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Neural Correlates of Processing Syntax in Music and Language – Influences of Development, Musical Training, and Language Impairment

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Diplom-Psychologe Sebastian Jentschke
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Gutachter der Arbeit

Prof. Dr. Angela D. Friederici
Max-Planck-Institut für Kognitions-
und Neurowissenschaften
Stephanstr. 1A
D-04103 Leipzig

Prof. Dr. Monika Knopf
Johann Wolfgang Goethe-Universität Frankfurt
Institut für Psychologie
Abt. Entwicklungspsychologie
Georg-Voigt-Str. 8
60486 Frankfurt

Prof. Dr. Eckart Altenmüller
Hochschule für Musik und Theater
Institut für Musikphysiologie und Musikermedizin
Hohenzollernstrasse 47
D-30161 Hannover

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Zusammenfassung der wissenschaftlichen Ergebnisse der Dissertation

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eingereicht an der Fakultät für Biowissenschaften, Pharmazie und Psychologie
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von Diplom-Psychologe Sebastian Jentschke

angefertigt am Max-Planck-Institut für Kognitions- und Neurowissenschaften, Leipzig

Einleitung

Musik und Sprache sind grundlegende, kulturgeschichtlich sehr alte und kulturübergreifende menschliche Fähigkeiten. Sie sind Beispiele für stark strukturierte Systeme: Beide sind aufgebaut aus Einzelelementen (z.B. Töne oder Phoneme) welche zu immer komplexeren, hierarchisch strukturierten Sequenzen zusammengesetzt werden. Die Anordnung dieser Elemente wird durch syntaktische Regeln bestimmt. Diese legen auch fest, welche Funktion den einzelnen Elementen zugewiesen wird.

Im Fokus der vorliegenden Arbeit stehen die neuronalen Korrelate der Verarbeitung musikalischer und sprachlicher Syntax. Sie weisen einige Gemeinsamkeiten auf. Diese zeigen sich zum einen funktionell: Die EKP-Komponenten, ERAN und ELAN, die frühe, hochautomatische Prozesse syntaktischer Strukturverarbeitung für Musik und Sprache reflektieren, haben ähnliche Merkmale. Beides sind frühe Negativierungen (maximal um 200 ms), die am deutlichsten an den frontalen Elektroden beobachtbar sind. Sie unterscheiden sich in ihrer hemisphärischen Gewichtung. Während die ELAN, die eine Verletzung sprachlicher Syntax widerspiegelt, eine stärkere Gewichtung über der linken Hemisphäre hat, zeigt die ERAN, die eine Reaktion auf die Verletzung musik-syntaktischer Regeln ist, eine stärkere Gewichtung über der rechten Hemisphäre. Anatomisch sind an musikalischer und sprachlicher Syntaxverarbeitung ähnliche Hirnregionen beteiligt. Diese befinden sich vor allem im superioren temporalen Gyrus und im inferioren frontalen Gyrus.

Ein Schwerpunkt der Arbeit war die Untersuchung von Gemeinsamkeiten musikalischer und sprachlicher Syntaxverarbeitung. Hierfür wurde, zum einen, die Verarbeitung musikalischer Syntax bei fünfjährigen Kindern mit einer spezifischen Sprachentwicklungsstörung (*specific-language impairment*; SLI) im Vergleich zu altersgleichen Kindern mit einer normalen Sprachentwicklung verglichen (Experiment II). Ein wichtiges Charakteristikum dieser Störung sind schwerwiegende Defizite bei der Verarbeitung sprachlicher Syntax. Daher sollte festgestellt werden, ob diese Kinder auch Schwierigkeiten mit der Verarbeitung musikalischer Syntax haben.

