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IMPLICIT STRUCTURED SEQUENCE LEARNING

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"…To him, the words on the page were a scramble of codes, indecipherable, mysterious. Words were secret doorways and I held all the keys…"

The kite runner, 2003
Khaled Hosseini

ABSTRACT

A simple question:

Do you know how you manage to speak your native language without making grammatical errors despite the fact that you probably do not know how to describe the grammatical rules you use?

Sometimes such simple questions do not have simple answers. The amazing capacity to effectively communicate complex information and thoughts through the medium of language is the result of the way language, and more specifically, linguistic rules are learned: in an *implicit* manner. Learning is *implicit* when we acquire new information without intending to do so and without awareness that knowledge is acquired (Forkstam & Petersson, 2005). In this thesis, an implicit artificial grammar learning (AGL) paradigm (Stadler & Frensch, 1998) was investigated from two perspectives: as a model probing the acquisition of structural, or syntactic, aspects of natural language (Petersson, 2005; Petersson, Forkstam, & Ingvar, 2004) and as a model for implicit learning. Reber, in his seminal work on AGL (1967), proposed that successful task-performance of participants is due to their ability to learn new grammatical rules implicitly. This ability, he claimed, is comparable to the way humans acquire the syntax-rules of their native language without systematic explicit guidance or awareness of what is learned.

The AGL paradigm used here is unique in combining implicit acquisition with core characteristics of the actual conditions for syntax learning: *implicit learning from grammatical examples without performance feedback*. Three studies employed the above paradigm in combination with functional magnetic resonance imaging (fMRI) to investigate structured sequence processing, while one study investigated a well-characterized natural language paradigm to investigate syntactic and semantic processing and their interaction. Consequently Reber's statement (1967) concerning the comparability of the processes involved in artificial and natural language syntax could be investigated at the neurobiological level.

LIST OF PUBLICATIONS

I. **Folia, V.,** Forkstam, C., Hagoort, P., Petersson, K.M. (2009). Language Comprehension: The interplay between form and content. Proceedings of the Cognitive Science Society, 1686-1691.

II. **Folia, V.,** Uddén J., Forkstam, C., Ingvar, M., Hagoort, P., Petersson, K. M. (2008). Implicit learning and dyslexia. Annals of the New York Academy of Sciences, 1145, 132-50.

III. **Folia, V.,** Forkstam, C., Ingvar, M., Hagoort, P., & Petersson, K. M. (2011). Implicit artificial syntax processing: Genes, preference, and bounded recursion. Biolinguistics, 5, 105-132.

IV. Petersson, K.M., **Folia, V.,** Hagoort, P. (2010) What artificial grammar learning reveals about the neurobiology of syntax. Brain & Language. doi:10.1016/ j.bandl.2010.08.003.

V. **Folia, V.,** Petersson, K.M. (submitted, 2013). Implicit Structured Sequence Learning.

LIST OF ADDITIONAL PUBLICATIONS

I. Uddén, J., **Folia, V.,** Forkstam, C., Ingvar, M., Fernandez, G., Overeem, S., van Elswijk, G., Hagoort, P., Petersson, K.M. (2008). The inferior frontal cortex in artificial syntax processing: An rTMS study. Brain Research, 1224, 69-78.

II. **Folia, V.,** Forkstam, Hagoort, P., Petersson, K.M. (2009). Language comprehension: The interplay between form and content. Proceedings of the Cognitive Science Society, 1686-1691.

III. **Folia, V.,** Uddén, J., Forkstam, C., de Vries, M., Petersson, K.M., 2010. Artificial language learning in adults and children. Language Learning 60(s2): 188-220.

IV. Uddén, J., **Folia, V.,** Petersson, K.M. (2010). The neuropharmacology of implicit learning. Current Neuropharmacology, 8, 367-381.

V. Nieuwenhuis, I., **Folia, V.,** Forkstam, C., Jensen, O., Petersson, K.M. (accepted 2013, PLOS ONE). Sleep promotes the extraction of grammatical rules

CONTENTS

LIST OF ABBREVIATIONS

AGL	Artificial grammar learning
ACS	Associative chunk strength
ANOVA	Analysis of variance
BOLD	Blood oxygen level dependent
CNTNAP2	Contactin associated protein-like 2
EEG	Electroengephalography
EPI-BOLD	Echo planar blood oxygenation level dependent
ERP	Event-related potentials
FMRI	Functional magnetic resonance imaging
FWE	Family-wise error
FWHM	Full-Width Half-Maximum
LIFG	Left inferior frontal gyrus
MUC	Memory, Unification and Control model
NLP	Natural language paradigm
SPM	Statistical parametric mapping
SPSS	Statistical Package for the Social Sciences

PREFACE

Unless I combine the words in the correct order to form grammatical English sentences one would have a hard time understanding the content of this thesis. Some of the sentences in this thesis, the reader has never encountered in her/his life, and still she/he will be able to comprehend them. This happens because the sentence structure follows what English syntax (grammar) demands.

The present PhD work on implicit learning and artificial grammars is an attempt to investigate the implicit acquisition and processing of sequence structure. Sequence learning and processing is needed in motor control, in music-related tasks, in arithmetic calculations and language. My thesis focuses on how syntactic sequence structure is acquired and processed in the human brain and how the brain uses this information to classify new structured stimulus that may or may not have been created from the previously acquired structural system. Sequence structure is by definition not random, but there are rules (regularities) defining the way that sequences with a given structure are assembled. Through the use of artificially constructed structured sequences I explore how the brain might process naturally occurring sequence structures, in this case natural language.

There were two main empirical objectives in the present thesis. The first was to investigate the influence of two different experimental instructions, the preference and the grammaticality instruction, in implicit artificial grammar learning and their effect on classification performance. The second main goal was to investigate the neural correlates of artificial syntax processing in healthy adults, as well as similarities and differences compared to natural syntax processing. In this project, knowledge from cognitive psychology, cognitive neurosciences and linguistics are put to use in order to obtain a better understanding of the ability of the human brain to learn to process structural information effortlessly.

The behavioral and neuroimaging evidence comprising this thesis suggests that natural and artificial syntactic processing engage the same brain regions in the inferior frontal cortex, which plays an important role in the acquisition and processing of rule-structured sequences. Moreover, these findings are independent of the two experimental instructions (preference or grammaticality) investigated in the thesis.

The thesis is divided into five chapters. **Chapter 1** gives the theoretical background to the empirical work. The experimental tools employed are outlined in some detail in **Chapter 2. Chapter 3** presents the experimental procedures used. In

Chapter 4 the experimental aims and results are briefly described and the main conclusions are summarized in **Chapter 5**. In **Chapter 6** the reader can find the 5 papers comprising this thesis.

The cognitive neurosciences field is rapidly developing, with enormous achievements during the last 10-15 years. It is expected that ideas and theories will continue to develop and I hope that the results and conclusions of my work will contribute to this development.

Vasiliki Folia
2013

1 CHAPTER – THEORETICAL BACKGROUND

1.1 NATURAL LANGUAGE ACQUISITION

1.1.1 Linguistic components

From birth, and over the next couple of years, the child manages to learn to speak its native language, a process that unfolds effortlessly, following roughly the same developmental path in all normal children despite differences in individual experience. This achievement will not repeat itself again in such a natural way when acquiring another language during adulthood, irrespective of the individual's advanced learning abilities. Natural language acquisition is a complex process during which the child understands and masters much information hidden within sentences. More specifically, it entails the acquisition of sounds (phonetics and phonology), parts of words (morphology), meaning (semantics), word-order (syntax), as well as discourse pragmatics.

1.1.2 Language-syntax learning: an unsupervised process in infants

Since language is a very complex system to acquire unaided it has been proposed that this achievement results from an innate mechanism (a "specialized language organ") found in the human brain, in broad terms defined as the *language acquisition device* (Chomsky, 1986; Pinker & Bloom, 1990), which provides a biological head-start in language acquisition (Chater & Christiansen, 2010). Equipped with this mechanism(s), the child's brain includes representations necessary for acquisition of all possible human languages but progressively "turns on" only the parameter settings the target language requires. Consistent with this view, research has shown that infants are sensitive to all categories of phonemes up to 8-12 months. By that age they lose this general sensitivity which becomes restricted to the native speech sounds (Lasky, Syrdal-Lasky, & Klein, 1975; Werker & Lalonde, 1988). Also, certain types of generalization errors are absent during the acquisition process, suggesting that the child comes equipped with innate language constraints. For example, it seems that children never consider rules solely based on serial position in sentences (Gómez & Gerken, 2000). The nature of this learning mechanism(s) and how language acquisition is achieved, given the limited perceptual and learning abilities of infants, remains a challenge to understand. The existence of such a specialized organ would point to a domain-specific brain mechanism, genetically specified and dedicated to language acquisition. Consequently, one source of evidence of a genetic background of a specialized linguistic system would be a genetic anomaly preventing afflicted individuals from acquiring certain aspects of their native language, while retaining other language abilities (Lieberman, 2002). One case, known as the KE family, was found to suffer from a genetically transmitted anomaly and was reported to be unable to acquire the regular past tense of English verbs and regular plural nouns (Gopnik & Crago, 1991). However, the KE family suffered from a number of other cognitive deficits as well, including oro-facial movement disorders (Vargha-Khadem, Watkins, Alcock, Fletcher, & Passingham, 1995; Watkins, Dronkers, & Vargha-Khadem, 2002), eliminating the chance that this particular genetic anomaly leads to specific loss of a linguistic ability.

During the last decade, the above hypothesis has been increasingly questioned on processing (M. H. Christiansen & Chater, 1999), on evolutionary (Chater, Reali, & Christiansen, 2009) and acquisition grounds (M. H. Christiansen & Chater, 2008), as well as on language diversity arguments (N. Evans & Levinson, 2009). It is argued that there is no need for an innate, language-specific learning mechanism but that language acquisition can be accomplished via domain-general mechanisms, shared even with other species, including for instance, mechanisms that detect statistical regularities (distributional frequency cues). For example, it has been shown that language learning starts already while the infant is in the uterus (Altman, 2001). In this way unborn babies learn prosodic characteristics, the melody of their native language to some degree. This mechanism could be domain general, operating on statistical information, facilitating acquisition of statistical dependencies found in the linguistic environment and such mechanism may not be unique to humans but may also be shared with other species (Altman, 2001; Conway, Pisoni, Anaya, Karpicke, & Henning, 2011). Studies of early language acquisition have highlighted the importance of prosodic and statistical patterns in the input during infant language acquisition (Kuhl, 2004). For example, the influence of statistical regularities was investigated in infant speech segmentation (Brent & Cartwright, 1996; Saffran, Johnson, Aslin, & Newport, 1999) and in the emergence of meaning and grammatical categories (Elman, 1991). Infants at 8 months can already make use of transition probabilities in artificial syllable sequences (Saffran, Aslin, & Newport, 1996), while recent studies in young infants indicate rapid rule-abstraction (Marcus, Vijayan, Bandi Rao, & Vishton, 2009).

Syntax learning, which is part of language learning, is considered also a largely unsupervised process assumed to take place implicitly and without systematic explicit feedback. During the interaction with the environment a child hears only a finite number of syntactically well-formed (Hanson & Negishi, 2002) utterances from its native (target) language and still manages to learn the correct generalizations necessary for the specific language (Chomsky, 1986; Pinker, 1994; Pullum, 1996). In addition, the internal mental structures representing linguistic information are not expressed in the surface form (i.e., the utterance) of a language. However, children manage to learn the regularities that govern sentence structure and word-order even if they initially lack knowledge of the syntactic categories (e.g., noun, verb). All these achievements are accomplished in an unsupervised and unstructured way. This is very different from the acquisition of reading and writing skills, which in comparison, requires systematic exposure to the learning material, typically in a supervised manner (i.e., with instruction and feedback) later on in school (Petersson, Ingvar, & Reis, 2009).

To conclude, it is likely that both domain general and specific learning mechanisms underlie implicit language learning (Folia, Uddén, De Vries, Forkstam, & Petersson, 2010; Hagoort, 2009). Concerning language processing this might also be the case. For example, domain-specific memories for syntax (e.g., lexical items) might recruit domain general mechanisms, such as unification processes, to produce (during speech) or decode (during listening/comprehension) the combinatorial aspects of language.

1.2 INTERACTION BETWEEN SYNTAX AND SEMANTICS

1.2.1 Tripartite parallel architecture-the unification model

Sentences contain phonological, syntactic and semantic information. These linguistic components have to be processed and combined in order for acquisition and comprehension to be achieved[1]. While in earlier linguistic work much attention was given to the syntactic component as the main structure upon which phonology and semantics build, recent models (Jackendoff, 2002; 2007) are treating the linguistic components as parallel and interacting. Moreover, the majority of these models make a distinction between retrieval of lexical information stored in long-term memory (the mental lexicon) and combinatorial/compositional processes (lexical items combined into structures), implying that sentences have an internal structure, typically not visible in the surface utterance. Vosse and Kempen (2000) proposed a

[1] The comprehension and production of sentences are known as the performance systems. There is one more system that of linguistic knowledge, with which the performance systems interact.

computationally explicit lexicalist *unification space model* that accounts for a large range of empirical findings in the parsing and neuropsychological aphasia literature (Vosse & Kempen, 2000). In this model, the store of words is defined as *mental lexicon* and the information is stored in the form of structured primitive representations, *lexical frames* or treelets (elementary syntactic trees). This information includes, apart from the meaning of the lexical item, information about the lexical form and the syntactic properties of the item (e.g., constituent class, syntactic gender etc.). At the level of combinatorial/compositional processes the words needed for sentence level integration are retrieved from the mental lexicon and specify possible structural environments for other input words (Kempen & Harbusch, 2002). Thus, only relatively generic structure building operations like *unification* (Vosse & Kempen, 2000) are necessary to complete the on-line combinatorial integration process into higher order representations, since the lexical frames are dynamically linked as the constraints are applied during processing. From that point the combinatorial processes will lead to an incrementally structural interpretation of the sentence.

