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**Author:** Kepinska, O.
**Title:** The neurobiology of individual differences in grammar learning
**Issue Date:** 2017-06-01
Chapter 1

General introduction
1.1 Introduction

In their 2008 paper reporting on the results of a large-scale research programme ‘High-level Proficiency in Second Language Use’, Niclas Abrahamsson and Kenneth Hyltenstam examined the role of age and language aptitude in near-native proficiency levels of Swedish as a second language (L2). Age of onset of acquisition (AoA) accounts for the largest proportion of variation in the outcomes of L2 learning in that the later someone starts learning, the more effortful the learning process and the lower the ultimate attainment levels are (see e.g., DeKeyser, 2000; Johnson & Newport, 1989; Lenneberg, 1967; Long, 1990). The question asked by Abrahamsson and Hyltenstam was whether a high degree of language learning aptitude (i.e., a specific, measurable talent for learning foreign languages) could alleviate such age effects and enable adult learners to reach a level in an L2 that is comparable to that of native speakers. Not only did the study reveal that a high degree of language aptitude was crucial for late learners (AoA ≥ 12) to attain a very high, near-native level of proficiency in L2, it also showed that it was an important factor influencing L2 proficiency of the early learners (AoA ≤ 11).

This widely cited study was the starting point for the ideas and concepts explored in the present thesis. The robustness of aptitude effects in second language acquisition (SLA) was evident (see also e.g., DeKeyser, 2000; Granena & Long, 2013; S. Li, 2016), yet at the time of conception of the research proposal for the present study (late 2011) hardly any study investigating their neurobiological underpinnings was available. Indeed, such sentiment was also expressed by the authors, and time and again by other researchers from the field of SLA. In the words of Ioup, Boustagui, El Tigi and Moselle (1994) (as cited by Abrahamsson & Hyltenstam, 2008), “how the talented brain acquires language in comparison with the normal brain remains a mystery” (p. 93).

Human brains differ from each other almost as much as our faces do (Schumann, 2014). For example, the size of different brain structures, the number of neurons used to perform certain functions and the integrity of white matter (bundles of fibres connecting different parts of the cortex) vary from person to person. Although there is some debate as to

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whether these parameters influence information processing, a growing body of research indicates that some of these inter-individual differences correlate with specific cognitive tasks, such as language learning (e.g., Coggins, Kennedy, & Armstrong, 2004; Golestani, Molko, Dehaene, Lebihan, & Pallier, 2007; López-Barroso et al., 2013; Mechelli et al., 2004).

Departing from the concept of a specific talent for learning foreign languages, and the idea that there are large differences in the way individual human brains work and are built, the main aim of this thesis is to advance the understanding of neural mechanisms and brain structures underlying individual differences in language acquisition.

The following sections of the General Introduction will, first, elaborate on previous language aptitude research, second, introduce the scope of the present investigations, and finally, present the methodology of the research.

1.2 Language aptitude research

Research into the phenomenon of language aptitude has been conducted in the context of individual differences in second language learning, other factors including learner’s age, motivation, personality, anxiety and learning style. According to a recent meta-analytic study on aptitude effects (S. Li, 2016), general L2 proficiency and language aptitude measurements correlate strongly with each other (\( r = .49 \)), making aptitude the best prognostic measure of language learning achievement (see also Dörnyei & Skehan, 2003; R. Ellis, 2008; Sawyer & Ranta, 2001).

Dörnyei and Skehan define language aptitude as “a specific talent for learning foreign languages, which exhibits considerable variation between learners” (2003, p. 613). It is viewed as a composite of general and specific abilities (R. Ellis, 2008). The question whether language aptitude is innate and remains stable throughout one’s life, or depends upon past learning experience is still a matter of debate (see Grigorenko, Sternberg, & Ehrman, 2000; Sawyer & Ranta, 2001). Yet by no means has language aptitude been considered a prerequisite of mastering an L2, rather it serves in the form of a capacity which improves the rate and ease of learning (Carroll, 1981).