Zum anderen wurde bei Kindern mit musikalischem Training untersucht, ob sich Transfereffekte von musikalischer zu sprachlicher Syntaxverarbeitung nachweisen lassen. Eine Vielzahl von Studien konnte verbesserte Verarbeitungsprozesse bei der Musikwahrnehmung von Musikern nachweisen (vgl. Münte, Altenmüller, & Jäncke, 2002). Diese Verbesserungen beruhen auf neuronaler Plastizität, d.h. der Anpassung des Gehirns an bestimmte Umweltanforderungen. Eine Veränderung der neuronalen Grundlagen durch musikalisches Training ließ sich auch für die Verarbeitung musikalischer Syntax nachweisen – Musiker zeigten eine größere ERAN-Amplitude als Nichtmusiker (Koelsch, Schmidt, & Kansok, 2002). Die Experimente III und IV untersuchen die Verarbeitung musikalischer und sprachlicher Syntax bei neun- und elfjährigen Kindern, die entweder ein Instrument lernten (bzw. im Chor sangen) oder die dies nicht taten. Es wurde erwartet, dass die Kinder mit musikalischem Training – ähnlich wie erwachsene Musiker – eine vergrößerte ERAN-Amplitude zeigen. Außerdem wurde erwartet, dass diese Kinder auf Grund der Überlappung in den an der Verarbeitung musikalischer und sprachlicher Syntax beteiligter Hirnregionen auch eine verbesserte Verarbeitung sprachlicher Syntax aufweisen würden.

Experimentelle Befunde und Diskussion

Experiment I untersuchte die Verarbeitung musikalischer Syntax bei zweieinhalbjährigen Kindern. Das EEG wurden aufgezeichnet während den Kindern Akkordsequenzen präsentiert wurden, die entweder mit einem regulären Akkord (einer Tonika) oder einem irregulären Akkord endeten. Der irreguläre Akkord war verschieden für zwei Untergruppen von Kindern, die an diesem Experiment teilnahmen. In einer Untergruppe ($N =$ 37) war dieser Akkord eine Subdominantparallele, in der anderen Untergruppe ($N = 32$) war es ein Neapolitanischer Sextakkord. Die zwei Klassen von irregulären Akkorden wurden verwendet, um zu untersuchen, ob sich die musikalische Syntaxverarbeitung für eine eher leichte Verletzung (die Subdominantparallele) oder eine deutlichere Verletzung (den Neapolitanische Sextakkord, der zwei leiterfremde Töne enthält) unterscheidet. Bei Erwachsenen und älteren Kindern konnte nachgewiesen werden (Koelsch et al., 2003; Koelsch, Gunter, Friederici, & Schröger, 2000), dass die irregulären Akkorde eine ERAN (um 200 ms; schnelle und automatische Prozesse musik-syntaktischer Strukturbildung widerspiegelnd) und eine N5 (um 500 ms; verbunden mit Prozessen harmonischer Integration) hervorrufen. Das Hauptergebnis dieses Experiment war, dass eine ERAN bereits bei zweieinhalbjährigen Kindern nachgewiesen werden konnte. Die Ergebnisse für die beiden verwendeten Klassen von Akkordsequenzen (d.h. für die Subdominantparallele *vs.* den Neapolitanischen Sextakkord als irregulärem Akkord) waren vergleichbar. Die relativ kleine ERAN-Amplitude und das Fehlen der N5 deuten jedoch darauf hin, dass die Prozesse musikalischer Syntaxverarbeitung sich noch in der Entwicklung befinden. Die Studie weist jedoch als erste Studie nach, dass diese Prozesse zu einem weitaus früheren Zeitpunkt, als bisher angenommen wurde, etabliert sind.

