.4 Different Theories On The Ability In Humans To Process Language/Recursive Structures

Concerning the source for the human ability to process recursion, different theories are available. These are now presented and discussed in this part of the chapter.

5.4.1 The Grammar Gene Theory

The Grammar Gene Theory assumes that the human ability to process language is due to our human version of the FOXP2 gene. This theory was first introduced by Chomsky and finds its evidence inter alia in both brain lesion studies and in studies about developmental disorder, like Williams syndrome and Down syndrome. Bishop (2009) notes that according to Chomsky's rejection of the Big Brain Theory, it would be of special interest to study language abilities, or rather syntactic abilities in particular, in children with primary microcephaly, since people who suffer from this genetic disorder, show dramatically reduced brain size. If someone could attest syntactic abilities in someone with such a disorder which causes brain size to be approximately like in chimpanzees, the theory about human brain size being responsible for recursive abilities could reliably be rejected (Bishop 2009:186).

5.4.2 The Recursive Brain Theory

This theory, however, assumes that the human Language Faculty comes from the fact that the human brain, in contrast to the brains of other species, contains a special mechanism that makes it possible for humans to comprehend and produce recursive structures. Since recursion is thought to need more than any memory device that is just big enough to save data while processing a long-distance dependency, human working-memory is considered by a number of researchers not being able to serve as this special mechanism. What is it then that could be this special mechanism assumed in the Recursive Brain Theory; and how does this theory distinguish from the Grammar Gene Theory that also assumes a special mechanism for recursion in the form of a special form of a particular gene. The Recursive Brain Theory is, if you will, an alternative to the Grammar gene theory, which refers to innate principles due to a special form of a gene, which causes the human specialization to recursive structure processing. Within this theory, it is rather the computational ability that makes human able to process this kind of structure than innate knowledge of principles and this is what makes the theory more acceptable to neurobiologists (Bishop 2009:189). However, this theory does not contradict a theory where working-memory plays a major role, since, as we have seen in Chapter 3, working-memory in humans is considered to contain different structures for processing different kinds of data, even for different kinds of syntactic processing.

5.4.3 The Big Brain Theory

The Big Brain Theory, in contrast to the two above discussed theories about what makes the human brain ready for recursion and thus for language, emphasizes the importance not of a special mechanism or special form of a gene as cause for the human ability of being able to process recursion, but overall brain size of humans to have caused this special human ability (Bishop 2009).
Roughly speaking, this theory claims that humans have bigger brains and thus more computational power, which makes them able to compute things and use abilities which are reserved to human beings. This early theory, however, was already rejected by Chomsky, who argued that syntax crucially differs from other cognitive

abilities. With respect to the theory of modularity in the human mind, this means that there is a separate module which is responsible for linguistic computation and can thus be separated from other cognitive functions. This separate module then, however, needs not only a different module, but also a qualitatively different neural substrate, rather than only a quantitative difference in the form of more computational power. Chomsky then proposed that there must have been occurred a change in the human genome that made the processing of syntax, and thus recursion possible. This theory is known as the Grammar Gene Theory, discussed above.

Calvin (2000) suggests that a large number of neurons is needed to maintain the signal fidelity needed for syntax in natural language, which means that the number of neurons is at least beside other factors crucial for the transmissions of signals within the brain. This speaks for the necessity of a "big brain" to process complex structures like recursive ones are. This assumption, however, does not reject the Grammar Gene Theory, not the Recursive Brain Theory, since additionally to a bigger brain in general being at least one of multiple factors, another factor, or even more than one, could have played a critical role in language evolution.

5.5 RECURSION AND LANGUAGE EVOLUTION

After Chomsky in the 1950s had written about the generative capacity of the language system and dealt with recursion in the forms discussed in the first and second chapter of this thesis, it had not been examined much further until 2002 when Hauser, Chomsky and Fitch published the article with the name "*The language faculty – What is it, who has it and how did it evolve?*", where they discuss the role recursion might have played in the evolution of language. This article, however, unleashed an upcoming debate about recursion in the evolution of *Homo sapiens* and of natural language evolution and human cognition, in particular. In this part of the chapter HCF's article is presented and afterwards discussed including the article published by Pinker and Jackendoff (2005).