1.2.2 Towards a neural implementation of the unification model

Based on the model of Vosse and Kempen (2000), Hagoort (2003; 2005) proposed the Memory, Unification and Control (MUC) model. This model is an attempt towards a neurobiological account for language processing. In the MUC model, integration of the various linguistic sources (e.g., phonological, syntactic, semantic) operate in parallel in a workspace for incremental unification of the structured representations. Thus, unification is a *recursive* and *incremental* process. The neurobiological account of the MUC model (Hagoort, 2005) suggests that the left posterior temporal cortex is the space involved in the retrieval of word information (mental lexicon), while the left inferior frontal gyrus (LIFG) is considered as the space for online unification processes. Research on the MUC model has identified distinct neural systems subserving lexical-syntactic retrieval located in the left posterior temporal cortex (Hagoort, 2005; Hammer, Jansma, Tempelmann, & Münte, 2011; Snijders et al., 2009) as well as supporting the role of the LIFC in the unification operations performed at the structural/syntactic level (Petersson et al., 2004; Snijders et al., 2009) and conceptual/semantic level (Hagoort, Hald, Bastiaansen, & Petersson, 2004; Menenti, Petersson, Scheeringa, & Hagoort, 2009; Tesink et al., 2009). However, except for studying each component separately, the interaction of the syntactic and semantic component (i.e., whether semantic parameters have an influence on the structure building process and vice versa) is an important topic for investigation in order to understand how language comprehension is achieved (Friederici, Steinhauer, & Frisch, 1999; Hagoort, 2003; Kuperberg et al., 2003; Osterhout & Nicol, 1999). The control component can be considered as the link between language and action. For example, this component operates in the context of communicative intentions and actions. Hagoort (2005) suggested that the control component is centered in the dorsolateral prefrontal (BA 9/46) and the anterior cingulate cortex (ACC). However, research on the control component is largely lacking.

1.2.3 Summary

(1) Language consists of components, including the phonological, syntactic and semantic components, which are independently specified and operating interactively in parallel in order for language comprehension/production to be achieved.
(2) Unification processes are responsible for the formation of higher level structured representations, via combinatorial operations performed in each component as well as in interaction between the different components.
(3) The Memory-Unification-Control model represents a neural account for language processing.
(4) The LIFG supports unification operations, while the left posterior temporal cortex subserves lexical retrieval operations. The control component of this model is the least investigated.
(5) The neural characterization for the syntactic and semantic interaction is an important topic to explore, in order to understand language comprehension.

1.3 INVESTIGATION OF SYNTAX LEARNING/PROCESSING IN ISOLATION

1.3.1 Syntax in natural language

Language includes a set of internal governing rules leading to syntactic and semantic comprehension. At present, it is far from understood how learning these rules at the synaptic level of the brain can give rise to the emergence of the actual language system (Hanson & Negishi, 2002). At the level of sentence construction, the individual words are related to each other in such a way as to reveal the meaning of the sentence, if the grammar of the language is mastered. This content, known as *propositional content* (Chomsky, 1996), reveals information about events and states of affaire (such as who did what to whom), information about the temporal order of events, as well as other semantic information. This propositional content is revealed via the syntactic structure in combination with lexical semantics (e.g., the meaning of words), referential binding, and various discourse factors.

Imagine the following sentence: “The woman reads my thesis”. When someone reads this sequence of words, he/she has to make sense of who does what, that is, to re-construct the correct relationships between the lexical elements in order to comprehend the sentence. The *syntax* of a language, what will be later called interchangeably grammar (*see section 1.4*) fulfills this function; it specifies how the elementary pieces can be placed together (words in this case) into a hierarchical structure interpolating between the sound and meaning levels. This process is called *parsing* on the comprehension side (when the listener has to break down the spoken utterance to a set of symbols and compare it to the grammar of the language) and *generation* on the production side (when a person uses the grammar to generate an utterance). In the example sentence the hierarchical structure constructed can be seen in **Figure 1**. It has to be emphasized that this kind of structures are linguistic representations of how the outcome of syntactic rule application can be represented and do not intend to explain how these rules are interpreted or implemented in neural terms.

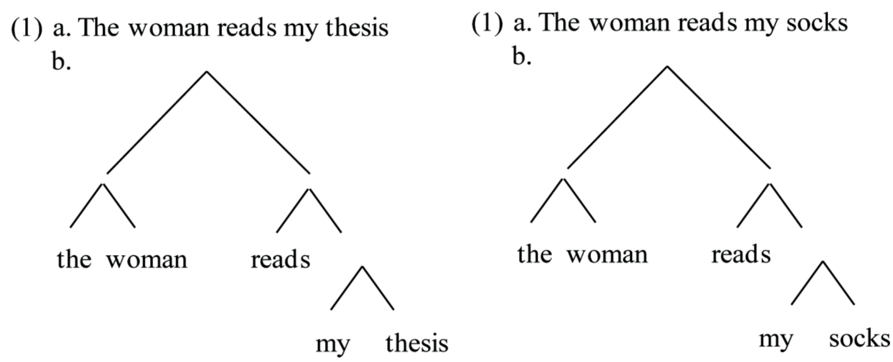

Figure 1. Examples of a hierarchical tree-structure of two syntactically correct sentences.

Syntax can be independent of meaning and sound interpretation (form) since it combines the units (elementary pieces) independent of their interpretation and the language system treats these units as *abstract symbols*. As a result, the sentence “The woman reads my socks” is as syntactically correct as the sentence “The woman reads my thesis”, even though the former is not semantically plausible. This realization is important for this thesis, where the representation of elements in a sequence structure (artificial grammar constructions) is proposed to be a relevant model for investigating natural language syntax independent of semantics. However, in everyday language usage, communication is the goal realized via semantic comprehension, and syntax is a means to reach this goal. In other words, syntax leads to semantically interpretable representations and consequently to language comprehension.

1.3.2 Artificial grammar learning: an experimental model for syntax processing

The parallel architecture with its interacting levels of representation for orthographic/phonological, structural/syntactic, conceptual/semantic information, and the interactive processes leading to linguistic comprehension, renders the investigation of syntax in isolation a difficult task. This is mainly due to the fact that semantics, phonology and syntax operate in close spatial and temporal proximity in the human brain. For this reason, the creation of an experimental paradigm to investigate syntax in isolation, in this case the artificial grammar learning (AGL) is one important approach to study syntax processing. The experimental tool has to model one important language characteristic, that is, the ability to combine units in a *recursive* manner, since as Humboldt (1836) stated: "language is the *infinite use of finite means"*, and since the 1950's a fundamental problem in theoretical linguistics has been to construct explicit models reflecting this intuition (Chomsky, 1965). Artificial grammars are tools developed to represent a small-scale model for exploring aspects of natural language rules. The Reber grammar, used in this thesis, is an instantiation of such a tool and will be introduced in the following sections.

1.4 FORMAL DEFINITION OF GRAMMARS

Formal language theory is a branch of mathematics that, via the study of formal (artificial) grammars and languages, tries to understand for example, the syntactic regularities of natural languages. Examples of formal languages are computer-programming languages finding applications in mathematical logic, computer science and linguistics. They may be classified according to the Chomsky hierarchy which will be described below and are entirely syntactic in nature. As discussed above *(see section 1.3.1)* natural languages have syntactic form separate from its semantics enabling thus, the use of formal languages as descriptions of natural language syntax.

1.4.1 Natural language grammars

Natural language grammars are defined as the rule systems that govern how the different linguistic elements (e.g., words) can be combined to form larger units (e.g., phrases and sentences). The set of rules is specific to a language and each language has its own distinct grammar. From now on we will use the terms grammar and syntax interchangeably.

Although different languages have different syntactic rules for sentence construction, most of them consist of the same basic syntactic categories (e.g., nouns, verbs, adjectives, adverbs, prepositions etc.). Once the syntactic *rules* of a language and its *vocabulary* are determined, one can create possible combinations of words into sentence structures of that language. An example of a "mini" English grammar can be seen in **Figure 2**. This grammar (G) contains the following sets of elements: (1) a set of *terminal* elements, which make up the surface form of the sentences. They are the actual words in language, thus these symbols cannot be replaced by anything else; (2) a set of *non-terminal* elements used in the derivation of a sentence (including the *start symbol* denoted with S from which all sentences derive). The non-terminal elements can be replaced/expanded to a sequence of symbols during the course of a derivation; (3) a set of *production rules* specifying what kind of combinations of terminal and non-terminal elements can be created. A production rule is applied to a sequence by replacing an occurrence of its left-hand side in the string by its right-hand side. When generating sequences one starts with the start symbol "S" and applies the rules. These rules describe how to replace symbols and eventually the created sequence that is derived cannot be expanded further. This sequence will consist of only terminal elements and such a sequence is called a word. The terminals appearing in the sentences of a language and the non-terminal symbols are two disjoint sets comprising the terminal and non-terminal *alphabet (vocabulary)*, respectively. The language (L) of a grammar (G) is the set of sentences generated by G, in this particular case the mini-grammar. Below we illustrate with an example. A sentence can be decomposed into a noun phrase and a verb phrase. The noun phrase can be compartmentalized into a determiner and a noun, which are the non-terminal elements of the grammar. The symbols "a" and "the" take the position of the determiner, the symbols "woman" or "man" take the position of the noun, and "reads" and "walks" take the verb position. These are the terminal symbols of the grammar. Following the specific rules and knowing the complete vocabulary, the construction of the complete set of possible sentences can be created.

A.

S (Sentence) → **NP** (Noun phrase) **VP** (Verb phrase)
NP → **D** (determiner) **(A)** (optional Adjective) **N** (noun)
VP → **V**

B.

D -> a
D -> the
N -> woman
N -> man
V -> reads
V -> walks

C.

Sentence -> NP VP
-> D N V
-> the woman reads

D.

L = {"A woman reads",
"a woman walks",
"the woman reads",
"the woman walks",
"a man reads",
"a man walks",
"the man reads",
"the man walks"}

Figure 2. An example of a "miniature" English language grammar **L**. A) Production rules; B) Production rules: The words that can take the place of the linguistic categories: determiner, verb, noun; C) The creation of the sentence "The woman reads" according to the "mini" English language grammar; D) The set of all possible grammatical sentences in **L**.

When working with grammars, the application of rules leads to a derivation of a sentence which can be represented in two ways. The first is the tree-representation of for example "the woman reads my thesis" (**Figure 1**). It describes how each symbol derives from other symbols in a hierarchical (or more precisely inductive) manner. The other way is a derivation as described above, where the rules are applied step-by-step and we substitute with words at the relevant positions.

1.4.2 Artificial grammars

Artificial grammars include, like natural grammars, a set of rules specifying a set of sequences over a finite vocabulary of terminal symbols. For a formal grammar the input is a start symbol; the output is a sequence of words which constitutes a sentence of the language. By analogy to the mini-grammar above (**Figure 2**) we present an example of a regular artificial grammar. This grammar has a collection of production rules of the form S→aB, B→bS, B→b. Here lower case letters indicate the terminal symbols and S, B the non-terminal symbols. Thus, the vocabulary-terminal symbols are "a" and "b" and the start symbol is "S". An example given can be for the creation of the sentence abab. The way to generate this is: S→aB → abS → abaB → abab. This is one example of a regular grammar. In this thesis, the Reber grammar was used, containing its own specific rules.

1.4.3 The Reber grammar

The Reber grammar is an example of a (non-deterministic) regular grammar. Regular grammars, and consequently the Reber grammar, can be described by finite state machines. The finite state mechanism that generates the Reber language includes the terminal symbols (M, X, V, X, R, S), the non-terminal symbols (State 0, State 1,..., State 6) and rules specifying which state can be followed from another, for example State 0 is followed by State 1 and it can either be assigned the terminal symbol M or V before continuing to State 2 etc. The transition graph **Figure 3** shows the implementation of this simple grammar.

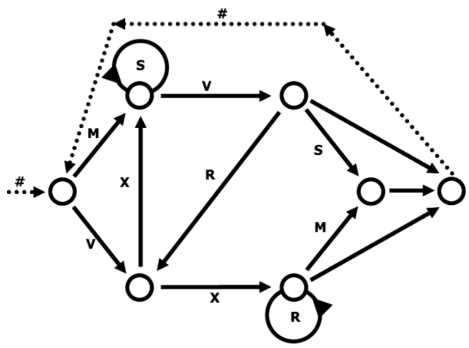

Figure 3. Transition graph representation of the Reber machine used as a system to construct grammatical (e.g., <MSSVRXM>) in contrast to non-grammatical sequences (e.g., <MSRXM>) used throughout this thesis.