The concept of aptitude of any kind entails existence of some capabilities which enable an individual to perform particular tasks better than others do. In the case of second language learning, it is assumed that aptitude can be measured, thus providing information as to the individ-
ual's achievement even before the actual learning takes place. As early as the 1920s, attempts were made to develop tools for predicting one's success in language learning. However, as it was the case that L2 learning which was based on the popular grammar-translation method of the time was seen as a purely intellectual exercise, most of the early language aptitude tests correlated rather highly with intelligence tests (Carroll, 1981). For a long time, it has therefore been widely assumed that linguistic abilities are inseparable from general intelligence. Recent studies elucidated the relationship between intelligence and language aptitude, suggesting the two constructs overlap but are distinguishable from each other (Granena, 2013; S. Li, 2016). Similarly, language aptitude has been found to correlate with measures of executive functioning, in particular of working memory capacity (S. Li, 2016).

A methodology for studying language aptitude and its nature was developed by the American psychologist John Bissell Carroll, whose work laid the ground for the majority of current studies into the concept. The main motive for these early investigations of language aptitude was “the wish to identify those learners who could benefit most from language instruction” (R. Ellis, 2008, p. 659). In his research, Carroll administered a series of potential tests aiming at pinpointing the different components of language aptitude to learners starting a language course. Subsequently, these tests were correlated with each other, and with tests measuring language proficiency at the end of the course, which enabled Carroll (1981) to distinguish the following four components of language aptitude:

1. phonemic coding ability, or the capacity to code unfamiliar sounds so that they can be retained;
2. grammatical sensitivity, which refers to the ability to identify the functions that words fulfil in sentences;
3. rote learning ability, or the ability to learn associations between lexical forms and meaning rapidly and efficiently and to retain these associations (i.e. to easily learn and remember new words);
4. inductive language learning ability, which is the capacity to infer or induce the rules of a set of previously unknown language materials.

(See also Abrahamsson & Hyltenstam, 2008; Dörnyei & Skehan, 2003; R. Ellis, 2008; Sawyer & Ranta, 2001; Skehan, 2002 for further elaboration of these components.)

On the basis of the empirically established components of language aptitude Carroll, together with Sapon (1959), devised a commercially
available test battery, the Modern Language Aptitude Test (MLAT), consisting of five sub-tests. Notably, in the interest of the predictive validity of the test, there was no one-to-one correspondence between the sub-components of language aptitude and the sub-tests (Dörnyei & Skehan, 2003).

Carroll’s findings concerning language aptitude almost completely shaped the way this subject was addressed within the SLA field, and although the results of post-MLAT research did not revolutionise the view of the nature of language aptitude outlined by Carroll, it certainly brought about a refinement of his initial theory. One important contribution was the development of a series of alternative language aptitude tests. The Pimsleur Language Aptitude Battery (PLAB) (Pimsleur, 1966) is a test developed as an alternative to the MLAT, targeted mostly at high school students. The Defense Language Aptitude Battery (DLAB) (Petersen & Al-Haik, 1976) aimed at discriminating learners at the high end of the aptitude range and has been used by the United States Department of Defence. Similarly, the recent Hi-LAB (Linck et al., 2013) also targets highly successful L2 learners. The Cognitive Ability for Novelty in Acquisition of Language (CANAL-F) is a dynamic test devised by Grigorenko et al. (2000), which underscores the role of coping with novelty in L2 acquisition. The Llama Language Aptitude Tests (LLAMA) (Meara, 2005) have been developed at the University of Wales Swansea through a series of research projects, including the development of the earlier version of the test – the Swansea Language Aptitude Test (LAT) v2.0 (Meara, Milton, & Lorenzo-Dus, 2003). The current LLAMA tests are based among others on the work of Carroll and Sapon (1959). The battery consists of the following four sub-tests: (1) LLAMA_B, a vocabulary learning task; (2) LLAMA_D, a test of phonetic memory; (3) LLAMA_E, a test of sound-symbol correspondence, and (4) LLAMA_F a test of grammatical inferencing. The tests can be used regardless of the linguistic background of the language learner. The sub-tests include linguistic materials from either artificial language systems or rare languages with which the participants are unlikely to be familiar. Furthermore, LLAMA is a freeware program, which is available online (through http://www.lognostics.co.uk/) and can be administered on a personal computer (see Section 1.4.1 below for further details concerning the LLAMA tests).