Hauser, Chomsky and Fitch in their article discuss what sets humans ready for language. Since other species, even those which are closely related to the human species, fail to develop language, it must be something that is present in humans but

lacks in all other species. For this purpose, they look at the properties of the Language Faculty and at different cognitive properties relevant for language.

Roughly speaking, Hauser et al. distinguish between the Faculty of Language in a broad sense (FLB) and in a narrow sense (FLN). While the former contains everything that is needed for language but is also found in other domains and/or in other species, the latter does only contain things that are exclusively needed for language, and are only present in humans (Hauser et al. 2002). With this distinction Hauser et al. aim to find out what sets human language apart from other communicative systems in other species and also what sets it apart from other cognitive domains.

Their conclusion is that there is something like a Language Faculty in the narrow sense that distinguishes from general linguistic abilities that are shared among other domains and other species and that this faculty at least contains recursion. Roughly speaking, Hauser et al. claim that recursion is at least what makes language uniquely human, or rather that recursion is what makes humans ready to have evolved a communicative system like natural language. They further argue that recursion is this special feature, since it is, according to Hauser and colleagues, a cognitive property that is both uniquely human and unique to the language ability (Hauser et al. 2002).

After the publishing of this article a big debate about what recursion is, what it is needed for and if it is what sets human natural language apart, started. Pinker and Jackendoff (2005), for example, argued in their article that some of the evidence, Hauser et al. brought up, is not good enough to sustain. They discussed in their article what is special to language and brought up several arguments against the "recursion only" hypothesis. But as pointed out by Corballis, recursion is not considered the only property that distinguishes language, but the minimum (Corballis 2006).

According to Pinker et al. (2005), Hauser, Chomsky and Fitch maintain that recursion is the mechanism which is responsible for everything that distinguishes language both from other human capacities and from the capacities in animals (Pinker et al. 2005). This does not necessarily mean that recursion, as a property of syntax in the sense of Merge or center-embedding, is the core mechanism or property that distinguishes language from any other communication system and lead to language emerging in humans. More likely, it is the case that recursion as a property of human cognition has lead to the emergence of language, since it makes humans able to

process recursive structures, and thus made it possible for a generative grammar, that is able to create infinity by finite means, and create and understand hierarchical structures, including center-embedding, to evolve. For example, Pinker et al. argued that "There are good adaptive reasons for a distinct level of combinatorial phonological structure to have evolved as part of the Language Faculty" (Pinker et al. 2005:212).

Of course, the principle known as *Speech is special* is also important for language, but in contrast to what Pinker et al. claim, it is not necessarily the case that Hauser et al. neglected this property of language as being a hallmark in its evolution, but rather that they did not include it in their theory, because it is not a part of the FLN in the sense that it could be responsible for the evolution of the *Faculty of Language* as a single property. This is plausible, because this phonological principle that describes the fact that humans when hearing language sounds categorize them, such that they hear either the one sound or another but never a mixture, is unique to language and does not count for non-linguistic sounds, but it seems not to be unique to humans, since chinchillas are able to make the same distinctions between sounds. This is what makes the theory of *Speech is special* indeed not unique to language, because language itself is unique to humans. This means that Speech is special is unique to humans in the language domain but not the concept of sound distinction behind it.

A further question is, whether recursion has directly evolved for a linguistic purpose or rather for another non-linguistic purpose.

One possibility, however, is that recursion evolved from the cognitive basis of grouping. Hunyadi (2006) argues that the same principles underlie visual, abstract prosodic and linguistic grouping.