Within the unification framework, the Reber grammar can be viewed as a right-linear unification grammar, described by a set of primitive structures called *lexical trees/treelets* (**Figure 4**). It is assumed, that each lexical item is encoded in treelets of syntactic control features, that is, a *root node*, a *foot node* and a *surface feature*. What these syntactic control features code for, in this particular case, is sequential order information as well as hierarchical dependencies. These representations of lexical items, lexical frames or treelets, are encoded in the mental lexicon as explained in the UMC model (*see section 1.2.2*).

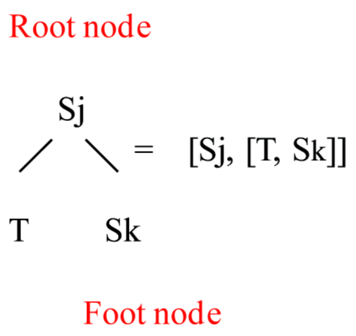

Figure 4. Structured representation of a lexical item (lexical frame or treelet).

Retrieval and unification in this artificial unification grammar is explained via an example depicted on **Figure 5**. Each incoming sequence of surface symbols, for example <MSSVRX>, initiates the retrieval of the corresponding lexical frame, which enters an online unification space where two lexical items unify only if the *foot node* of the current partial structure, constructed so-far, is the same as the *root node* of the one entering. If participants have learned the information that each lexical item carries then they can judge accordingly what can be a grammatical item or not. When encountered with the target item <MSSVRX> the composition of the sequence will be parsed in the unification space as a valid structure and the relevant information over the allowed rules that the sequences can be combined will be present. Unification may be prevented in case a foot node does not eventually find an identical root node to merge with, and this results in unification “failure”. In neural terms, neural activity during unification failure does not cease, instead repeated unification attempts lead to maintained or increased activity. In the case of natural languages, the semantic component plays an important role in unification resolution.

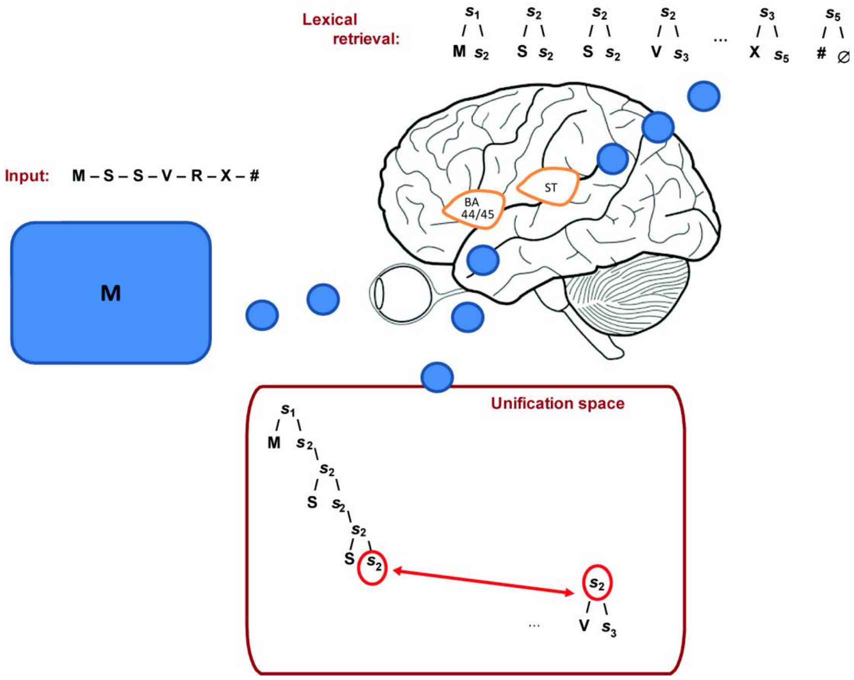

Figure 5. Example of the unification space online. Primitives derived from the acquisition of a formal grammar are thought to be accessible to the cognitive system in the unification space. When encountered with the target item <MSSVRX>, the primitive composition of the sequence will be parsed in the unification space as a valid structure (Forkstam, Hagoort, Fernandez, Ingvar, & Petersson, 2006)

1.4.4 Chomsky's hierarchy

Chomsky (1956) proposed a hierarchy for the classification of grammars. In the traditional *Chomsky Hierarchy* there are four levels of complexity leading to four different types of grammars, depending on the nature of the restrictive conditions on the production rules. The Type 0 grammars are not restricted by any limiting condition, while Type 3 grammars follow more limiting conditions on what type of sequences can be created according to the production rules. The difference thus, between these types of grammars (and consequently languages) is that they have increasingly stricter production rules and can express fewer formal languages. In Type 3 grammars the production rules are limited allowing the creation of the sentences following only the rule forms $A \rightarrow a$ or $A \rightarrow aB$. Type 3 grammars are known as finite state grammars (finite state automata[2]). Starting from the recursively enumerable grammars (Type 0), to regular grammars (Type 3), the regular grammars are considered to be the ones with the most restricted expressive power.

During the last decade, there has been an intense discussion about which aspects of our mental faculties are shared with other species and which are specific to the human language faculty (Hauser, Chomsky, & Fitch, 2002). To distinguish between the human capacities and capacities in other species, research has focused on formal syntactic complexity and the core syntactic aspects that render the human capacity for language unique. *Recursion* was claimed to be such an aspect found only in human linguistic capacity. The theoretical construct of the Chomsky hierarchy has had a major influence on this debate, since through the different grammars the recursive processing in language can be investigated. Recursion can be defined as an iterative operation that takes two elements and combines them in order to create a new expression and this operation can extend to *infinite* binding process of elements. This phenomenon has attracted a lot of attention, both in AGL and in natural language research (Chomsky, 2005; Chomsky, Fitch, & Hauser, 2005; de Vries, Monaghan, Knecht, & Zwitserlood, 2008; Fitch & Hauser, 2004; Friederici, Bahlmann, Heim, Schubotz, & Anwander, 2006; Nowak, Komarova, & Niyogi, 2002). In English, recursive structure is exemplified by sentences such as "*The rat* [*the cat ate*] *was brown*". Here, the element "the rat" is linked to an element that is further away in the sentence, namely "was brown"; a so-called *non-adjacent dependency*. Crucially, additional embeddings are possible, resulting in sentences such as "*The rat* [*the cat* [*the boy chased*] *ate*] *was brown*". Moreover, it has been argued that the finite-state grammars are too restrictive to capture all syntactic phenomena found in natural languages. This rendered regular grammars to be interpreted as less relevant for natural language investigation, and on the other hand, only Type 2 and 3 grammars were thought to be relevant models for language (Chomsky, 1957). However, as noted by, for example by Pullum & Scholz (2009) regular parsing is powerful and they argue it can model human linguistic processing. Moreover, in natural language data, it is well-documented that people are typically only able to deal with non-adjacent dependencies structures to a certain extent. Unlimited recursion creates incomprehensible sentences, clearly an impossibility from the point of view of the neurobiology of language, thus raising the issue of the

[2] Formal grammar can be thought of as a language generator OR as a function establishing whether a

value of unlimited usage of such operations. For this reason, it is not unreasonable to investigate regular grammars in neurobiological and cognitive neuroscience research on the human brain (with its finite storage capacity).

When examining the neurobiological roots of language processing one can also ask how the structure and flexibility of the brain mediates the structure and flexibility of language (Belsky & Pluess, 2009; Friederici, 2009). The human brain shapes language and inevitably provides a substantial contribution in the way human languages are structured. This brain system has a finite capacity, which has implications for the way the notion of language can be construed, and a finite memory system, upon which linguistic comprehension depends. For example, recursive computations may be unlimited with respect to the number of the iterated computations they can produce but processes such as memory and comprehension will have an effect on the amount of the computations processed by the human brain. Thus, rather than giving "recursion'' and "infinity" the centre stage, some of the real issues in the neurobiology of syntax, and language more generally, are related to the nature of the neural code (i.e., representation), the character of human on-line processing memory and the character of the underlying neural computations. Thus, from the point of view of natural language, the relevant issue is the human capacity to process patterns of non-adjacent dependencies-not arbitrarily "long" non-adjacent dependencies because there is a definite upper-bound set by the brain and its underlying neurophysiology. The *real challenge* in the neurobiology of syntax is to understand syntax processing in terms of noisy spiking network processors. Here, we take natural language to be a neurobiological system, and paraphrasing Chomsky (Chomsky, 1986), two outstanding fundamental questions to be answered are:

— What is the nature of the brain's ability for syntactic processing?
— How does the brain acquire this capacity?

An answer to the first question is that the human brain represents knowledge of syntax in its connectivity (i.e., in its parameterized network topology including its adaptable characteristics).

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string is grammatical or non-grammatical. Automata theory describes such recognizers.

1.5 IMPLICIT LEARNING

1.5.1 Characteristics of implicit learning

One key point in this thesis is the usage of the term "implicit learning". As briefly mentioned, syntax, and in general language, is learned or acquired without particular effort by infants in complete opposition to the way reading and writing skills are acquired in school. According to Ullman (2001), the implicit memory system, or procedural system, is implicated in the learning of new cognitive skills. It is still an open question whether implicit learning abilities can predict language abilities, or whether such learning is related to language acquisition (Conway, Pisoni, & Kronenberger, 2009). Typically, five characteristics are used to describe implicit learning (Reber, Walkenfeld, & Hernstadt, 1991; Seger, 1994):

(1) Implicit learning is relatively independent of measures of higher cognitive functioning (e.g., IQ) (Gebauer & Mackintosh, 2007); (2) there is limited explicit access to the acquired knowledge; (3) the nature of the knowledge acquired is more complex than simple associations; (4) implicit learning does not involve explicit hypothesis testing, or other explicit problem solving strategies, but is an incidental, automatic consequence of the type and amount of processing performed on the stimuli; and (5) implicit learning does not rely on declarative memory mechanisms that engage the medial temporal lobe (MTL) memory system.

In general, researchers have suggested that implicit learning plays an important role in the acquisition of language skills, such as word segmentation (Saffran et al., 1996), the learning of phonotactic (Chambers, Onishi, & Fisher, 2003) and orthographic (Pacton, Perruchet, Fayol, & Cleeremans, 2001) regularities, as well as social-communicative, and motor skills (Conway et al., 2009 ; Gomez & Gerken, 1999; Reber, 1993). There is also some evidence suggesting a link between implicit learning ability in visual sequence learning and the development of spoken language (Conway, Karpicke, & Pisoni, 2007). However, a causal connection is still lacking, since these results can be explained also in the reverse order; that is, spoken language development may have an effect on implicit sequence learning. The need for longitudinal studies is necessary to clarify these issues (Conway & Pisoni, 2008b; Newman, Bernstein Ratner, Jusczyk, Jusczyk, & Dow, 2006; Tsao, Lui, & Kuhl, 2004). Perhaps the way to establish a close link between the two cognitive processes is to assess language impaired individuals in terms of implicit learning and determine whether an implicit learning deficit is present. Using this approach, researchers have, for instance, found an implicit sequence learning deficit in dyslexics. It has also been shown that agrammatic patients show deficits both in terms of language performance and implicit sequential learning compared to matched control participants (M. H. Christiansen, Kelly, Shillcock, & Greenfield, 2010). The challenge is to convincingly show whether both natural language processing and implicit learning tasks tap into the same underlying cognitive process or neurobiology (*see Chapter 4*).

1.5.2 Current paradigms for rule learning

There exist three types of paradigms employing artificial constructions as models for rule learning of potential language relevance. One type of paradigm explores rule learning via *natural language* material. Syntax rules obtained from natural languages which are different from the native language of the participants are presented. The learning of new natural language rules with "non-language" rules is compared (Musso et al., 2003). Another paradigm uses material from *artificial languages* imitating language-like rules that may exist in the native syntax of the participants (Opitz & Friederici, 2003). The third paradigm, and described in detail in this thesis, is the paradigm of *artificial grammar learning*, in which the rules of the artificial grammar may imitate rules encountered in natural language syntax.

Rule learning can be described as implicit depending on whether one focuses on the acquisition or retrieval processes or on the knowledge resulting from the acquisition episodes (Cleeremans, Destrebecqz, & Boyer, 1998). Thus, the above three paradigms can be explicit or implicit in nature. One way to accomplish this is through instruction manipulation in the acquisition and/or classification phase. For example, it is possible that the participant is explicitly informed and tested that he/she is learning some sort of rules, while this is not the case for implicit manipulations (**Figure 6**). In this thesis, an implicit AGL paradigm, based on structural mere-exposure, was developed and used throughout. More specifically, we used an implicit acquisition paradigm based on mere exposure to grammatical items, while the experimental instruction varied in the classification phase. This is discussed in greater detail in the following section.