In terms of elaboration on the components of language aptitude in the post-MLAT research, Skehan (2002) proposed a more parsimonious structure of the construct, consisting of three instead of four components. Next to phonetic coding and rote learning, he suggested that
since grammatical sensitivity and inductive language learning ability are both associated with analytic aspects of aptitude, they can be both unified as language analytical ability (LAA). Furthermore, on the basis of his research with learners of colloquial Arabic within the British military, Skehan (1986, 2002) proposed that success in L2 learning may be a consequence of the learner’s strength in only one of the components of language aptitude. In fact, he stated that “successful learners either achieved their success through strong involvement of language analytic abilities or through high memory, but surprisingly few students appeared to have high scores in each of these” (2002, p. 76). Another idea concerning the components of language aptitude put forward among others by Robinson (2005) is that they are dynamic in nature, in that different aspects of language aptitude may operate differently during the course of language learning (but see Granena (2013), and Section 1.4.1 below for data concerning the stability of aptitude measurements – i.e., the LLAMA tests – over time).

1.3 Scope of the present study

Following Skehan’s (2002) suggestion indicating that successful L2 learning can be due to benefitting from either one’s memory, or analytical abilities, this study set out to constrain its scope to LAA only. The analytic component of language aptitude has been shown to be best at predicting grammar learning, underscoring its link with learning of the morphosyntactic aspects of an L2 (S. Li, 2016). Since one of our main goals was to investigate the neural mechanisms coupled with high aptitude (and thus high LAA in particular), a grammar learning task was incorporated in our experimental design, in order to – as it were – observe the LAA effects for successful grammar learning “in action”. Furthermore, since, as pointed out by Robinson (2005), aptitude levels can change over time, reliable neurobiological observations of the aptitude construct should either encompass a longitudinal design with a series of measurements, or be restricted to one stage of learning. Considering the limited time available within the present project, the latter option was chosen, and the beginning stage of the grammar learning process was investigated.

An added value of this approach was that it enabled a scrutinised exploration of the initial phase of novel grammar acquisition. Mastery of grammatical rules of a language is a complex and demanding task, in particular for adult L2 learners (Abrahamsson & Hyltenstam, 2009; Antoniou, Ettlinger, & Wong, 2016). The experiments reported in the present thesis shed light on how the adult brain acquires new grammatical sensitivity and inductive language learning ability are both associated with analytic aspects of aptitude, they can be both unified as language analytical ability (LAA). Furthermore, on the basis of his research with learners of colloquial Arabic within the British military, Skehan (1986, 2002) proposed that success in L2 learning may be a consequence of the learner’s strength in only one of the components of language aptitude. In fact, he stated that “successful learners either achieved their success through strong involvement of language analytic abilities or through high memory, but surprisingly few students appeared to have high scores in each of these” (2002, p. 76). Another idea concerning the components of language aptitude put forward among others by Robinson (2005) is that they are dynamic in nature, in that different aspects of language aptitude may operate differently during the course of language learning (but see Granena (2013), and Section 1.4.1 below for data concerning the stability of aptitude measurements – i.e., the LLAMA tests – over time).
ical rules and what mechanisms are typical of good performance. Moreover, effort was made to relate our findings to earlier studies concerned with novel grammar learning. To this end, an established experimental protocol was used (see below), and an attempt was made at reproducing and extending previous results reported in studies employing it (see in particular Chapter 2).

Experiments investigating the neural architecture behind language learning make frequent use of designs which are highly controllable, and tap into isolated aspects of an otherwise complex process. In case of research into the neurobiology of syntax acquisition, the so-called artificial grammar learning (AGL) paradigms (Reber, 1967) are commonly employed (e.g., Antonenko, Meinzer, Lindeberg, Witte, & Flöel, 2012; Brod & Opitz, 2012; Friederici, Steinhauser, & Pfeifer, 2002; Goranskaya, Kreitewolf, Mueller, Friederici, & Hartwigsen, 2016; Hauser, Hofmann, & Opitz, 2012; Opitz, Ferdinand, & Mecklinger, 2011; Opitz & Friederici, 2003, 2004, 2007). They offer a view on the neurobiological mechanisms of syntax acquisition in real time, without the interference of semantics, phonology or pragmatics. Moreover, due to the synthetic nature of the stimuli, strict control over prior exposure is guaranteed (cf. e.g., Petersson, Folia, & Hagoort, 2012; Petersson & Hagoort, 2012). Such an approach was also used in the present study (see Section 1.4.2 below for a further elaboration on the employed experimental design).