Furthermore, he argues that from the evidence that both new-born humans and tamarin monkeys are able to recognize speech in natural order, one can suggest that new-borns as well as tamarin monkeys have the general ability to receive the hierarchical organization of elements. This in turn, according to Hunyadi, indicates that also tamarins possess the general cognitive mechanism of recursion (Hunyadi 2006:111). Hunyadi considers grouping as a cognitive basis for recursion in language, because combining phrases via Merge is a kind of grouping and requires the cognitive prerequisites to do this. Hunyadi conducted an experimental study where he tested the mechanisms underlying different kinds of grouping to observe the correlation between them. He came to the conclusion that, since the same

principles were identified to underlie both linguistic and non-linguistic grouping, syntactic recursion in language did not evolve specifically for language, but rather as a more general cognitive mechanism (Hunyadi 2006:67)

One possibility is that recursion in syntax is language specific in the sense that it derived from the more general ability to process recursion in other domains, in the first place, but then, as an exaptation, developed separately within the Faculty of Language, such that recursion in language differs from recursion in general cognition and thus belongs to something like a Faculty of Language in the narrow sense.

Recursion in the syntax of human natural language can be seen as the ability humans needed to be able to process something like syntax, which in turn made it possible for natural language with its syntactic infinity to emerge.

5.6 SUMMARY AND DISCUSSION

Since recursion is assumed to be a hallmark, or at least one of the hallmarks of human language, the evolution of this ability has to be considered. Applying the concepts of evolutionary theory to language seems to be rather problematic, since no fossils can serve as direct evidence in contrast evidence for early stages of human language ability is exclusively indirect. Evidence in this case is such as evidence from cognitive archeology and other findings that allow conclusions about brain size and cognitive abilities. Moreover, there appear to be different general questions concerning the evolution of human language and syntax, in particular. Different theories exist about how and especially why language evolved. Concerning the question why language evolved in humans, it is of great interest why this only happened in humans and did not in any other species. Another question concerning this issue is whether language is an adaptation or and exaptation and whether language appeared gradual or as a saltation. In order to approach to this question, brain areas that process syntax/recursion and homologues in closely related animal species are considered.

One possibility of the evolution of recursive language, which I want to illustrate here, is that several genetic changes caused the evolution of the nervous system by natural selection. The neuronal differences then, led to the ability in hominids to process more complex, hierarchical and recursive structures, which made them able

to use and manufacture tools and also able to interact socially in a more complex way. The complex social interaction could then have led to the need of a more precise communicative system, which can be provided by grammatical language. Since the hominid brain had been able to handle structures necessary for such a communicative system, syntactic complex structures in communications emerged by occurring in the form of learned syntax in the first place. Abstract thinking, particularly the emerging ability to learn and apply abstract rules then led away from learned to generated syntax, which in turn could have led to an even more complex syntax, since a grammar with a recursive generating system can create infinite number of sentences with a small amount of rules. And with the progress of syntactic language in humans a distinct module, specialized for language evolved, which can account for the neuronal differences between the processing of linguistic and non-linguistic hierarchical structures. Since some animals show a large number of the cognitive abilities, needed for grammatical language there must be a slight difference which made the big step for humans in evolution. One possibility is that humans both show motor skill learning and complex abstract thinking. Recursion or more particularly the concept of Merge could also be the possible step that made humans ready for language or at least pushed human cognitive abilities in the right direction. Experimental studies with animals seem to provide a helpful insight into the puzzle of how human language could have evolved and what distinguishes it from other communicative systems. But until now the question of how this happened remains, but again and again some pieces of this complex puzzle are solved and help solving this "hardest problem in science".

CONCLUSION

In Chapter 1, a short introduction to the concept of recursion was given and different fields where recursion appears were illustrated. Furthermore, we have taken a look at some controversy about the term recursion and its concept with respect to linguistic syntax. I have come to the conclusion that a differentiation between recursion, iteration and "simple repetition" is not useful, or rather doesn't make any sense, since, as I argued, recursion in natural language syntax is evident in every sentence, since recursion is represented by a combining operation like Merge, which is always recursion. Furthermore, it is sometimes argued that a recursive process does not always yield a recursive structure, or rather embedding. Here again, I argued that this differentiation is not plausible, since, according to X'-Theory a sentence with more than one clause as well as a sentence with only one clause is represented hierarchical and thus yields an embedded structure. The example given by Luuk et al. (2011), who compare a box within a box with an NP within another NP, is not helpful, nor plausible in this sense, since a box within a box, which clearly is not recursive, does not have anything in common with a linguistic structure like an NP within an NP. Karlsson (2009) in his paper argued that only center-embedded CPs yield what he referred to as true recursion, which I claimed to be implausible, since every sentence shows embeddings and is combined by the recursive operation as well.