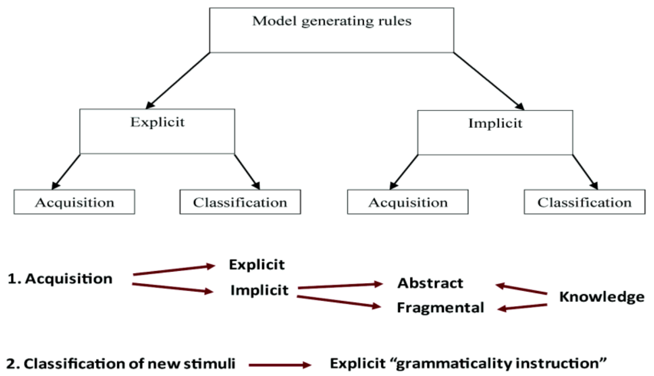


Figure 6. Investigation of rule learning necessitates a model generating arbitrary rules; **1.** The rule acquisition can be either explicit or implicit in nature. Implicit acquisition can be abstract or include fragmental knowledge (cf., 2.1.2 *Associative Chunk Strength*) **2.** A way to assess learning is via the explicit "grammaticality instruction".

1.6 AGL PARADIGM

In the artificial grammar paradigm the purpose of the *acquisition*, or learning, sessions is to expose the participants to the underlying regularities of the grammar, while the purpose of the *classification* session is to quantify the level of learning after acquisition. Participants are exposed to an acquisition phase during which they see a representative sample of sequences created according to the grammar rules. After the learning phase, they are asked to classify novel sequences as grammatical (following the rules), or not, in the classification session.

1.6.1 Explicit AGL paradigm

So far, most of the fMRI studies investigating rule learning via AGL have made use of explicit acquisition and classification instructions (**Table 1**). Participants are given explicit information about the presence of underlying rules and it is the participants' task to figure out the rules as best they can by trial and error, typically in combination with immediate performance feedback for each item during the acquisition and/or classification phases. This version of the AGL paradigm investigates explicit mechanisms involved in rule learning and the cognitive system learns through trial-and-error and deliberation, by which the underlying structure is explicitly discovered. This differs from implicit acquisition (Bauernschmidt, Conway, & Pisoni, 2009). Consequently, the fMRI results obtained from the explicit acquisition and classification might be of a different nature to those obtained by investigating implicit procedures during acquisition and classification (Bahlmann, Schubotz, & Friederici, 2008). It is often argued that the reason for choosing an explicit approach is that implicit acquisition in AGL is not robust enough as a paradigm to provide measurable behavioral and functional neuroimaging results (Kachergis, 2010; Robinson, 1997). However, it is questionable whether the explicit approach provides an adequate model of human grammatical learning during language acquisition, since the learning involved in the case of natural language syntax does not depend on external feedback. On the contrary, the acquisition of natural language syntax is mainly an unsupervised course of action, and takes place implicitly rather than being a systematic, deliberate process (Bauernschmidt et al., 2009).

Table 1. Three types of paradigms are used in the investigation of linguistic relevant rule learning. Most of the studies so far used explicit acquisition and classification sessions with only a few exceptions of implicit investigation.

Model Generating Rules	Acquisition	Classification	Literature
Natural Language Paradigms	Explicit	Explicit	*Musso 2003*
Artificial Language Paradigms	Explicit	Explicit	*Optiz & Friederici 2003*
Artificial Grammar Paradigms	Explicit	Explicit	*Strange 2001*
	Implicit	Explicit	*Seger 2000; Kosnik 2002*
	Implicit	Implicit	*Lieberman 2004*

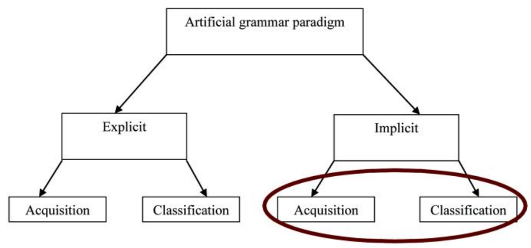
1.6.2 Mere exposure effect and preference instruction

One aspect of implicit learning is the fact that repeated exposure to the same stimulus can, and typically does, lead to successful unintentional learning of the stimulus at hand and consequently to an enhanced preference over new stimuli. This is the definition of the *classic* mere exposure effect. Zajonc (1968) was the first to experiment with this effect and since then it has been investigated with a variety of stimuli, including words, non-words, abstract symbols and faces (Luka & Barsalou, 2005).

The *structural* mere exposure effect is based on the concept of classic mere exposure and is characterized by a greater tendency to prefer new stimuli that conform to an implicitly acquired underlying rule system (Gordon & Holyoak, 1983). Because of the structural mere exposure effect, participants develop a preference for items that are structurally similar, or identical, to the items presented in the acquisition phase (Bornstein, 1989; Zajonc, 1968). Regarding implicit AGL paradigms, the structural mere exposure effect does provide a sensitive indirect measure of linguistic grammatical knowledge (Manza et al., 1999; Zizak & Reber, 2004) and it has been also investigated with fMRI and abstract stimuli, such as Japanese ideograms (Elliott & Dolan, 1998) but has rarely been used in psycholinguistic research (Luka & Barsalou, 2005).

Manza and Bornstein (1995) argue that participants who are not informed of the existence of the grammar are able to acquire and utilize its structure just as well as those who are informed. This issue was explored in this thesis via the preference classification instruction, which makes use of the structural mere exposure effect.

Preference classification is a relatively “novel” version of the AGL paradigm used to investigate syntactic processing via unsupervised learning. This instruction minimizes the risk that participants will develop and/or use deliberate explicit (problem-solving) strategies (**Figure 7**). During the acquisition phase participants are exposed for one or several days to grammatical items during a short-term memory (STM) task, which serves as a cover task. The STM task consists of immediate serial recall of each sequence without performance feedback. After the acquisition phase participants are asked to classify new items, according to whether they like them or not, following their immediate impression (“gut feeling”). Participants are told that there is no right or wrong answer, which eliminates the impression that they undergo any particular performance task in which their performance is tested. The difference between this type of paradigm and the explicit AGL paradigm is that in the former both the acquisition and classification phases are implicit, and there is at no reference to any previous acquisition episode (Shanks & St. John, 1994). Moreover, the subjects are not informed about the existence of an underlying generative mechanism. Instead, participants are asked in post-experimental interviews about their knowledge acquired, which is characterized through the use of several measures, such as completion, prediction, sequence/rule production and rule recognition tasks (for further discussion of the topic, cf., (Rünger & Frensch, 2009; Shanks & St. John, 1994). These verbal/written reports typically reveal a lack of awareness and explicit knowledge about the underlying rules or regularities related to the grammar (Curran & Keele, 1993; Willingham, Nissen, & Bullemer, 1989).



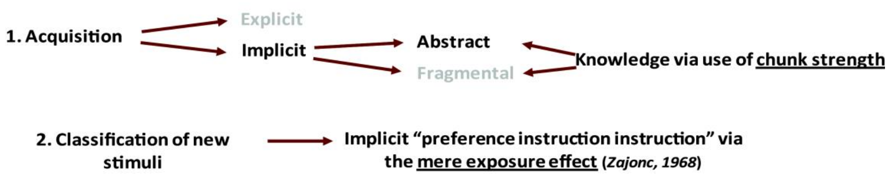


Figure 7. Artificial grammar paradigm is one of the three paradigms of linguistic rule learning **1.** Implicit acquisition of the AGL rules is abstract. Fragmental knowledge is avoided through the use of a measure controlling for it (*see section 2.1.2*) **2.** Learning is accessed via the preference classification instruction.

1.6.3 The grammaticality instruction

The grammaticality version of the AGL paradigm is divided into implicit acquisition sessions and a classification session in which the grammaticality instruction is utilized. Participants are exposed to grammatical items in an STM cover task. Subsequently, just before grammaticality classification, they are informed that the sequences they saw in the acquisition sessions were created according to a set of complex rules. Participants are asked to classify novel sequences based on their immediate intuition whether the sequences violated the rules or not (i.e., whether the sequences were grammatical or not based on "gut feeling"). This type of paradigm is an example of implicit acquisition with partial explicit classification, since participants are informed about the existence of an underlying generative rule set just before the classification session but are not provided with information about the nature of those rules, nor is any performance feedback provided during either acquisition or classification. This type of instruction is called the *grammaticality instruction* in this thesis.

1.6.4 The reason for employing artificial tools in the investigation of natural syntax

Earlier, it was explained that AGL is a useful tool for studying the processing of structural (i.e., syntactic) regularities independent of semantics. Exploration of the neurobiological basis of implicit structured sequence learning is expected to lead to a better understanding of natural language acquisition and processing (Conway & Pisoni, 2008). Artificial grammars do not attempt to model natural language syntax in every respect, rather, in experimental AGL work it is necessary to focus on particular aspects of syntax and this also holds for experimental work in natural language syntax.

There are several other reasons why researchers employ artificial constructions to investigate syntactic structures in isolation. For example, their use can serve to determine structural elements that can be acquired by the learner (Clark, 2001). Also, probing implicit learning via preference classification is a useful method in providing insight into the unsupervised acquisition of complex behavior, such as music and social rule learning. Finally, artificial syntax can be used to investigate the key components humans share with other species, or whether human infants have different innate recourses compared to other species (O'Donnell, Hauser, & Fitch, 2005; Ouattara, Lemasson, & Zuberbühler, 2009). In clinical practice, artificial sequence processing might be useful as an intervention in clinical populations and when investigating individual differences. Especially the later might provide new insight into the cognitive processes involved in AGL and provides a basis for investigating sequence processing in special populations such as patients with neurological lesions and dyslexic people (Folia et al., 2008; Zimmerer, Cowell, & Varley, 2011)

1.6.5 Summary

(1) Artificial grammars are models of aspects of natural language syntax in isolation of other aspects of natural language, including sentence-level semantics.
(2) As a model of natural language acquisition, the AGL paradigm has to simulate the conditions under which natural syntax is acquired: implicit acquisition without performance feedback extended over time.
(3) The fMRI studies of AGL that have so far been conducted have mainly used explicit versions of the AGL paradigm.

(3) The use of the preference instruction in AGL should be investigated for its behavioural and neural characteristics in relation to the grammaticality instruction.
(4) Research on the learning effect after implicit acquisition via the preference instruction extended over several days is lacking.

1.7 PREFRONTAL CORTEX AND BROCA'S REGION

1.7.1 The prefrontal cortex in humans

The investigation of the relationship between brain structure and brain function is one of the central tasks in the field of neurosciences (Innocenti & Price, 2005). This is a particularly challenging task since the brain is an intricate organ containing of about 10^{10} neurons. The macroscopic level (brain regions, large-scale connectivity, and cognitive functions) is the level at which most research in the neurobiology of language is focused at present. At the microscopic level, cognitive functions require a characterization in terms of membrane potentials and the generation of spike-trains in complex local and large-scale networks. The prefrontal cortex is a brain region central to higher cognitive functions, including decision-making, working memory, problem solving, language and social cognition. In language research, the prefrontal cortex is of particular interest due to its capability of actively maintain representations of various types of information and selecting and integrating among competing sources of information (Thompson-Schill, Bedney, & Goldberg, 2005). Because language comprehension and production requires a space adequate for the online unification operations taking place during language processing, the prefrontal cortex, in particular the LIFG, is a good candidate for the integration of information online (Mesulam, 2002).

1.7.2 The left inferior frontal region (LIFG)

The LIFG is divided into three subparts, pars opercularis or Brodmann's area (BA) 44, pars triangularis (BA 45), and pars orbitalis (BA 47; **Figure 8**). A part of the LIFG centered on BA 44/45 is also named Broca's region after Paul Broca, who provided the first evidence that lesions in this region lead to problems in speech production. The use of a standardized coordinate system, such as the atlas of Tailarch and Tournoux (1988), is one of the best options to describe findings from functional neuroimaging studies. The identification of Broca's region in such terms, Broca's region extends in coordinates from x -28 to -55, y -8 to +34, and z 0 to 28 (Embick & Poeppel, 2005). There is a degree of between-subject variance in the coordinates, which is due to the fact that there are inter-individual differences concerning the size and volume of Broca's region in the human brain (Keller, Crow, Foundas, Amunts, & Roberts, 2009). This results in, for example, one particular difficulty with separating the BA 44 and BA 45 since in functional neuroimaging the bordering pieces between BA 44 and BA 45 are not always possible to segregate due to localization uncertainties in fMRI. The localization imprecision in fMRI is on the order of 10 mm (Brett, Johnsrude, & Owen, 2002; Petersson, Nichols, Poline, & Holmes, 1999) and this needs to be taken to account when trying to distinguish between regions in close proximity with functional neuroimaging methods.

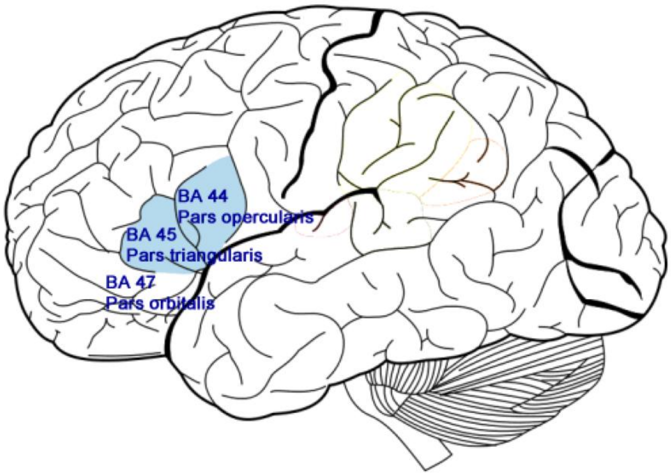


Figure 8. The left inferior frontal gyrus is divided into three subparts, pars opercularis or Brodmann's area (BA) 44, pars triangularis (BA 45), and pars orbitalis (BA 47).