In ***Experiment II*** wurde die Verarbeitung musikalischer Syntax bei fünfjährigen Kindern mit einer normalen (N = 20) und einer verzögerten Sprachentwicklung (SLI; N = 15) verglichen. Wie in Experiment I wurden EEG-Messungen durchgeführt, während die Kinder auf Akkordsequenzen hörten, die entweder regulär (mit einer Tonika) oder irregulär (mit einer Subdominantparallele) endeten. Eine Reihe zusätzlicher Testverfahren (z.B. der Sprachentwicklungstest SETK 3-5) wurde durchgeführt, um Charakteristika der Kinder in beiden Gruppen genauer beschreiben zu können. Das wichtigste Ergebnis dieses Experiments war, dass sich bei Kindern mit einer normalen Sprachentwicklung die ERAN und die N5 nachweisen ließen, während sie in der Gruppe der sprachentwicklungsgestörten Kinder nicht beobachtet werden konnten. Dies deutet darauf hin, dass die sprachentwicklungsgestörten Kinder bei der Verarbeitung musikalischer Syntax ähnliche Defizite aufweisen, wie bei der Verarbeitung sprachlicher Syntax. Um sicher zu stellen, dass die nachgewiesenen Unterschiede nicht auf Defizite bei der frühen auditorischen Verarbeitung zurückgeführt werden können, wurde die EKP-Antwort auf den Beginn der Akkordsequenzen bei Kindern der beiden Gruppen miteinander verglichen. Da sich keine Unterschiede nachweisen ließen, kann geschlussfolgert werden, dass die Unterschiede in der Verarbeitung musikalischer Syntax wahrscheinlich durch Defizite bei Prozessen bedingt sind, die sowohl für die Verarbeitung von sprachlicher als auch musikalischer Syntax entscheidend sind. Ein weiteres Argument für diese Annahme ist, dass sich signifikante Korrelationen der ERAN-Amplitude mit allen Untertests des SETK nachweisen ließen, da die meisten Untertests die Verarbeitung sprachlicher Syntax messen und die ERAN reflektiert die Verarbeitung musikalischer Syntax. Zusätzlich ließen sich mit der ERAN-Amplitude als Prädiktorvariable in einer Diskriminanzanalyse 77,1% der Kinder korrekt ihrer Gruppe zuordnen.

Experiment III verglich die Verarbeitung musikalischer und linguistischer Syntax bei neunjährigen Kindern, die entweder musikalisch trainiert waren (N = 19) oder nicht (N = 13). Bei diesen Kindern wurden EKPs aufgezeichnet während die Verarbeitung musikalischer oder sprachlicher Syntax untersucht wurde. Im Musikexperiment wurden die gleichen Akkordsequenzen verwendet wie in Experiment II. Im Sprachexperiment wurde die Verarbeitung syntaktisch korrekter und syntaktisch inkorrekter Passiv-Sätze miteinander verglichen, die bereits in einer großen Zahl früherer Studien mit Erwachsenen (z.B. Friederici, Pfeifer, & Hahne, 1993) und Kindern (z.B. Hahne, Eckstein, & Friederici, 2004) verwendet wurden.

Das wichtigste Ergebnis dieses Experiments war, dass die ERAN-Amplitude – die eine Verarbeitung musikalischer Syntaxverletzungen reflektiert – bei Kindern mit musikalischem Training (im Vergleich zu Kindern ohne musikalisches Training) vergrößert war. Dies steht im Einklang mit Ergebnissen einer früheren Studie (Koelsch, Schmidt et al., 2002), die ebenfalls eine vergrößerte ERAN-Amplitude bei erwachsenen Musikern nachweisen konnte. Trotzdem ist dieses Ergebnis bemerkenswert, weil es zeigt, dass eine vergleichbar kurze Zeit musikalischen Trainings (im Mittel 39 Monate) ausreicht, um eine plastische Veränderung der neuronalen Prozesse hervorzurufen, die musikalischer Syntaxverarbeitung zu Grunde liegen. Die Amplitude der N5 wurde durch musikalisches Training nicht moduliert. Eine solche Veränderung wurde nicht erwartet und ist im Einklang mit früheren Befunden. Im Sprachexperiment war die untersuchte EKP-Komponente eine späte Negativierung. Während bei älteren Kindern und Erwachsenen eine ELAN als EKP-Antwort auf eine Verletzung der sprachlichen Syntax in Passivsätzen nachgewiesen werden konnte, findet sich bei jüngeren Kindern (bis zum ca. 13. Lebensjahr) diese späte Negativierung, die im Vergleich zur ELAN eine größere Latenz aufweist und die länger anhält. Diese Komponente unterschied sich nicht zwischen den Gruppen. Daraus lässt sich ableiten, dass die relativ kurze Zeitdauer des musikalischen Trainings nicht ausreicht, um einen Transfer-Effekt und eine Veränderung der neuronalen Korrelate der Verarbeitung sprachlicher Syntax hervorzurufen. Im Experiment wurde statistisch kontrolliert, ob es einen Einfluss des Sozialstatus und der Bildung der Eltern und des Intelligenzquotienten der Kinder auf die untersuchten EKP-Komponenten gab. Dies war nicht der Fall, die untersuchten Korrelationen waren nicht signifikant.