Understanding any cognitive phenomenon from the neurobiological perspective entails unravelling and integrating many layers of information. In this vein, in order to gain a comprehensive account of individual differences in grammar learning and language aptitude, the present study used a variety of neuroimaging data. Combining several analytical approaches to the data enabled us to investigate the phenomenon of language aptitude and grammar learning from a range of perspectives that complement each other, and – desirably – will improve the validity of the conclusions to be drawn.

1.4 Methodology

The workflow for the present study consisted of (1) a large-scale pre-test of language aptitude, (2) a multi-modal magnetic resonance imaging (MRI) paradigm consisting of several experiments, and (3) an electroencephalography (EEG) experiment. The following sections describe the distinct steps and elaborate on the methodology applicable to each of them.
1.4.1 LLAMA measurement

The first step of the present study consisted of administration of the LLAMA tests to a large sample of participants in order to choose participants for further experiments. The LLAMA tests (see also Section 1.2 above) and their earlier version, the Swansea Language Aptitude Tests (LAT) (Meara et al., 2003) have been widely used within the field of SLA, for example in studies of ultimate L2 attainment (Abrahamsson & Hyltenstam, 2008; Granena & Long, 2013) and effects of feedback during L2 instruction (Yilmaz, 2012). In a paper reporting on an exploratory validation study of the LLAMA tests, Granena (2013) presented results on its reliability: internal consistency, assessed by means of Cronbach’s alpha, and test-retest reliability, derived from correlation of test scores obtained on two time points, two years apart. The LLAMA tests proved to have a good reliability, Cronbach’s $\alpha = .77$ and to be stable over time ($r = .64$, $p = .002$).

The goal of the LLAMA measurement was to discriminate between learners with high and average language aptitude in one domain of language acquisition, namely grammar learning. To this end, the LLAMA-F test of grammatical inferencing was used, see Figure 1.1. In this test, twenty pictures are presented together with sentences in an unknown language that describe them. In the learning phase (lasting five minutes), participants are asked to discover grammatical rules (concerned mainly with agreement features) of this unknown language, and they are allowed to take notes. In the test phase, they are presented with a series of pictures, combined with two sentences and they have to decide which sentence is grammatically correct. Participants can score from 0 to 100, and according to the LLAMA manual, 80-100 is defined as outstandingly good and 25-45 as average (Meara, 2005). However, since the scores are awarded at intervals of 10, a slightly adjusted interpretation of the scores was used in the present study and an average score was defined as 30-50.
Figure 1.1 One of the items from the LLAMA_F test (Meara, 2005). The illustration on the right is described by a sentence (*unak-ek eked-ilad*) in a language unknown to the participant. On the basis of twenty such examples, participants discover grammatical rules which they are subsequently supposed to apply to new materials in the test phase of the experiment.

1.4.1.1 Procedure

The LLAMA test was administered on Personal Computers in a computer lab at the Faculty of Humanities at Leiden University. A maximum of 20 participants could take the test at the same time. Upon arrival, each participant was given a set of headphones and an instruction booklet (see Appendix 1) explaining the procedure.

Participants were asked to read the instructions and ask any questions before starting the tests. At least one experimenter was present at all times during the test. The order of the subtests was the same for all participants: they started with the LLAMA_B, followed by LLAMA_D, LLAMA_E and finished with the LLAMA_F. Following the language aptitude tests, the participants were asked to fill in an online questionnaire (see Appendix 2).

1.4.1.2 Participants

In total 307 participants were recruited at Leiden University through posters, flyers, email invitations and by word of mouth advertising. 239 of them completed all parts of the test and the biographical information...
General introduction

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groups of learners: those who scored within the average range (30-50),
and those who obtained an “outstandingly good” score (80-100) per
LLAMA manual. Figure 1.2 shows the distribution of scores on the
LLAMA_F subtest; the two groups of learners are highlighted in the
graph. In total, 67 participants scored within the average, and 93 with-
in the high range. Only right-handed, healthy individuals with no con-
tra-indications for an MRI scan (e.g., neurological disorders, metal im-
plants) were approached to take part in the follow-up neuroimaging
experiments. In total, 47 participants took part in the EEG, and 42 in
the MRI experiments.