1.7.3 Broca's role in unification operations

While there is accumulating evidence for a role of Broca's region as an online unification space (Hammer et al., 2011; Snijders et al., 2009) there is also evidence for a different view claiming that Broca's region is not involved in general combinatorial processes but in specific grammatical operations, including for instance syntactic movement operations and processing of hierarchically nested non-adjacent dependencies. Grodzinsky and colleagues have claimed that Broca's region is specifically related to syntactic movement operations (Ben-Shachar, Hendler, Kahn, Ben-Bashat, & Grodzinsky, 2003; Ben-Shachar, Palti, & Grodzinsky, 2004; Santi &

Grodzinsky, 2007a, 2007b). Syntactic movement is an operation in which certain constituents appear to have been displaced from the position where they receive features of interpretation within a sentence. FMRI studies employing sentences with syntactic movement operations have showed activations in a set of brain regions, including the LIFG, left ventral precentral sulcus (vPCS), and bilateral posterior superior temporal sulcus (pSTS). Concerning the processing of non-adjacent dependencies, some current views on the topic suggest that Broca's region (or subregions) is specifically related to the processing of central-embedded structures. In particular, the syntactic feature of center- or nested embedding (Type 2, or context-free, grammars in the Chomsky's hierarchy) has been the focus of recent fMRI research, where it is argued that Broca's region plays a specific role in the processing of hierarchically nested non-adjacent dependencies. Friederici and colleagues (Friederici et al., 2006) divided the left frontal region into two cytoarchitectonically and phylogenetically different brain regions, one being the "frontal operculum" (FOP) and the other "BA 44", based on their fMRI findings. They suggested that a possible functional differentiation between FOP and BA 44, with the FOP merely being activated during local (adjacent) violations. Later studies (Bahlmann, Schubotz, Mueller, Koester, & Friederici, 2009; Makuuchi, Bahlmann, Anwander, & Friederici, 2009) using adjacent versus hierarchical (non-adjacent) dependencies report that Broca's region is particularly engaged in processing hierarchical compared to non-hierarchical structures. Makuuchi and colleagues (2009) suggested that the left pars opercularis (LPO), is a candidate region for the processing of hierarchical structures. To put things into perspective, a recent intra-cranial electorphysiological investigation of Broca's region (Sahin, Pinker, Cash, Schomer, & Halgren, 2009) showed that, at a microscopic level (electrodes being implanted 5mm distant from each other), lexical identification, grammatical inflection, and phonological processing in the production of nouns and verbs alike are all taking place at different timing (~200 ms, ~320 ms, and ~450 ms respectively) but within the same region, that is, in Broca's region. This finding is consisted with the MUC model since Broca's region is found to be involved in unification operations of different linguistic components.

Although much attention is paid to Broca's region and its properties, as well as its role in syntax processing in this thesis, its role at any given moment in time is dependent on the functional network of interacting brain regions in which it participates, none of which is uniquely involved in syntactic processing or language more generally (Hagoort, 2009; Kaan & Swaab, 2002). The idea that Broca's region is, in any relevant sense, a syntax specific region is, overall, not entirely supported (Marcus, Vouloumanos, & Sag, 2003). It seems that the role of a given brain region at any given moment in time is determined by its full spatio-temporal processing context in which it participates, that is, which other brain regions it interacts with in a given instance. Syntactic processing is the result of cooperation between different brain regions, including the left superior anterior temporal lobe, the posterior parts of the left superior and middle temporal gyri, and right hemisphere regions (Bookheimer, 2002; Kaan & Swaab, 2002). Moreover, the left inferior frontal region seems to have a broad cognitive role ranging from lexical to phonological tasks (Zatorre, Evans, Meyer, & Gjedde, 1992), musical syntax, absolute pitch perception, and interpretation of human action (Marcus et al., 2003).

1.7.4 On the similarities of artificial & natural syntax processing

A crucial assumption in research of artificial language learning and structured sequence processing is that the mechanisms involved are shared with natural language acquisition and processing. Behavioral investigations suggest that artificial language learning and processing is relevant to natural language learning and processing, including parallel developmental trajectories mapped with artificial (Gómez & Maye, 2005) and natural language material (Santelmann & Jusczyk, 1998), as well as brain lesion studies, which suggest that language processing deficits are paralleled by impairment in structured sequence learning and processing (M. H. Christiansen et al., 2010; J. L. Evans, Saffran, & Robe-Torres, 2009; Hoen et al., 2003; Hsu, Christiansen, Tomblin, Zhang, & Gómez, 2006; Reali & Christiansen, 2009; Richardson, Harris, Plante, & Gerken, 2006). So far the extent to which artificial and natural syntax recruit the same neural networks in the same study subjects has not been experimentally investigated. However, a meta-analysis showed that the brain regions engaged by natural language syntax coincide with those reported active in artificial syntax processing (Forkstam et al., 2006; Petersson et al., 2004), but no study has *directly* compared the regions involved in artificial and natural language processing (**Figure 9**). If the same network is involved in both natural and artificial syntax processing in the same subjects, then that would provide evidence to justify the use of artificial grammars to probe the neurobiological substrates of natural language syntax, in particular Broca's region.

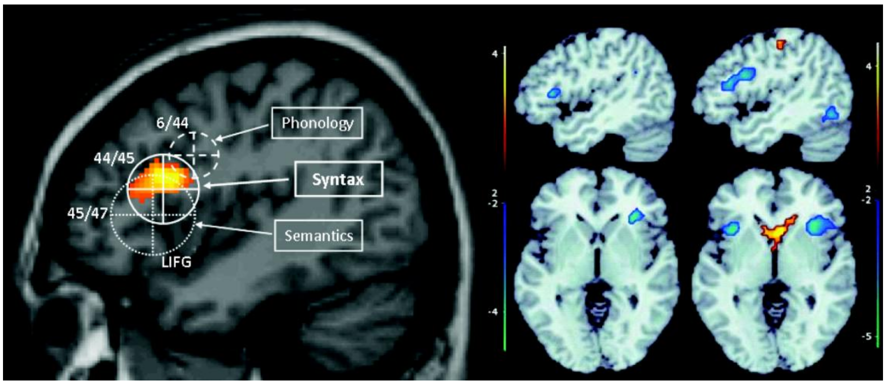


Figure 9. **Left**: Activation related to artificial syntactic violations (Petersson et al., 2004). Superimposed to these activations, regions related to phonological, syntactic, and semantic processing are indicated in circles where the centers correspond to the mean coordinates of local maxima activation and the radii denote the standard deviations of the distance between the local maxima and their means after being calculated from a meta-analysis study (Bookheimer, 2002; Hagoort, 2005). **Right**: Regions active in artificial grammatical vs. non-grammatical items in red and non-grammatical vs. grammatical in blue (Forkstam et al., 2006). These results provide *indirect* evidence for a similarity of the regions involved in both artificial and natural syntax processing.

1.7.5 Summary

(1) Broca's region is centred on BA 44/45. Due to the close proximity of these two Brodmann's areas, 44 and 45, the bordering region is difficult to reliably segregate with current fMRI technology due to limitations on localization precision, in particular in group studies but also in single-subject studies.

(2) The role of Broca's region is controversial. Evidence supports the involvement of Broca's region in generic online unification operations, while other results suggest a specific involvement of this region in syntactic operations.

(3) There is no direct evidence to what extend artificial and natural syntax are processed in the same regions of the human brain.

2 CHAPTER – EXPERIMENTAL TOOLS

In order to pursue the experimental questions posed in this thesis (*see Chapter 4*) on implicit learning and sequence processing, behavioral and neuroimaging tools were used. The behavioral tools used were the implicit artificial grammar learning paradigm (Reber, 1967) as described in *Chapter 1* as well as a natural language paradigm. The investigation of the neural correlates of implicit sequence processing was conducted via fMRI.

2.1 BEHAVIORAL TOOLS

2.1.1 AGL tool

The implicit AGL paradigm is a powerful tool in terms of robustly replicable effects and an adequate mean for the exploration of structured sequence processing, of implicit syntax acquisition and statistical learning. Both the sensory modality and the materials used can be manipulated in various ways that enable the investigation of specific experimental questions. For example, the stimulus material can be presented visually, acoustically or even through tactile stimulation (Eitam, Schul, & Hassin, 2009). Moreover, the nature of the material used can vary from an alphabet which participants are familiar with, to shapes, patterns, colors, ideograms, and so-forth, in which participants might have no previous experience (Pothos, Chater, & Ziori, 2006; Zizak & Reber, 2004). This renders AGL a well-controlled and flexible experimental tool. The presentation mode of the stimulus can be manipulated in order to investigate the processing of serial versus whole sequence presentation. More specific to the research conducted in this thesis, letter-by-letter sequence presentation was used instead of whole sequence presentation. Sequential presentation was chosen in order to simulate as much as possible the way children hear normal speech and pick up sequential order information in contrast to whole sequence presentation that is found mainly in written information. In our experiments the visual modality for learning and classification sessions was used. Visual learners have been found to be largely unbiased in their classification judgments, that is, they do not judge a test sequence as grammatical if it has statistical structure similar with training items at the beginning/ending of the sequence (however, this is not always the case, though the bias tends to be small to modest). In contrast the tactile/auditory learning appears more sensitive to statistical structure at the beginning and final item structure, findings that might suggest that different computational strategies are recruited by different modalities (Conway & Pisoni, 2008). Also, the usage of the different sequence complexity levels (*see Chapter 1, Chomsky hierarchy*) allows for the investigation of the acquisition of specific structural regularities such as local, adjacent or long-distance/non-adjacent dependencies. Structural complexity can be systematically varied in artificial grammars, thus making it possible to experimentally manipulate the level of structure in the stimulus material in a precise manner (Petersson, 2005; Petersson, Grenholm, & Forkstam, 2005). In addition, by controlling or manipulating subsequence familiarity, so-called associative chunk strength (*ACS; see below*) it is possible to separate the effects related to local sub-sequence regularities from those of structure abstraction in a precise manner. Consequently, the behavioral AGL tool can be carefully controlled with respect to the parameters of the stimulus material enabling in this way the systematic investigation and characterization of the processing properties of specific brain regions.

2.1.2 Associative chunk strength

One important aspect of implicit AGL is that it is possible to control for (alternatively, investigate) biases in the participants' acquisition of structural knowledge via stimulus material design. For example, participants might show improved performance in correctly classifying new items after acquisition, leading to the conclusion that they have successfully acquired the underlying grammar. Improved performance however, might be due to the fact that the acquisition sequences participants were exposed to, contain subsequences or chunks (e.g., bi- and trigram fragments) highly similar to the chunks of the sequences presented in the classification session, that is, the superficial resemblance of the novel items to the acquisition set is high. In such a case participants might classify the novel sequences based on superficial subsequence resemblance and not on grammaticality status (i.e., "rule use"). The local subsequence familiarity is thus a way to control or investigate to what degree participants classify based on grammaticality status or ACS. In the studies of this thesis, ACS is controlled independently of the grammaticality dimension and therefore specific inferences about the acquisition of structural knowledge from the results can be made.

2.1.3 Natural language processing tool

Syntactic anomalies in natural language processing (NLP) inevitably have an effect on the semantic linguistic component. It is thus difficult to investigate NLP with respect to for example syntax independent of sentence-level semantics. In one study of this thesis, NLP was investigated with respect to syntactic gender mismatches and semantic anomalies. In Dutch language nouns are distinguished in two syntactic gender categories, the common or the neuter gender. When accompanied by a definite article then the gender is denoted within the article. The definite article "de" is used for nouns of common gender, whereas the definite article ''het'' is used for nouns of neuter gender. Such syntactic gender mismatches are grammatical anomalies that can be considered as *local*, that is, they do not affect the general sentence structure and they also leave sentence-level semantics (largely) intact.

This enables an independent analysis of the syntactic and semantic component since the syntactic ambiguity resolves in a deterministic way, without more than one structural assignment processes possible, therefore without placing extra load in the semantic interpretation of a sentence. In this manner, the investigation of unification success as well as failure can be studied simultaneously in the same task. Moreover, the gender agreement of the noun phrase is a grammatical relationship involving local dependencies (Clahsen & Felser, 2006) similar to the grammatical violations of the simple artificial grammar we used. This fact renders the syntactic violations and consequently the neuroimaging results obtained between AGL and NLP stimuli comparable.

2.2 NEUROIMAGING TOOLS

2.2.1 Techniques for Brain Investigation

Research in neurolinguistics demand the integration of multi-disciplinary conceptual frameworks such as neuropsychology, cognitive neurosciences, linguistics, and biology. The domain of cognitive neurosciences offers tools for the inquiry of complex cognitive functions and their neural implementation (Posner & McLeod, 1982). The techniques used for exploring the neural correlates of linguistic processing in general are fMRI, electroencephalography (EEG) and magnetoencephalography (MEG). More recent techniques include repetitive transcranial magnetic stimulation (rTMS) (Uddén et al., 2008). Recurrent neural network models is a way to simulate syntactic learning while recently the role of the genetic influence to language processing is under investigation (Kos et al., 2012).