Experiment IV untersuchte die Verarbeitung sprachlicher und musikalischer Syntax bei elfjährigen Kindern und verglich Kinder mit (N = 21) und ohne musikalisches Training (N = 20). Das verwendete experimentelle Paradigma entsprach dem in Experiment III verwendeten. Wie in Experiment III wurde eine vergrößerte ERAN-Amplitude bei Kindern mit musikalischem Training gefunden. Darüber hinaus unterschieden sich aber auch die Amplituden der EKP-Komponenten die sprachliche Syntaxverarbeitung widerspiegeln, zwischen den beiden Gruppen: Bei Kindern mit musikalischem Training ließ sich sowohl eine ELAN als auch eine vergrößerte Amplitude der späten Negativierung nachweisen. Dies zeigt, dass musikalisches Training nicht nur zu einer verbesserten Verarbeitung musikalischer Syntax, sondern auch zu einer vergleichbaren Verbesserung der Verarbeitung sprachlicher Syntax führen kann. Besonders bedeutsam ist, dass sich in der Gruppe der Kinder mit musikalischem Training eine ELAN bereits zu einem früheren Zeitpunkt in der Entwicklung nachweisen lässt als bei Kindern ohne musikalisches Training. Das heißt, dass musikalisches Training zu einer früheren Etablierung der schnellen und automatischen Strukturverarbeitungsprozesse, die durch die ELAN reflektiert werden, beiträgt. Diese Ergebnisse verdeutlichen, dass es wahrscheinlich einen hohen Grad an gemeinsam genutzten neuronalen Ressourcen bei der Verarbeitung musikalischer und sprachlicher Syntax gibt. Auch bei diesem Experiment wurden Einflüsse der Bildung und des Sozialstatus der Eltern und die Intelligenz des Kindes kontrolliert, indem die zwei Gruppen in Bezug auf diese Merkmale parallelisiert wurden.

Tabelle 1 gibt einen zusammenfassenden Überblick über die wichtigsten Ergebnisse der vorliegenden Arbeit. Eine ERAN konnte bei Kindern aller Altersgruppen nachgewiesen werden. Sie wurde nicht gefunden bei (fünfjährigen) Kindern mit SLI. Bei (neun- und elfjährigen) Kindern mit musikalischem Training war sie signifikant größer als bei altersgleichen Kindern ohne musikalisches Training. Eine N5 konnte, abgesehen von den zweieinhalbjährigen Kindern bei allen älteren (fünf-, neun- und elfjährigen) Kindern dokumentiert werden. Kinder mit SLI zeigten keine N5. Musikalisches Training beeinflusste die Amplitude der N5 nicht. Die ELAN und eine späte Negativierung (SN) spiegeln Prozesse sprachlicher Syntaxverarbeitung wider. Die SN wird als ein Vorläufer der ELAN in der Zeit, in der sich diese EKP-Komponente entwickelt, angesehen (vgl. Hahne et al., 2004). Daher konnte keine ELAN bei neunjährigen Kindern nachgewiesen werden. Bei elfjährigen Kindern war die Amplitude dieser Komponente nur bei musikalisch trainierten Kindern statistisch signifikant. Die späte Negativierung ließ sich bei neun- und elfjährigen Kindern beobachten. Während ihre Amplitude sich bei neunjährigen Kindern nicht zwischen den Gruppen unterschied, war sie bei elfjährigen Kindern mit musikalischem Training signifikant größer als bei altersgleichen Kindern ohne musikalisches Training. Es liegt nahe, anzunehmen, dass der geringere Umfang des musikalischen Trainings bei neunjährigen Kindern nicht ausreicht, um solche Transfereffekte hervorzurufen, die sich dann aber bei elfjährigen Kindern, auf Grund ihres umfangreicheren musikalischen Trainings beobachten lassen.