Additional psychometric measurements were collected from the partici-
pants of the MRI and EEG experiments. The tests were administered
after the main part of the study (the grammar learning task, see Sec-
tion 1.4.2 below) and included a nonverbal test of general fluid intelli-
gence, the Raven Advance Progressive Matrices (RAPM, Hamel &
Schmittmann, 2006) and a test of working memory span, Automated
Operation Span Task (AOSPAN, Unsworth, Heitz, Schrock, & Engle,
2006). As expected on the basis of the previous research into the apti-
tude construct (see Section 1.2 above, and S. Li, 2016), the highly
skilled learners had on average higher scores on both the reasoning
abilities and working memory tests (RAPM: M = 24.57, SD = 4.35, and
M = 20.36, SD = 5.07; AOSPAN: M = 48.04, SD = 13.26, and M = 36.76,
SD = 19.11, for the high and average LAA participants, respectively).

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Table 1.1 Average scores and standard deviations on each of the LLAMA subtests.

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The difference was statistically significant for the EEG cohort ($t(44) = 4.16, p < .05$, and $t(44) = 3.56, p < .05$, for RAMP and AOSPAN, respectively); the scores of highly and moderately skilled participants who took part in the MRI experiments did not differ significantly ($t(40) = 1.88, p = .07$, and $t(40) = 1.11, p = .27$, for RAMP and AOSPAN, respectively).

![Figure 1.2](image1.png)

**Figure 1.2** Distribution of scores on the LLAMA_F subtest. The shaded bars mark scores which were relevant for the later experiments, i.e. the average (30-50) and high (80-100) range.

### 1.4.2 Grammar learning task

For both MRI and EEG parts of the present study, the same paradigm was used: a study design enabling an investigation into rule learning in real time, in which learning is simultaneous to the recording of the data. The paradigm is based on the artificial language BROCCANTO (Brod & Opitz, 2012; Friederici et al., 2002; Hauser et al., 2012; Opitz et al., 2011; Opitz & Friederici, 2003, 2004, 2007) comprising a set of pronounceable pseudo-words, combined in ways following rules found in many natural languages. The artificial grammar is presented to the participants over the course of several learning and test phases. During learning, correct grammatical sentences are shown one by one on the screen and participants are instructed to extract the underlying rules. The test phases consist of both grammatical and ungrammatical items.
and participants’ task is to assess the grammaticality of the sentences. The accuracy of these grammaticality judgements serves as an indication of the learning progress. See Chapter 3 and Chapter 4 for further details concerning the BROCANTO rules and the presentation of the task.

1.4.3 Neuroimaging methods

Brain imaging techniques can be divided into functional and structural methods. All methods directly (e.g., through electrophysiological measures) or indirectly (e.g., investigating levels of blood oxygenation) recording brain activity patterns fall under the umbrella of functional neuroimaging. Techniques dealing with the anatomical make-up of the central nervous system are referred to as structural. Both were used in the present study, and are shortly discussed hereunder (and in detail in Chapters 2-6).

1.4.3.1 fMRI

By detecting changes in blood oxygenation, functional magnetic resonance imaging (fMRI), together with its various applications, offers an indirect measurement of brain's activation levels. For example, the activation levels can be related to performance of a cognitive task (such as grammar learning) through a subtraction method utilised in event-related designs. At least two conditions of interest are presented to the participant, in our case, the grammatical and ungrammatical sentences comprising the test phases of the AGL experiment. The difference in the blood-oxygen-level dependent (BOLD) signal between them is then computed and localised, and can be taken as an indication of the brain’s reaction to the particular stimulation. Moreover, inferences about how such localised activity patterns differ between groups of participants can be made by performing statistical comparisons, see Chapter 4.

Another possibility of approaching fMRI data is to explore correlated BOLD signal fluctuations of different brain areas, in order to visualise and quantify the brain’s functional connectivity patterns at rest or during cognitive tasks. Here, at least two methods are available. First, insights concerning the cooperation between pre-defined regions of interest (ROIs) can be obtained from psychophysiological interaction (PPI) analysis (Friston et al., 1997). Such an approach aims at detecting regions in the brain whose activity levels can be explained by the activity pattern of the predefined ROI (during a specific cognitive process, such as novel grammar learning). Prior hypotheses about regions involved
are a prerequisite for performing such an analysis, hence the present study (see Chapter 2), utilised it in an effort to build on previous research concerning the functional interactions of Broca’s region and the hippocampal system in the acquisition of grammar rules.