The research methods chosen for the research described in my thesis are behavioural measures (performance in task) in combination with fMRI techniques. FMRI is a useful tool to make conclusions about macroscopic descriptions of cognitive processes and behaviour. Thus, fMRI is chosen to provide spatial information with ~10 mm localization precision on the group-level (Brett et al., 2002; Petersson et al., 1999). When the time scale of the cognitive function is under investigation, that is, when neural activity happens one needs to use either EEG measurements of voltage fluctuations or combine functional neuroimaging methods with EEG (Opitz, Mecklinger, Friederici, & von Cramon, 1999)

2.2.2 Functional Magnetic Resonance Imaging (fMRI)

FMRI provides a fairly precise topographical configuration of where in the brain neuronal processing takes place in relation to a given cognitive task participants execute. What fMRI measures are changes in brain oxygen consumption indirectly via the measurement of the concentration of oxy/deoxy-haemoglobin. Oxygenation consumption in a brain region varies according to the levels of neural activity. This means that when neuronal activity increases in one region there is an increased demand for oxygen which results in increased regional blood flow.

Oxygen is delivered to neurons by hemoglobin, which is diamagnetic when oxygenated but paramagnetic when deoxygenated. This difference in its magnetic properties leads to differences in the MR signal measured by the MR scanner. These relative differences between dia- and paramagnetic hemoglobin can thus be used to detect changes in regional brain activity. This form of MRI is known as blood oxygenation level dependent (BOLD) imaging. Measuring BOLD using fMRI requires at least two experimental conditions (usually an experimental and a control condition). The differences in the signal between two cognitive states are therefore relative. Consequently, results from activation imaging experiments depend on the design since task difficulty, response styles, and strategies can affect the magnitude of the neural activation in fMRI experiments (Raichle, Fiez, Videen, MacLeod, & Pardo, 1994). In order to eliminate potential confounds, we used within-subject designs. This design limits the measurement error in the obtained results, since there is less noise in the gathered data that are present due to individual differences (the personal confounds are less).

2.2.3 Image processing and statistical analysis in fMRI

The BLOD-fMRI data have to undergo several steps of image- and statistical analysis in order to deliver results for the group of participants under investigation. A first step concerns data analysis on the individual brain (the data obtained from each participant). Data are realigned and slice-time corrected in order to compensate and correct for subject movement and acquisition time differences in the scanner. Then the data are spatially normalised and typically filtered with an isotropic Gaussian convolution kernel [(Full-Width Half-Maximum (FWHM) = 10mm) in the studies presented in this thesis)] in order to account for between-subject and residual anatomical variability, respectively. The spatial normalization step compensates for anatomically differences between individual brains and in order to draw conclusions about group-effects in a standardized stereotactic space. The objective of spatial filtering is related to minimizing individual residual differences in functional-anatomy after anatomical normalization. After this a statistical model is created and statistical tests can be used to investigate differences between conditions (*see Data analysis*).

3 CHAPTER – EXPERIMENTAL PROCEDURES

The data presented in this thesis comprise of behavioral and fMRI data. The sample of the population under investigation was the same throughout the whole project since the comparison between the different tasks in the same sample was a main experimental concern. Below there is a description of the participants, the stimulus material used, the experimental process and the data analysis.

3.1 PARTICIPANTS

Thirty two right-handed (16 females, mean age ± SD = 22 ± 3 years; mean years of education ± SD = 16 ± 2), healthy Dutch university students volunteered to participate in all the studies comprising this thesis. They were pre-screened and already present in the center's database (Donders Institute for Brain, Cognition and Behavior). None of the subjects used any medication, had a history of drug abuse, head trauma, neurological or psychiatric illness from the beginning till the termination of the experiments. All subjects had normal or corrected-to-normal vision. Written informed consent was obtained according to the Declaration of Helsinki and the local medical ethics committee approved the study. Participants received payment for their participation in the studies.

3.2 STIMULUS MATERIAL

3.2.1 Natural language study

The natural language material was carefully constructed and pre-tested. The sentence material has been experimentally validated in an EEG study and is known to generate the classical N400 and P600 effects due to semantic and syntactic anomaly manipulation, respectively (Hagoort, 2003). In more detail, the stimulus material consisted of 160 sentences obtained from the stimuli used in the study of Hagoort (2003). The sentences consisted of four versions:

(1) Syntactically and semantically well-formed, correct sentences (CR); (2) Semantically correct sentences with a gender agreement violation between the definite article and the related (critical) noun (SY); For the SY violation we made use of the properties of the grammatical gender system in Dutch. Dutch nouns have either one of two grammatical genders: common gender and neuter gender. When nouns are produced with a definite article, the definite article reveals the gender of the noun, in

this case the definite article “de” is used for nouns of common gender, whereas the definite article ‘‘het’’ is used for nouns of neuter gender; (3) Syntactically correct sentences including a lexical semantic anomaly that consisted of a semantically unacceptable combination of the adjective and the related (critical) noun (SE); (4) A combination of the syntactic and semantic anomalies (CB) described in (2) and (3).

The *critical noun* was termed as the noun in which the syntactic or semantic violation became clear. No subject saw more than one version of a sentence quartet since the material was distributed among four versions of the experiment. Words in the sentences were never longer than 12 letters. All sentences were simple active or passive constructions. Examples of the sentence types are provided in **Table 2**. Fifty percent (50%) of the sentences contained a syntactic and 50% a semantic anomaly. Participants practiced 10 example items before the actual testing.

Table 2. Examples. *Critical noun*. **Incorrect articles** and **anomalous adjectives**. CR = correct; SY = syntactic anomaly; SE = semantic anomaly; CB = combined syntactic and semantic anomalies; com = article/noun of common gender; neut = neuter gender article. In this example the noun “paraplu” is common gender, thus the definite article “het” is used to generate the gender agreement violation between the definite article and the noun in (SY).

De kapotte *paraplu* staat in de garage.	**(CR)**
Het kapotte *paraplu* staat in de garage.	**(SY)**
De **eerlijke** *paraplu* staat in de garage.	**(SE)**
Het eerlijke *paraplu* staat in de garage.	**(CB)**
The$_{com}$/**The$_{neut}$** broken/**honest** *umbrella*$_{com}$ is in the garage.	

3.2.2 AGL studies

The stimulus material used in four of the AGL studies consisted of a simple right-linear unification grammar. We generated 569 grammatical (G) sequences from the grammar, with a sequence length ranging from 5 to 12. For each item we calculated the frequency distribution of 2 and 3 letter chunks for both terminal and complete sequence positions. In this way we derived the ACS for each item (Forkstam et al., 2006; Meulemans, 1997). For the acquisition set we randomly selected in an iterative way 100 sequences that were representative, in terms the letter chunks, for the complete sequence set. In the next step, we generated the non-grammatical (NG) sequences, derived from non-selected G sequences, by switching letters in two non-terminal positions. The NG sequences matched the G sequences in terms of both terminal and complete-sequence ACS. Finally, two sets of 56 sequences each from the remaining G sequences were selected, to serve as *classification sets*. These sets thus consisted of 25% G/high ACS; 25% G/low ACS; 25% NG/high ACS; and 25% NG/low ACS sequences. In summary, the stimulus material included an acquisition set and two classification sets. The classification sets were used in a 2x2 factorial design with the factors Grammaticality and ACS.

3.2.3 Associative Chunk Strength calculation

To determine the ACS strength, we first calculated the frequency distribution of 2 and 3 letter chunks in the sequences appearing in the acquisition phase. We did the same for the items in the classification set. We then calculated the mean chunk frequencies for each classification item in order to obtain each item's global ACS. In other words, the global ACS of each item was calculated by averaging its different bigram and trigram frequencies. We also calculated for each item the frequency for both the initial and terminal positions of the sequences. In order to do this we calculated the frequency of every chunk appearing in initial and final position in the sequences and we calculated the ACS as in the global ACS (Knowlton & Squire, 1996; Meulemans, 1997). Then we randomly selected 100 sequences, generating an acquisition set which were comparable in terms of 2 and 3 letter chunks to the complete sequence set. The non-grammatical sequences were selected to match the grammatical sequences in terms of both terminal and whole-sequence ACS. These grammatical and non-grammatical sequences were further classified as high/low ACS in terms of their ACS status independent of grammatical status. High/low ACS refers to classification sequences composed of common/uncommon bi- and trigrams in the acquisition set, respectively.

3.3 EXPERIMENTAL PROCEDURE

3.3.1 NLP study

This was the first experiment that participants were tested on. Subjects were informed they were to participate in a language experiment. During the classification task they were instructed to read the sentences attentively and indicate whether the presented sentence was acceptable (grammatically correct) or not. FMRI data were acquired during classification of the sentences. All stimulus items in the experiment were presented visually with the help of Presentation software (http://nbs.neuro-bs.com). The stimulus items were presented via an LCD-projector standing outside the scanner room, projecting the computer display onto a semi-transparent screen that the subject comfortably viewed through a mirror device mounted on the head-coil. Sentences were presented word by word at the center of a computer screen. Each word was presented for 300 ms, followed by a blank screen for another 300 ms, after which the next word of the sentence appeared. The final sentence word ended with a period. After a variable delay (1000-2000 ms) from sentence offset, an asterisk appeared on the screen, signaling to the subjects that they had to push one of two response buttons indicating whether the sentence was acceptable or not. The asterisk remained on the screen for a period of 2000 ms, followed by a blank screen for a period of 2000-5000 ms preceding the next sentence (**Figure 10**).

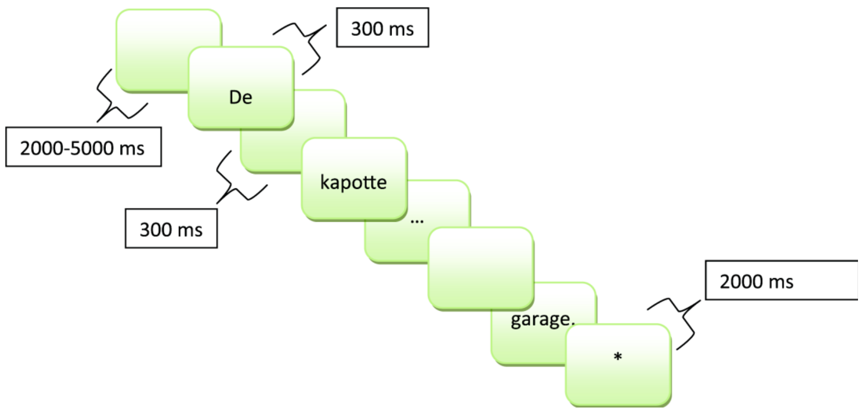


Figure 10. Example of the NLP experimental paradigm during fMRI measurements. Time is depicted in milliseconds.

Before the classification session, the subjects practiced on 10 practice sentences in order to fully master the experimental paradigm. The experimental sentences were presented in 4 blocks of approximately 10 minutes each, with a short break between each block. The response hand was balanced over subjects and over experimental blocks.

3.3.2 AGL studies

The AGL paradigm used in this thesis includes several implicit acquisition and classification sessions. The AGL procedure outlined in time can be seen in **Figure 11.** On the first day, participants started with preference classification while fMRI data was acquired. This served as a baseline measurement (i.e., baseline classification before exposure to the grammar). After five days of implicit acquisition sessions they underwent a preference fMRI session followed by a grammaticality fMRI classification. Thus, in total there were 3 classification fMRI sessions and 5 acquisition sessions.

During acquisition, participants were engaged in an STM task, used as a cover task, and exposed to a representative sample of sequences generated from the grammar (grammatical items only) with no performance feedback. Participants were not informed about the presence of the underlying grammar and they were instructed to indicate whether they like, or not, the presented sequences in each of the two preference classification sessions. The same 100 acquisition sequences throughout the five days were used, presentation order randomized for each acquisition session. Participants were instructed to retype the sequence on a keyboard. No performance feedback was provided, and only grammatical sequences were presented. The acquisition phase lasted approximately 20-40 minutes over the five consecutive days. This time variation was due to the fact that the STM task was self paced, with some participants being quicker than others in typing their response on the keyboard.

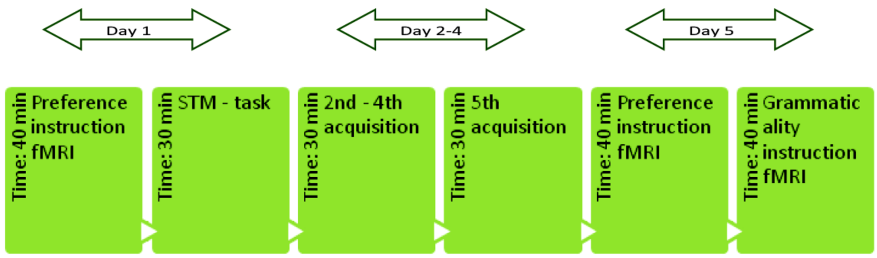


Figure 11. The AGL experimental paradigm outlined through time (5 days in total). On Day 1 participants were exposed to the NLP task before the preference instruction (baseline) fMRI task took place.