Tabelle 1 Übersicht der wichtigsten Ergebnisse der vorliegenden Arbeit: Die Verarbeitung musikalischer Syntax (d.h. der EKP-Komponenten ERAN und N5) wurde bei Kindern aller Altersstufen untersucht, die sprachliche Syntaxverarbeitung (d.h. die EKP-Komponenten ELAN and LSN) bei neun- und elfjährigen Kindern

Experiment		ERAN	N5	ELAN	SN
I	2½ Jahre alte Kinder	N	–		
II	5 Jahre alte Kinder	N	N		
III	9 Jahre alte Kinder	M > N	M = N	–	M = N
IV	11 Jahre alte Kinder	M > N	M = N	M	M > N

Anmerkung: Die Buchstaben in den Zellen der Tabelle zeigen, in welcher der untersuchten Gruppen die untersuchte EKP-Komponente statistisch signifikant war. „N“ bezeichnet die Kinder mit normaler Sprachentwicklung und ohne musikalisches Training, „M“ die Kinder mit musikalischem Training und „S“ die Kinder mit einer spezifischen Sprachentwicklungsstörung. „=“ bedeutet, dass die Amplitudengröße in den beiden untersuchten Gruppen gleich war, „>“ eine signifikant größere Amplitude in einer der beiden Gruppe.

Schlussfolgerungen

Einflüsse von Sprachentwicklungsstörungen (SLI): Ein wichtiges Charakteristikum von Kindern mit SLI sind ihre Defizite bei der Verarbeitung sprachlicher Syntax. In Experiment II konnte gezeigt werden, dass diese Defizite nicht auf die Verarbeitung sprachlicher Syntax beschränkt sind, sondern sich auch für die Verarbeitung musikalischer Syntax nachweisen lassen. Zwei – einander nicht ausschließende – Klassen von theoretischen Annahmen können als mögliche Erklärung für diese Schwierigkeiten herangezogen werden. Die Defizite könnten durch den hohen Grad an gemeinsamen neuronalen Ressourcen bei der Verarbeitung musikalischer und sprachlicher Syntax bedingt sein. Sie könnten auch durch eine Beeinträchtigung eher domänenübergreifender Verarbeitungsprozessen bedingt sein (die sowohl für musikalische als auch sprachliche Syntaxverarbeitung benötigt werden).

Einflüsse von musikalischem Training: Einflüsse musikalischen Trainings konnten sowohl für die Verarbeitung musikalischer als auch sprachlicher Syntaxverarbeitung nachgewiesen werden. Zum einen konnte in beiden untersuchten Altersgruppen (neun- und elfjährige Kinder) eine vergrößerte ERAN-Amplitude beobachtet werden. Dieser Befund deckt sich mit einer großen Zahl von Studien, die neuronale Plastizität in Folge musikalischen Trainings nachweisen konnten. Zum anderen konnte bei elfjährigen Kindern mit musikalischem Training eine ELAN beobachtet werden (die sich bei nicht-musikalisch trainierten Kindern nicht fand). Außerdem hatte die späte Negativierung (eine EKP-Komponente, die Vorläufer der ELAN während deren Entwicklung darstellt) eine signifikant größere Amplitude bei musikalisch trainierten Kindern. Dies zeigt, dass musikalisches Training auch zu einer verbesserten Verarbeitung sprachlicher Syntax und zu einer früheren Etablierung schneller und automatischer syntaktischer Strukturverarbeitungsprozesse beitragen kann. Diese Transfereffekte lassen sich sehr wahrscheinlich auf gemeinsam genutzte neuronale Ressourcen bei der Syntaxverarbeitung in für Musik und Sprache zurückführen.