Chapter 2 was concerned with recursion in linguistic theory, and thus recursion in different generative theories was presented. Furthermore, we looked more closely at the issue concerning the question what is recursive in natural language syntax. I argued that every sentence is equally recursive, since it is generated by the same rules, independent of whether multiple CP-embedding occurs or not. CP-embedded sentences seem to differ from other sentence in they need more working-memory to be processed. One claim about the differentiation between CP-embedded recursion and recursion on other phrases was made, which refers to what was called the strong and the weak form of recursion, where the strong form is related to CP-embedding,

with higher working-memory demands and the weak form is related to the embedding of other phrases, yielding simpler sentences and thus requires less working-memory. This, however, is considered to be a differentiation rather of degree than kind. Furthermore, Progovac argued that Root Small Clauses are not recursive, since they cannot be embedded within each other, and thus show the fact that Merge is not recursion, and these sentences display an earlier stage of human language evolution, which I again claimed to be not really plausible, since even if today's human beings utter some sort of sentences that cannot be embedded within each other, the computational system from today's humans is used and not the cognitive system of any pre-grammatic being and thus some other reason than the one pointed out by Progovac makes these sentences unable to be embedded into each other.

The 3rd chapter was about the relation of recursive processing to the brain, both within the linguistic and the non-linguistic domain. Moreover, the role of modularity and working-memory here was discussed. It seems to be the case that processing different kinds of syntactic structures activates different areas within Broca's complex. BA 44 is considered to be responsible for processing what Friederici et al. (2011) referred to as complexity while BA 45/47 is rather activated when processing distance dependencies. When processing what is in general referred to as simple sentence only the fOP is activated. From these data, Friederici et al. (2011) deduce that recursive processing, reflected by "complexity", is processed mostly by BA 44. I propose at this point that this activation reflects working-memory load, since complex sentence which have multiple clauses have higher working-memory demands than simpler sentences. The fact that different areas are activated with respect to syntactic structure (e.g. complexity versus distance) can be explained by Santi et al.'s finding that there seem to be different kinds of working-memory for different kinds of syntactic structure. This theory would also explain why in simple sentences these regions do not show such a great response: This leads to the assumption that BA 44 is not active in simple sentence, because they are not recursive, but rather because they do not require working-memory to that extend.

In Chapter 4, the role of recursion in human cognition and the probability of such ability in non-human species was looked at more closely. Recursion is evident in multiple non-linguistic domains and seems to be a necessary ability to process

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language. Concerning the debate about the indigenous language Pirahã which had been claimed to be not recursive by Daniel Everett, seems to be nevertheless recursive, in different senses. Despite the fact that it must be recursive, since it uses the same generative mechanisms like any other language and thus makes it possible for its speakers to create and understand new sentences, it seemingly as well yields multiple CP-embedding, at least in the form of conditionals as for example Sauerland (2010) found. When assuming that Everett is right with his claim, this would mean that recursion is not a human universal, which seems rather implausible, since it is not only evident in language, but also in multiple other domains of human thinking, as action planning, that are considered a hallmark of human cognition.

It has been shown that songbirds, though having a more complex structure within their communicative signals, and are vocal learners like humans are, some non-human primates show a more complex non-linguistic behavior, for example in the field of social interactions.

Concerning animal cognition in general, these seem to be capable of cognitive abilities in the same domains as humans, like generalizing from past experience, planning future behavior and social cognition and social learning as well as learning by observation. The question then was, in how far humans differ from other species, especially from non-human primates, where a differentiation in neuronal structures gets evident.