All the three classification tasks were performed in the MR scanner and in each classification session new items were presented, which participants have never seen before and these were not be used in the acquisition session. On the first day they underwent a preference classification. Participants were instructed to indicate, based on their immediate intuitive impression whether they liked or disliked the sequences presented to them. On the last day of the experiment, subjects underwent a preference classification session with new letter sequences. Procedures and instructions were identical to the ones used in baseline classification. After this session, the grammaticality classification took place. Participants were informed that the sequences were generated according to a complex set of rules. They were not informed about the nature of the rules, and were asked to classify novel items, as grammatical or non-grammatical based on their immediate intuitive impression. The classification sequences were presented via an LCD-projector on semi-transparent screen that the subject comfortably viewed through a mirror mounted on the head-coil. Each part lasted approximately 20 minutes. After a 1000 ms pre-stimulus period, the sequences were presented sequentially, letter-by-letter, followed by a 3000 ms response window (*see Study 2 for a more detailed description of the methods*). A low-level baseline condition was also included. This was a sensorimotor decision task in which sequences of either P or L, matched for sequence length to the classification set, were presented in the same fashion as the classification sequences. An overview of the presentation stimulus can be seen in **Figure 12.** The different sequence types were presented in random order and balanced across subjects.

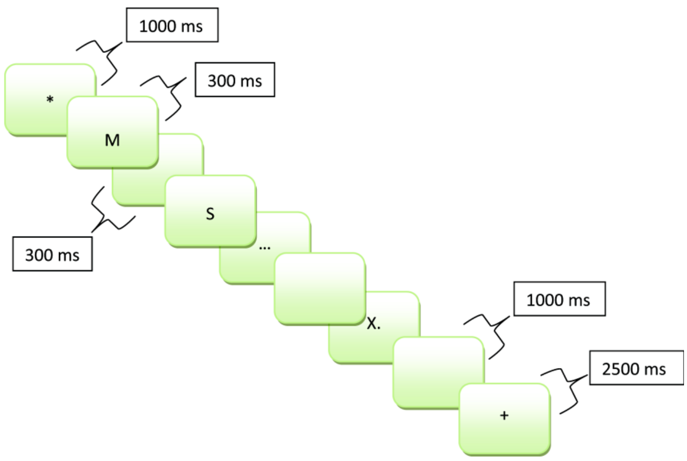


Figure 12. Example of the AGL classification paradigm time during fMRI measurements. Time is depicted in milliseconds.

3.4 DATA ANALYSIS

The following description is a summary of the data analysis outlined in more detail in the articles included in this thesis. For a detailed description the reader is referred to the articles of this thesis (*see Chapter 6*).

3.4.1 Behavioral data analysis

For the NLP study, the percentage correct scores were calculated. For the AGL behaviour data analysis, we analysed three different measures of performance; the percentage correct scores, the endorsement rates (i.e., sequences accepted as grammatical or preferable regardless of actual grammaticality status), which is translated into calculation of hits and false alarms, and the statistical signal detection score d-prime (Macmillan & Creelman, 1990). Throughout all the different studies we applied repeated measures analysis of variance (ANOVA) using the statistics package Statistical Package for the Social Sciences (SPSS 15.0). An overall significance level of $P < 0.05$ was used for statistical inference, and post hoc analysis was conducted when appropriate.

3.4.2 FMRI data analysis for the NLP & AGL studies

A significance level of $P < 0.05$ (family-wise error corrected) (FEW) was used throughout. Whole head T2*-weighted functional echo planar blood oxygenation level dependent (EPI-BOLD) fMRI data where acquired with a SIEMENS Avanto 1.5T scanner in a randomized event related fashion. Statistical parametric mapping (SPM5) software (www.fil.ion.ucl.ac.uk/spm) for image preprocessing and statistical analysis was used.

3.4.3 FMRI image preprocessing for the NLP & AGL studies

The EPI-BOLD volumes were realigned and slice-time corrected. The subject-mean EPI-BOLD images were subsequently spatially normalized to the functional EPI template provided by SPM. The normalization transformations were generated from the subject-mean EPI-BOLD volumes and applied to the corresponding functional volumes. The functional EPI-BOLD volumes were transformed into an approximate Talairach space (Talairach & Tournoux, 1988) defined by the SPM template and spatially filtered with an isotropic 3D spatial Gaussian filter kernel (FWHM = 10 mm). The fMRI data were analyzed statistically using the general linear model framework and statistical parametric mapping (Friston, Ashburner, Kiebel, Nichols, & Penny, 2007) in a two-step mixed-effects summary-statistics procedure. At the first-level, single-subject fixed effect analyses were conducted.

3.4.4 FMRI Statistical analysis results: NLP & AGL studies

For the NLP study the critical word position was manipulated independently in a 2x2 factorial design and the fMRI data analysis was time-locked on the onset of the critical word position. The linear model included explanatory regressors (independent variables) modeling the sequence presentation period from the critical word onset for the CR, SY, SE, and CB conditions separated on correct and incorrect responses. The initial part of the sentences was modeled separately as were the filler items and the inter-sentence interval.

For the AGL study at the first-level, single-subject analyses were conducted. The linear model included explanatory regressors modeling the sequence presentation period from the position of the anomaly in the High Non-Grammatical (HNG) and Low Non-Grammatical (LNG) conditions and their correct counterparts in the High-Grammatical (HG) and Low Grammatical (LG) conditions. This was done separately for correct and incorrect responses. The initial part of the sequences was modeled separately, as was the baseline and the inter-sequence-interval.

Then both in the NLP and AGL study we temporally convolved the explanatory variables with the canonical hemodynamic response function provided by SPM. We also included the realignment parameters for movement artifact correction and a temporal high-pass filter. For the second-level analysis in the NLP study, we generated single-subject contrast images for the correctly classified CR, SY, SE, and CB sentences from the critical word onset until the sentence final word relative the pre-critical sentence part in a one-way subject-separated random effects repeated measures ANOVA with non-sphericity correction and unequal variance between conditions. For the AGL study at the second-level, we generated single-subject contrast images for the correctly classified HG, LG, HNG, and LNG sequences, relative to the sensorimotor decision baseline. These were analyzed also in a random-effects repeated-measure ANOVA with non-sphericity correction for repeated measures and unequal variance between conditions.

Both for NLP and AGL statistical inference was based on the cluster-size test-statistic from the relevant second-level SPM[T] maps thresholded at $P = .001$ (uncorrected). Only clusters significant at $P_{FWE} < .05$, FWE corrected for multiple nonindependent comparisons, based on smooth random field theory (Adler, 1981; Adler & Taylor, 2007; Friston et al., 2007; Worsley et al., 1996) were taken into account as results.

4 CHAPTER – EXPERIMENTAL STUDIES

4.1 AIMS OF THE THESIS

1. To characterize the syntax-semantics interface in the brain, that is, where syntax and sentence-level semantics interact.
2. To investigate the grammatical and preference classification behavioural performance. We tested whether the development of preference will correlate with the grammaticality status of the classification items. Furthermore, the qualitative-quantitative equivalence of the behavioural results of this classification in relation to the grammaticality classification was investigated.
3. To characterize the neural infrastructure involved in artificial syntax processing for both grammaticality and preference classification.
4. To explore the effects of contactin-associated protein-like 2 (CNTNAP2) polymorphism on artificial grammar learning, behaviourally and with functional neuroimaging.
5. To investigate whether the same brain regions involved in the unification processes for syntax in natural language processing are also implicated in artificial syntax processing, irrespective of experimental instruction (grammaticality and preference classification).
6. Finally, to characterize the learning effect resulting from five days of implicit AGL by means of fMRI, by determining baseline and end-state activity during preference classification.

4.2 STUDY 1 - LANGUAGE COMPREHENSION: THE INTERPLAY BETWEEN FORM & CONTENT

In this study we investigated the neural correlates of the Unification-Memory-Control model proposed initially by Hagoort (2005) (*see Chapter 1*). The neural correlates of syntax and sentence-level semantic unification were investigated and their interaction, i.e., where natural language syntax and semantics interface in the brain **(Aim 1)**. Another goal of this study was to provide fMRI data to serve as a basis for the comparison of the brain regions responsible for natural syntax processing and those responsible for artificial syntax processing of Study 4 in the same participants **(Aim 5)**. We employed the NLP linguistic comprehension task developed especially to reveal the interaction between syntactic gender violations and semantic anomalies. As presented in the description of the experimental material, the particular material comprised of syntactic gender anomalies allowing for an investigation of the syntactic unification success or its failure, as well as semantic anomalies. This type of syntactic violation resolves in a deterministic way, leaving no space for ambiguity, allowing for an independent investigation of semantic violations. The interaction of the linguistic components has already been characterized by means of ERPs in a previous EEG study (Hagoort, 2003). Thus, in this study we sought to explore how these ERP results compare with fMRI results.

4.2.1 Results and Discussion

In this study we show that the brain differentiates between syntax and semantics, not only in terms of ERP components, but also in terms of activated brain regions characterized with fMRI. The results suggest that the anterior inferior frontal cortex (BA 45/47) is recruited in sentence-level semantics, in particular in semantic unification. The effect of syntactic gender violations engaged the middle frontal cortex (BA 9/46) without engagement of Broca's region, which is observed in incremental syntactic unification processing (**Figure 13**). Resolution of the particular syntactic anomalies (gender violation) was immediate without the need for Broca's region recruitment. Instead, we observed an engagement of the dorsolateral prefrontal cortex (BA 9/46), hypothesized to subserve the control component of the language system (*see Summaries 1.1 – 1.2*). The left dorsolateral prefrontal cortex is related to performance monitoring and is activated for the detection of the syntactic anomalies at hand.

Figure 13. Regions significantly sensitive to the effect of syntactic anomaly. The effect of syntactic gender violations engaged the middle frontal cortex (BA 9/46).

A significant interaction between sentence-level semantics and syntax was found in the left temporo–parietal cortex, in the vicinity of Wernicke's region (**Aim 1; Figure 14**). Overall, the results of Study 1 add to a more complete understanding of how the levels of syntactic and semantic representations interact and unify and how the unification model is conveyed in neural terms.

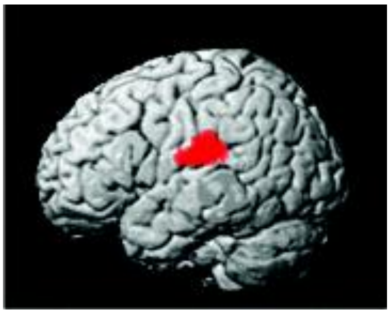


Figure 14. Regions significantly sensitive to the interaction between semantics and syntax factors. A significant interaction was found in the left temporo–parietal cortex (BA 22/40)

4.3 STUDY 2 - BEHAVIORAL RESULTS FROM THE FMRI AGL STUDIES

This study reports the behavioral results concerning the classification performance for both the preference and grammaticality classification task (**Aim 2**). We sought to investigate whether there is a difference between the preference and grammatically instruction and characterize the nature of any differences (qualitative vs. quantitative). On day 1, participants classified items according to their preferences. This was used as baseline/chance level performance prior to any exposure to the artificial grammar. On day 5, participants underwent the same task. Regarding grammaticality classification, participants classified items according to grammaticality only on day 5 subsequent to the preference classification task. The behavioral results concerning classification performance for both preference and grammaticality were calculated as *endorsement rates* (i.e., items that the participants considered as grammatical independent of their actual status; i.e., hits and false alarms). Endorsement rate percentages of day 1 and day 5 classification were compared, while for the grammaticality classification task, endorsement rates of day 5 classification were compared to chance level (i.e., 50%).

4.3.1 Results and Discussion

The behavioral results of the preference classification task showed that participants after five days were able to perform well-above chance levels scored on day 1 (on day 5: hits > false alarms, resulting in a higher endorsement rate). For the grammaticality classification task participants performed above chance and scored higher in choosing the correct responses in comparison to the preference task performance. Thus, the pattern of results was strengthened in grammaticality compared to preference classification, while all the effects significant under one instruction were also significant under the other (and conversely). This suggests that there is a quantitative rather than a qualitative difference between the two types of instructions at the behavioral level. Thus, preference and grammaticality classification appear equivalent in terms of behavioral effects **(Aim 2; Figure 15).**

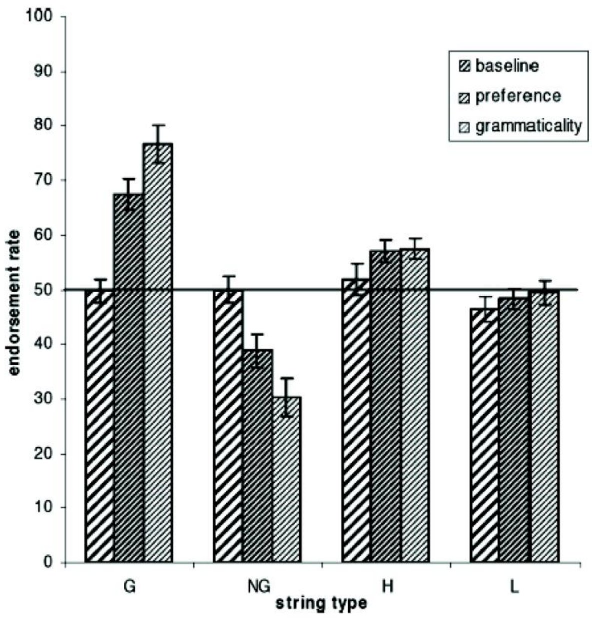


Figure 15. Endorsement rates over grammaticality and ACS main factor categories. The endorsement rates as a function of grammaticality status (G = grammatical sequences, NG = non-grammatical sequences) as well as associative chunk strength (H = high ACS sequences, L = low ACS sequences). The endorsement rate for grammatical vs. non-grammatical items increases as a function of repeated acquisition sessions. This is not observed for high vs. low ACS items. Error bars correspond to standard error of the mean.