Entwicklungseinflüsse auf die Verarbeitung musikalischer Syntax:[1] Um den Entwicklungsverlauf musikalischer Syntaxverarbeitung zu beschreiben, wurden die EKP-Daten der Kinder aus den verschiedenen Altersgruppen (zweieinhalb, fünf, neun und elf Jahre) direkt miteinander verglichen. Eine ERAN ließ sich zum ersten Mal bei zweieinhalbjährigen Kindern nachweisen, sie hat aber eine relativ kleine Amplitudengröße. Dies ist sehr wahrscheinlich dadurch bedingt, dass sich die zu Grunde liegenden Prozesse noch entwickeln. Bei fünfjährigen Kindern (mit normaler Sprachentwicklung) hatte die E-RAN eine größere Amplitude. Die Amplitude verringerte sich im Entwicklungsverlauf, jedoch ist der Unterschied zwischen den Altersgruppen nicht statistisch signifikant. Auch die Latenz der ERAN verringerte sich im Altersverlauf. Die N5 konnte bei zweieinhalbjährigen Kindern nicht beobachtet werden. Sie lässt sich jedoch ein den fünfjährigen Kindern und den älteren Kindern nachweisen. Die Amplitude verringert sich (ähnlich der ERAN-Amplitude) im Altersverlauf. Diese Daten zeigen, dass die neuronalen Korrelate musikalischer Syntaxverarbeitung eine hohe Kontinuität aufweisen. Friederici (2005) zeigte eine ähnlich Kontinuität für die EKP-Komponenten, die Prozesse der Sprachverarbeitung widerspiegeln.

Gegenwärtig gibt es über den Zeitpunkt, zum dem musik-syntaktische Regularitäten erworben werden, kontroverse Meinungen. Die meisten theoretischen Annahmen gehen davon aus, dass solches Wissen erst in der relativ späten Kindheit (mit ca. 6 bis 7 Jahren) erworben wurde (vgl. Trehub, 2003b). Experiment I zeigt, dass die neuronalen Korrelate der Verarbeitung musikalischer Syntax bereits bei zweieinhalbjährigen Kindern beobachtbar sind. Es sind die ersten Daten, die das Vorhandensein dieser Prozesse bei so jungen Kindern belegen. Dies zeigt, dass der Erwerb von musik-syntaktischem Wissen und Verarbeitungsprozessen viel früher statt findet, als bisher angenommen wurde.

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[1] Der Entwicklungsverlauf der sprachlichen Syntaxverarbeitung (für die verwendeten Passivsätze) sind, zum einen, bereits Gegenstand einer Studie gewesen (Hahne et al., 2004). Zum anderen hätten die zwei Messzeitpunkte, zu denen in der vorliegenden Arbeit die sprachliche Syntaxverarbeitung untersucht, wurde nur eine relativ oberflächliche Beschreibung des Entwicklungsverlaufs erlaubt. Daher wurde auf eine solche Analyse verzichtet.

1 Introduction

Language and music are important communication systems of human species and very closely connected cognitive domains. Both consist of hierarchically structured sequences that are organized of perceptually discrete elements. The set of principles governing the combination of these structural elements into sequences is denoted as syntax. The neural correlates of the processing of musical and linguistic syntax, their development and the influence of musical training and specific language impairment (SLI) are the main focus of the present work.

The introduction contains six chapters that introduce the main topics that were investigated in the present work. The chapter "Music Perception" provides an overview of processing steps during music perception, their development, and their neural correlates. It puts specific emphasis on the processing of musical syntax (e.g., by describing theoretical and computational models that account for particular aspects of it). The chapter on "Musical Training" will introduce how such training influences the neural correlates of music processing. It summarizes these influences on skills, brain anatomy and neurophysiological-functional markers of cognitive processes. Furthermore, the chapter describes which transfer effects to other cognitive domains were found in earlier studies. The chapter "Music and language" presents an overview of the relations of these two cognitive domains. Some researchers proposed that music and language evolved from a common ancestor. Of specific importance for the present work is that the neural correlates of syntactic processing in music and language were demonstrated to strongly overlap. Moreover, further commonalities between music and language were found – e.g., comparable mechanisms in the acquisition of music and language, and a strong influence of prosody (i.e., the musical aspects of speech) on the acquisition of syntactic regularities in language.

The chapter "Language perception" outlines how language is acquired and how it is processed. A specific emphasis in this chapter is put on linguistic syntax, e.g., the mechanisms of its acquisition, and the neural correlates of its processing. Children with specific language impairment are considered to have deficiencies especially in their processing of linguistic syntax. A thorough discussion of the characteristics of this impairment, and possible risk factors contributing to its occurrence will be given in the chapter "Specific Language Impairment". Finally, the chapter "Electroencephalography and Event-related brain potentials" will provide a brief introduction regarding the primary method of this work.