In the 5th chapter, finally, the concept of recursion in natural language syntax related to language evolution was discussed. Concerning the question why and how language evolved in humans, different theories are available, as it is for the evolution of syntax in particular. Moreover, there exist different theories on how the human brain evolved to be capable of syntactic language. One possibility is, however, that factors from different theories have interacted with each other, such that language-like utterances, that probably did not serve communication, but rather the avoidance of inbreeding, made linguistic units, like words, to appear, which probably lead to social interaction, which in turn affected the development of the human brain and thus the emergence of language. Recursion plays a crucial role here, since it is the basic mechanism that makes it possible to combine linguistic units by abstract rules, such that they yield a concatenated new one, as well as it is basically responsible for the human ability to use language as not only referring to the here-and-now, but also

as referring to past, future and imaginary events. Moreover, the recursive ability in humans is probably also responsible for the complex social interactions in humans, which are often considered to be linked to the evolution of language in humans.

One of the main questions within this concern is, of course, why only humans developed such a complex communicative system, like language, if some animal species show rather complex cognitive behavior, partly even within the same domains as humans. When assuming this, there could only be one rather small difference between humans and these animal species which makes such a big difference. Some of these abilities seem to exist both in humans and in non-human species at a distinct degree like the ability to abstract things. The question is, whether human cognitive abilities only differ in degree, or as well in kinds, which would mean that humans have some ability that all other species lack, and such made it possible for language to evolve in humans, but not in any other species.

Open questions, however, are in how far and in what extend working-memory is involved in the observed brain activity while processing different kinds of complex sentences and thus plays a role in recursive structure processing, both in the linguistic and non-linguistic domain. The involvement of working-memory in processing recursion raises the question of how human working-memory capacity is critical for the processing of recursion, and thus language, in general. A rather strong claim here would be that working-memory alone makes humans able to process language, in that it can handle the complex structures language processing requires in the sense that humans have some special sort of working-memory that is responsible for syntactic operations, and thus also for recursion. One argument in favor of this hypothesis is that not only long sentences with multiple CP-embedding, or even center-embedded CPs need a well enough qualified working-memory, but short, simpler sentences with only one CP are rather complex structures that require a certain amount of working-memory load. However, independent of the question whether working-memory capacity is the only thing that makes humans able to process recursion, and thus language, working-memory seems to be a crucial part of it.

A further question here is in how far working-memory is specialized to particular syntactic structure, or specialized to syntactic structure in general, or whether linguistic tasks are shared with more general working-memory function, where a third

possibility would be that this part of working-memory is not specialized to the language domain, but rather to a domain that is specialized to process syntax-like structures, yielding a specialized working-memory for recursive structures.

When assuming that the big working-memory in humans is responsible for human language ability, it, however, is not necessary to assume a big brain to be the cause for this. Equally well, a genetic predisposition as well as structural predisposition in a hypothetical module sense is possible to be the reason.

Of course, one crucial question is as well, whether Merge indeed is recursion and thus makes each and every sentence in a natural language recursive. Concerning this issue, the base question for this matter is whether a recursive process always yields a recursive structure or not. I argued that this in fact is the case, since, according to X'-Theory, every sentence is considered to be represented via a hierarchical structure, including domination of constituents through other constituents. The suggestion that phrase structure rules do not yield recursion, because they are linear, and thus not every sentence is recursive, to my knowledge, can be disproved rather easily by two arguments: The first argument is that the linear structure of phrase structure rules is just one possibility of representing these, such that they could also be represented via hierarchy. Moreover, according to Ullman (2004), hierarchical dependencies within phrase structure rules are achieved through the fact that one constituent contains another one.