Contrary to previous literature suggesting that only explicit instruction in artificial grammars can deliver observable/robust effects, these results strongly support the view that humans implicitly acquire knowledge about a complex system of interacting rules by mere exposure to the acquisition material. This knowledge can be effectively put to use and yield robust behavioral results after five days of exposure. We argue that preference classification (or structural mere exposure AGL) is an alternative way to assess implicit acquisition (*see Summaries 1.3 – 1.7*). The structural mere exposure AGL version is based on the finding that repeated exposure to a stimulus induces an increased preference for that stimulus compared with novel stimuli. As described earlier during this classification participants are asked to make like/not-like judgments (preference instruction) and therefore it is not necessary to inform them about the presence of a complex rule system before classification, which can thus be repeated. Moreover, from the subject's point of view, there is no correct or incorrect response, and the motivation to use explicit (problem-solving) strategies is minimized. Thus, in the preference version participants are kept unaware of the underlying generative mechanism, while in the grammaticality version, the subjects have, at least in principle, been informed about the existence of an underlying complex set of rules at the point of classification (but not during acquisition).

4.4 STUDY 3 - ARTIFICIAL SYNTAX: PREFERENCE, GRAMMATICALITY & FINITE RECURSION

The main objective of this study was to compare the brain networks engaged by artificial syntax processing during preference and grammaticality classification after implicit acquisition of the grammatical rules **(Aim 3)**. Based on previous behavioural results including Study 2, which show that subjects perform qualitatively identical on preference and grammaticality classification, we expected that the brain regions engaged by artificial syntax processing during preference classification would not differ significantly from those observed during grammaticality classification. This would strengthen the notion that preference and grammaticality classification in the implicit AGL paradigm are essentially equivalent. We also investigated the influence of CNTNAP2 gene on structured sequence processing on neural and behavioral level **(Aim 4)**. Evidence is accumulating for a role of CNTNAP2 gene on the brain response during language comprehension (Snijders et al., 2010, submitted) and specifically of the effects of a common single nucleotide polymorphism (SNP)

RS7794745 found in the CNTNAP2 gene. A single nucleotide polymorphism is a genetic variation in a DNA sequence occurring when a single nucleotide in a genome is altered. In the particular case of (SNP) RS7794745 two alterations-variations are observed in the DNA of the human population. Part of the population carries a single T-nucleotide at RS7794745 and in this study these individuals were labelled as T-group or AT- and TT-carriers. The other part of the population does not carry this nucleotide and in this study this group was labelled as nonT-group or AA carriers.

This was a first small scale investigation of possible related effects of the particular common polymorphism in the context of artificial syntax acquisition and structured sequence processing.

4.4.1 Results and Discussion

The comparison of the fMRI results for grammaticality and preference classification showed that the left inferior frontal region (BA 44/45) is active for both types of classification after five days of implicit exposure to the grammar. The results show that preference and grammaticality classification engage virtually identical brain regions (**Aim 3; Figure 16**). These results are consistent with our previously reported behavioral findings (*Study 2*), where there is no apparent qualitative difference between the two types of classification tasks.

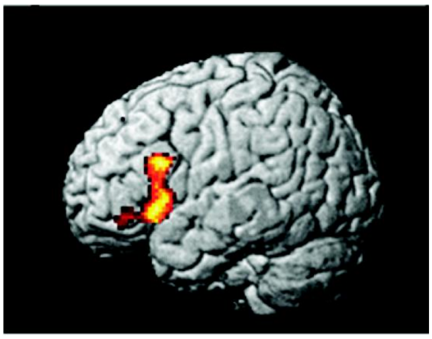


Figure 16. Brain regions engaged during both preference and grammaticality classification. The NG > G effect of Folia (2011, submitted) masked with the related effect observed in Petersson et al. (2010).

With reference to **Aim 4** differences between the two groups classified according to the common polymorphism (RS7794745) under investigation were found. At a behavioral level the T-group was better than the non-T group at making grammaticality judgments relatively independent of ACS, the use of which is not a predictive indicator for grammaticality status. Thus, the absence of a T nucleotide from RS7794745 seems to be associated with a greater dependence on ACS during the grammaticality classification task. These results might indicate that individuals carrying a T nucleotide acquire structural knowledge more rapidly, utilize the acquired knowledge more effectively, or are better able to ignore cues related to local subsequence familiarity in comparison to the nonT-group.

Concerning the fMRI results, Broca's region showed different levels of activation between the two groups during the grammaticality classification task (these results were essentially identical for the preference classification task). We observed significantly greater activation in Broca´s region and the left frontopolar region (BA 10) in the non-T group compared to the T-group (**Figure 17**). This discrepancy in recruited regions could be following the differences among the two groups observed at the behavioral level i.e., different behavioral performance leads to differences in neural recruitment or it could have anatomical origins i.e., divergence in neural recruitment due to genetically shaped anatomical differences leads to behavioral variance. In either case, these initial efforts suggest that it is worthwhile to try to understand the genetic basis for language as well as the capacity for structured sequence processing in large-scale studies by investigating the relevant biological pathway(s).

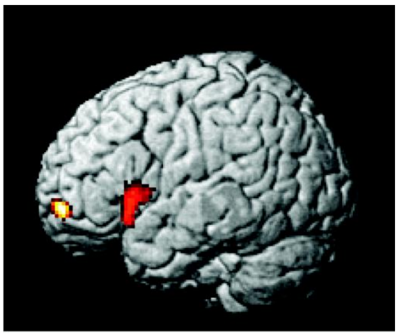


Figure 17. Brain regions differentiating the T- and the nonT-groups. **Left**: Group differences related to grammaticality classification (nonT > T). **Right**: Group differences related to grammatical sequences of high local subsequence familiarity (nonT > T).

4.5 STUDY 4 - WHAT ARTIFICIAL GRAMMAR LEARNING REVEALS ABOUT THE NEUROBIOLOGY OF SYNTAX

The main objective in this study was to investigate the brain regions responsible for natural and artificial syntax processing in the same sample of participants **(Aim 5)**. Moreover, some characteristics of the processing properties of Broca's region could be delineated. The previous literature has suggested that Broca's region is sensitive to the presence of specific processing requirements related to hierarchically nested structures and to syntactic operations such as syntactic movement *(see Summaries 1.3 – 1.7)*. Thus, we investigated whether Broca's region can be considered specific to syntactic movement operations or the processing of hierarchically nested non-adjacent dependencies via the use of a simple right-linear unification grammar. Such grammar generates hierarchical structures but lacks nested non-adjacent dependencies as well as filler-gap relationships (syntactic movement).

4.5.1 Results and Discussion

The results showed that during the processing of well-formed sequences, artificial syntax processing engages the left inferior frontal region, centered on BA 44 and 45. Concerning the processing of non-grammatical sequences Broca's region was found to be engaged to a greater extent. The results show that artificial syntax processing engages essentially the same neocortical territory of Broca's region as observed in natural syntax processing. So far Broca's region has been found to be activated in different experimental studies of artificial and natural language processing in different samples. Study 4 is the first study to show that the human brain treats artificial syntactic and natural syntactic violations alike, namely as violations in the acquired sequential structure **(Aim 5; Figure 18)**. Crucially, the presented sequences lacked requirements for syntactic movement or nested embedding processing. The conclusion we draw from these findings is that the left inferior frontal region (BA 44/45) cannot be specific to the processing of syntactic movement or nested structures. These results support the notion that the left inferior frontal region is related to generic on-line structured sequence processing, irrespective of whether these include nested or moved structures (*see Summaries 1.3 – 1.7*). We suggest that there is a quantitative difference (e.g., in terms of minimal memory requirements) in processing sequences with adjacent and non-adjacent dependencies, but that the nature of the processing is the same (i.e., the underlying neural hardware performs the same set of operations).

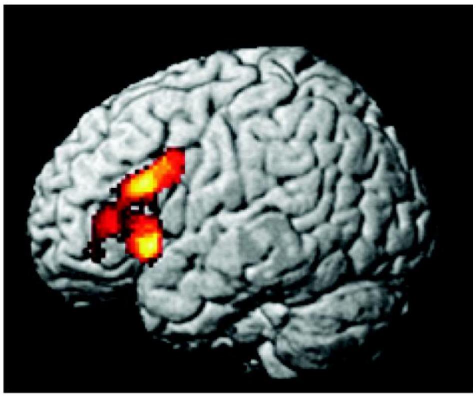


Figure 18. Brain regions engaged during both artificial and natural syntax processing. The main effect NG > G masked with the syntax related variability observed in Petersson et al. (2010).

4.6 STUDY 5 - LEARNING TO "LIKE" STRUCTURED SEQUENCES ACTIVATES INFERIOR FRONTAL CORTEX

In this final study, we investigated the neural correlates of the learning/acquisition process in the implicit preference artificial grammar paradigm (**Aim 6**). In relation to previous AGL literature, the novel preference classification paradigm is based on the structural mere exposure effect. During this version as described also in Study 2 there is no correct or incorrect response, and the motivation to use explicit strategies for task performance is minimized. This is essential since different neural correlates are involved during explicit learning. Moreover, the exposure to learning is longer than one day allowing for consolidation as well as abstraction processes to take place. Participants were tested twice on the same preference classification task while being in the fMRI, once before the AGL exposure and once after 5 days of implicit acquisition *(Study 2)*.

4.6.1 Results and Discussion

In comparison to the first day (baseline measurement) the inferior frontal region, centered on Broca's region (BA 44-45) became sensitive to the actual grammaticality status of structured sequences after 5 days of implicit exposure to the underlying grammar (**Figure 19**). Broca's region is engaged in correct classification of grammatical items (Study 3 & 4) and its involvement is a gradual incremental learning process, which becomes apparent after at most 5 days of acquisition. Moreover, this learning process is successful in the extraction of complex structure from separate learning instances (over 5 days). Our novel paradigm (structural mere exposure AGL) exposing participants for more than one day to artificial syntax can be considered as a more valid tool in simulating the way natural syntax is acquired over time. We used the same paradigm before exposure to the grammar as an appropriate baseline for preference AGL classification. Thus, we were able to characterize the true learning effect (**Aim 6**).

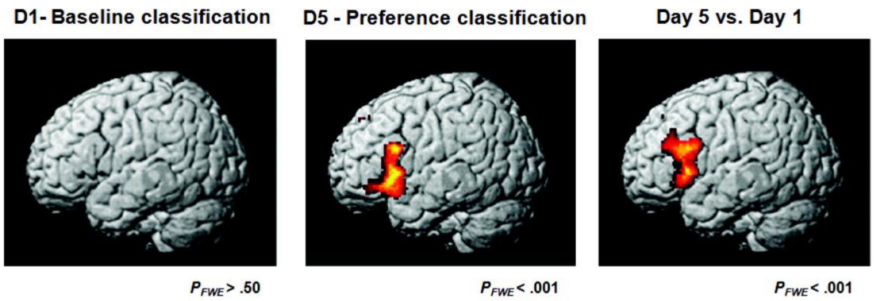


Figure 19. Brain regions engaged during correct preference classification. The main effect nongrammatical versus grammatical sequences on Day 1 (D1), Baseline (preference) classification (left hand side); on Day 5 (D5), and preference classification after 5 days of implicit acquisition (middle); the effect of implicit acquisition (right hand side).

5 CHAPTER – CONCLUSIONS

Two main questions were pursued in this thesis as stated in the preface. The first was the investigation of the preference instruction and whether preference classification can deliver robust results at a behavioral and neural level. The second question was to investigate to what extent NLP and AGL are processed alike in the human brain.

On a behavioral level, the studies included in this thesis conclude that the implicit AGL paradigm based on the structural mere-exposure effect (preference classification task) delivers robust acquisition results that are qualitatively the same in comparison to classification based on the grammaticality instruction, provided that one allows sufficient time for consolidation and abstraction processes to take place.

On a neuronal level the studies in this thesis show that artificial and natural language processing make use of the same brain networks irrespective of the nature of the instruction (preference or grammaticality) used for the AGL classification.

Concerning the genetic influence of the common polymorphism RS7794745 on sequential processing, it is not clear how it affects language. The behavioral and FMRI results found in this thesis suggest that the CNTNAP2 gene might be related to structured sequence acquisition and to performance classification.

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My goal has been completed but the one who inspired me to achieve this path is no longer close. I devote this work to this beloved one with the hope one day we will meet again.

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