The connectivity question can also be approached in a data-driven manner, by investigating the intrinsic organisation of the brain as different networks without any spatial constraints. A method allowing for such an approach is the independent component analysis (ICA) of fMRI data. This technique allows for the detection of structured spatiotemporal processes in neuroimaging data (Beckmann et al., 2006) by means of their decomposition into a set of spatially independent activation maps (components) and their time courses. The components are seen as a representation of interconnected networks of brain regions that coactivate when certain types of tasks or cognitive processes are being performed, see Chapter 3. Moreover, inter-individual differences within the components can be assessed, providing information on brain’s functional organisation coupled with, e.g., a certain trait (such as high language analytical abilities).

1.4.3.2 EEG

Electroencephalography measures repetitive neuronal firing (i.e., oscillations) of large populations of neurons. EEG signals recorded during a cognitive task, such as grammar learning, can be—among others—quantified by means of power spectrum and synchronisation analyses (cf. e.g., M. Siegel, Donner, & Engel, 2012; X.-J. Wang, 2010). Spectral power variations reflect the number of neurons discharging at the same time (Kiiski et al., 2012; Klimesch, 1999), thus indicating local neuronal activity. EEG also offers a view on functional cooperation between brain regions by means of coherence analyses. The premise of this approach is that brain areas activated by a particular cognitive task (e.g., learning of a novel grammar) exhibit increased coherence, and high coherence between two EEG signals is indicative of high cooperation (degree of information flow) and synchronisation between underlying brain regions within a certain frequency band (Weiss & Mueller, 2003), see Chapter 5.

1.4.3.3 DTI

Diffusion tensor imaging (DTI) is a structural neuroimaging technique based on MRI. Thanks to the magnetic gradient, it measures diffusivity of water along different directions. One of its applications, deterministic

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tractography, offers visualisation of white matter pathways by inferring the movement of water molecules (Catani & Mesulam, 2008; see also Le Bihan, 2003). Brain images obtained with the DTI method can be quantified, offering a measure of the microstructural tissue properties underlying the white matter pathways. The technique thus enables comparisons between individuals (e.g., as determined with a language aptitude test), and establishment of functional correlates of particular anatomical structures, see Chapter 6.

1.5 The neurobiology of individual differences in grammar learning

The goal of the present thesis was to employ the above methodological approaches to neuroimaging data and produce a comprehensive – albeit undoubtedly not exhaustive – picture of the neural mechanisms and brain structures underlying individual differences in L2 grammar acquisition, with a special focus on language learning aptitude, viz. language analytical abilities.

Chapter 2 and Chapter 3 both report on the functional MRI data collected during the learning phases of the AGL task. In Chapter 2, an investigation into the functional architecture of the language learning brain following directly from previous studies employing the paradigm utilised in the present study is presented. PPI analysis was used in order to build upon previous findings (Opitz & Friederici, 2003) and to set the scene for further investigations involving the between-group comparisons of the highly and moderately skilled learners. In Chapter 3, whole-brain functional connectivity was investigated with the above-mentioned ICA approach. After decomposition of the fMRI data into maps representing separate cognitive processes, we explored whether the brain’s networks were represented differently among participants with high and average language analytical abilities. Event-related fMRI was employed in the experiment reported in Chapter 4. Its goal was to establish where in the brain the novel grammar is processed, how the activity patterns differ between highly and moderately skilled learners, and how they change over the course of a task as a function of participants’ behavioural performance. Chapter 5 reports on an EEG experiment, in which we investigated whether learners with different degrees of LAA exhibit different oscillatory patterns during acquisition of a novel grammar. The paper reports moreover on the dynamics of the learning process reflected in short- and long-range brain oscillations. Finally, Chapter 6 presents results of a structural imaging experiment employ-
Chapter 1

Deterministic tractography of the main language-related white matter pathways. How the microstructure of these pathway relates to one's language analytical abilities was at the centre of this experiment.