Concerning the controversy about the term recursion within linguistic frameworks, I propose that this is at least partly due to the confusion about different uses of the term *embedding*, where in claims that recursion is only present in CP-embedded sentences, recursive embedding is confused with subordination of clauses, yielding hypotaxis. Recursive embedding, however, does not only exist in hypotaxis, since embedding as linguistic term, exists, as I argued throughout this thesis, in every sentence. In this case, it has to be investigated why brain responses to recursive sentence processing are only evident in sentences with multiple embedded clauses or center-embedding and do not occur in simpler sentences with one clause and why the activated brain areas differ with respect to whether a distance, a center-embedded structure or Movement is involved. Santi et al.'s suggestion that there are

different kinds of working-memory available for this seems rather plausible and also explains why such an activation is not observed when processing simpler sentences, since these need less working-memory load. Moreover, it has to be kept in mind that all measurements of brain responses to cognitive tasks are highly indirect and thus cannot assure unambiguous results.

Generativity in natural language goes hand in hand with recursion, both in a structural as well as in the sense of computational procedure. A further question here is whether in other domains than language, generativity is accompanied by recursion. Corballis (2011) made a distinction between a recursive I-Language and recursive E-Language. Concerning Pirahã, he pointed out that it is possible that even lacking recursion in their E-Language, they might have a recursive I-Language, containing an operation like "Chomsky's Merge" (Corballis 2011:35). He further notes that Merge indeed holds for I-Language, but does not for E-Language, since in order to get a sentence from I-Language to E-Language additional operations like Movement are needed, and thus these differ cross-linguistically, "Chomsky's notion of unbounded Merge, recursively applied, is therefore essentially an idealization, inferred from study of external languages, but is not itself directly observable" (Corballis 2011:24). However, as I have argued, even if not observable directly, as a number of linguistic operations are, Merge is the mechanism that makes language recursive and applies equally for CPs as for all other phrases, with a difference in working-memory load.

I suggest that the reason for the assumption that recursion is overtly apparent in CP-embedded sentences, but not in sentences with a single CP, is that CP-embedding yields clausal subordination and thus is more clearly observable, since a clause contains a main verb and is thus easily observable. This, nevertheless, doesn't have to mean that there appears to be a structural difference between these kinds of sentences, since they both are concatenated by the same mechanism. That is also why it is assumed by Corballis that Pirahã is recursive in I-Language, but probably lacks recursion in E-Language. Nonetheless, I suggest that every sentence in every natural language has to be recursive and so does its underlying structure, since the syntactic operation Merge combines linguistic units, such that we are able to theoretically create infinity by finite means, and thus yields embedding and moreover does this equally for all phrases, only that for embedded *clauses* working-memory load is higher.

When assuming that recursion is the basic cognitive distinction between humans and other species, this could be a distinction in kind as well as in degree. The assumption that there is a distinction only in degree can be supported by the findings that some animals show a quite good understanding of recursion in some domains as do some non-humans primates concerning Theory of Mind. On the other hand it seems to be more than a distinction of kind, since no other species seems to have a communicative system that is that complex both in structure as well as in meaning as human language is. I, however, come to the conclusion that working-memory has to play a crucial role concerning the issue of how humans and other species differ with respect to cognitive abilities and linguistic syntax, in particular. Further studies within this field of research could concentrate on the role that working-memory might play within this issue and also look more closely on brain responses concerning simple sentences, perhaps in the sense that longer sentences without any additional syntactic operations, nor long-distance dependencies or multiple CP-embedding are considered further.

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APPENDIX A: ABSTRACT (ENGLISH)

This thesis concerns the topic of recursion in human cognition with respect to natural language syntax.

Since mostly only sentences with multiple CP-embedding, especially center-embedding, and thus the embedding of clauses, are considered recursive, this thesis considers the question, what recursion in language exactly is, as well as the question, which role recursion plays within human cognition, such that language in humans could evolve.

For this purpose it has to come clear in how far language differs from other communication systems and what exactly these mechanisms are, how they are processed in the brain, whether and where they appear in non-linguistic domains and in how far other species than humans are capable of these mechanisms.

The **1st chapter** introduces the term *recursion* and the concept that stands behind it, and moreover shows its application in different fields. Further, this chapter presents and discusses possible differences between recursion and other types of repetition, such as iteration. In the 1st chapter it is concluded that a differentiation between recursion, iteration and "simple repetition" is not useful, or rather doesn't make any sense, since, as I argued, recursion in natural language syntax is evident in every sentence, since recursion is represented by a combining operation like Merge, which is always recursion. Furthermore, it is sometimes argued that a recursive process does not always yield a recursive structure, or rather embedding. Here again, I argued that this differentiation is not plausible, since, according to X'-Theory a sentence with more than one clause as well as a sentence with only one clause is represented hierarchical and thus yields an embedded structure.

Chapter 2 presents recursion in linguistic theory, particularly generative theories as phrase structure grammar and the Minimalist Program. Moreover, within this chapter, it is discussed, what the mechanism is, that makes syntax recursive, and whether there is good reason to believe that all sentences yield recursion, or if there are special properties that make only sentences recursive that contain subordinated clauses. In the 2nd chapter it is argued that every sentence is equally recursive, since

it is generated by the same rules, independent of whether multiple CP-embedding occurs or not. CP-embedded sentences seem to differ from other sentence in they need more working-memory to be processed.

In **Chapter 3**, brain structures that are considered to represent the activation pattern during syntactic and recursive processing, within and outside the linguistic domain, are looked at more closely. Additionally, it is investigated which role has to be dedicated to working-memory, since it seems to play a crucial role within this issue.

Chapter 4 is about recursion within human cognition and the cognition of non-human species. More particular, the first part of this chapter is concerned with the role recursion plays within domains outside language, and what this means for recursion in linguistic syntax and for the human language ability as a whole. Moreover, this part of the chapter also discusses the need for recursion in human language on the example of the language Pirahã, which had been considered by Daniel Everett to be a non-recursive language, which is, however, rather controversial. The second part of the 4th chapter is concerned with probable language-like processing and general cognition in non-human species. As an example for this, songbirds and non-human primates are looked at in particular.

The **5th chapter** investigates recursion within the framework of language evolution and especially the evolution of syntax. For this purpose, different theories on language evolution are discussed as well as the evolution of the human brain with respect to syntax. Moreover, the role of recursion for the human language ability is looked at more closely. Concerning the question why and how language evolved in humans, different theories are available, as it is for the evolution of syntax in particular. Moreover, there exist different theories on how the human brain evolved to be capable of syntactic language. One possibility is, however, that factors from different theories have interacted with each other, such that language-like utterances, that probably did not serve communication, but rather the avoidance of inbreeding, made linguistic units, like words, to appear, which probably lead to social interaction, which in turn affected the development of the human brain and thus the emergence of language. Recursion plays a crucial role here, since it is the basic mechanism that makes it possible to combine linguistic units by abstract rules, such that they yield a concatenated new one, as well as it is basically responsible for the human ability to use language as not only referring to the here-and-now, but also as referring to past, future and imaginary events. Moreover, the recursive ability in humans is probably

also responsible for the complex social interactions in humans, which are often considered to be linked to the evolution of language in humans. One of the main questions within this concern is, of course, why only humans developed such a complex communicative system, like language, if some animal species show rather complex cognitive behavior, partly even within the same domains as humans.

APPENDIX B: ABSTRACT (GERMAN)

Diese Arbeit beschäftigt sich mit dem Thema Rekursion, also der selbstähnlichen Wiederholung, in der menschlichen Kognition bezogen auf natürlich sprachliche Syntax.

Da meist nur Sätze, die mehrfache Einbettung von CPs enthalten, insbesondere zentral-eingebettete CPs, als rekursiv angesehen werden, da von diesen angenommen wird, dass sie eine immer komplexer werdende Einbettung von Konstituenten erzeugen, beschäftigt sich diese Arbeit ebenfalls mit der Frage, was sprachliche Rekursion tatsächlich ist und welche Rolle Rekursion in der menschlichen Kognition spielt, sodass sich Sprache beim Menschen entwickeln konnte.

Zu diesem Zweck muss klar sein, inwiefern sich Sprache von anderen Kommunikationssystemen unterscheidet und zudem, was die Mechanismen sind, die diesen Unterschied hervorrufen, wie sie im Gehirn verarbeitet werden und ob sie auch in nicht-sprachlichen Domänen auftauchen und ob sie zudem von anderen Spezies kognitiv verarbeitet werden können.

Das **erste Kapitel** ist eine Einleitung zu dem Begriff *Rekursion* und zu dem Konzept dahinter. Des Weiteren wird die Anwendung dieses Konzepts in verschiedenen Gebieten veranschaulicht. Dieses Kapitel zeigt und diskutiert ebenfalls mögliche Abgrenzungen von Rekursion zu anderen Mechanismen der Wiederholung, wie Iteration. Zusammenfassend wird in diesem Kapitel geschlussfolgert, dass eine Unterscheidung zwischen Rekursion, Iteration und „einfacher Wiederholung", oder „einfacher Einbettung weder notwendig noch plausibel ist. Auch die Annahme, dass rekursive Prozesse und Strukturen voneinander zu trennen sind, ist nicht nachvollziehbar, da folgend der X'-Theorie jeder Satz, auch wenn er nur eine CP enthält, eingebettet ist, und somit jeder Satz, der laut Phrasenstrukturregeln rekursiv durch seine Ersetzungsregeln ist, auch eine rekursive Struktur mit Einbettungen erzeugt.

Kapitel 2 hat Rekursion innerhalb linguistischer generativer Theorien zum Thema. In diesem Kapitel geht es unter anderem darum, was der Mechanismus ist, der Sprache

rekursiv macht, wobei die Schlussfolgerung ist, dass jeder Satz gleichermaßen rekursiv ist, dadurch, dass die Operation Merge rekursive Eigenschaften besitzt und für die Indefinitheit natürlicher Sprache sorgt. Des Weiteren wird begutachtet, ob es Gründe gibt, anzunehmen, dass nur Sätze mit mehreren CPs rekursiv sein können, wobei darauf geschlossen wird, dass der einzige wichtige Unterschied darin liegt, dass bei Sätzen mit mehreren CPs mehr Arbeitsgedächtniskapazität gefordert wird.

In **Kapitel 3** werden die neuronalen Mechanismen, die für Syntax, bzw. Rekursion verantwortlich sind, betrachtet. Dabei wird ebenfalls die Rolle, die das Arbeitsgedächtnis einnimmt, berücksichtigt, da es eine wichtige in diesem Belang zu spielen scheint.

Kapitel 4 beschäftigt sich mit Rekursion im menschlichen Denken außerhalb der Sprache und mit der Wichtigkeit, die Rekursion als menschliche Universal für natürliche Sprache hat. Dies geschieht am Beispiel der indigenen Sprache Pirahã, die laut Daniel Everett nicht rekursiv ist, was jedoch durchaus umstritten ist. Im zweiten Teil des Kapitels geht es um die Kognition nicht-menschlichen Spezies in Bezug auf Rekursion und Sprache. Hierbei werden Singvögel und nicht-menschliche Primaten als Beispiel näher betrachtet.

Das **fünfte Kapitel** widmet sich der Frage, welche Rolle Rekursion bei der Entstehung der Sprache beim Menschen spielt, wobei festgestellt wird, dass Rekursion vermutlich eine wichtige Rolle gespielt, da die Fähigkeit, rekursiv zu denken nicht nur zu der Möglichkeit geführt hat, abstrakte Regel anzuwenden und somit unendlich lange, immer neue Äußerungen zu produzieren, sondern auch die hauptsächliche Rolle dabei spielt, dass menschliche Sprache, im Gegensatz zu Kommunikationsformen anderer Tiere, dazu in der Lage ist, sich nicht auf das Hier und Jetzt zu beziehen, sondern neben Vergangenheit und Zukunft auch auf mögliche Welten. Eine wichtige Frage diesbezüglich ist natürlich, wieso Menschen, nicht aber andere Spezies diese Fähigkeit der Kommunikation entwickelt haben, da einige Tiere gute kognitive Fähigkeiten sogar innerhalb der gleichen Domänen wie Menschen zeigen.

APPENDIX C: CURRICULUM VITAE

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