Four experiments are contained in the present work. These were set up to investigate the processing of musical and linguistic syntax in children of different age groups. Currently, knowledge regarding the development of music-syntactic processing is relatively sparse. Most of the evidence that considers this issue comes from behavioural studies, and only few studies investigated these issues using neuropsychological methods (Jentschke, Koelsch, & Friederici, 2005 [with EEG]; Koelsch, Fritz, Schulze, Alsop, & Schlaug, 2005 [with fMRI]; Koelsch et al., 2003 [with EEG]). The youngest group of children in which the neural correlates of music-syntactic processing were demonstrated are 5-year-olds. It is not known whether these processes are already established in younger children. Thus, one objective of the current thesis was to extend the age range for which these processes were investigated to 2½ year old children (Experiment I). Another objective was to describe in more detail the development of the neural correlates of music-syntactic processing (in 2½, 5, 9, and 11 year old children – Experiments I to IV).

A further topic of investigation was the influence of language impairment on music-syntactic processing. The deficiencies in processing of linguistic syntax in these children and the strong relation of the neural correlates of music- and linguistic-syntactic processing led to the expectation that they may have comparably difficulties in their music-syntactic processing. Experiment II investigated these issues, comparing the processing of musical syntax in children that either had typical language development or specific language impairment.

A third topic was to evaluate the influence of musical training on the processing of musical and linguistic syntax. Musical training was observed to influence the neural correlates of music syntactic processing (Koelsch, Fritz et al., 2005; Koelsch, Schmidt et al., 2002) and to enlarge the amount of neural resources involved in that task. The overlap in the neural resources involved in the processing of musical and linguistic syntax led to the hypothesis that the processing of syntax in these two cognitive domains might be interrelated. Furthermore, the processing of musical and linguistic syntax was demonstrated to interact (Koelsch, Gunter, Wittfoth, & Sammler, 2005). Thus, it was expected that musical training might lead to an enlarged neural response to violations of both musical and linguistic syntax. Experiment III and IV investigated the processing of musical and linguistic syntax using a within-subject comparison. In Experiment III (9-year old children) and in Experiment IV (11-year old children) two groups of participants that either had or had not musical training were compared. It should be determined how children of these age groups process musical and linguistic syntax and if these processes were influenced by musical training.

2 Music Perception

Music is one of the oldest, most basic and ubiquitous socio-cognitive domains of the human species: in every human culture, people have played and enjoyed music (Huron, 2001). Only humans cooperatively play instruments or sing together in groups. Music perception and, even more, music production is considered as one of the most demanding tasks for the human brain engaging virtually all cognitive processes (Koelsch & Siebel, 2005). This richness makes music an ideal tool to investigate the functioning of the human brain (Münte et al., 2002). Moreover, musical communication in early childhood (such as maternal music) might play a major role in the emotional, cognitive and social development of children (Trehub, 2003b). Music is also a very personal experience, influenced by a combination of genetic and environmental factors, such as training, previous exposure, personal preference, and emotional involvement (Schlaug, 2001).

In contrast to the general acceptance of the evolutionary value of language, the evolutionary significance of music is a matter of debate. Since it has no readily apparent functional consequence, it has been grouped together with art and other cultural activities as by-products of the evolution of the human brain ("a cultural cheesecake" according to Pinker, 1997, p. 528). Recently, there is an increasing interest in the origins of music (Wallin, Merker, & Brown, 2000). It led to various proposals concerning a possible evolutionary origin and function of music (e.g., Huron, 2001). Apart from music's powerful capacity of conveying emotion and regulating mood (Thayer, 1996), there are three major theoretical approaches to account for the evolutionary function of music: [1] ***Mate selection***: Music making may have arisen as a courtship behaviour to attract female mates and to dispel male rivals (Darwin, 1871/1989; Slater, 2000). In humans, the ability to sing or to play an instrument might imply that the individual is in good health. It might serve as indicator of intact and rich brain functioning and the ability to acquire elaborate behaviour. In humans, musical ability is usually related with sensibility, sophistication, and other social values and, thus, highly esteemed. [2] ***Social cohesion and coordination***: Music might create or maintain social cohesion (Hagen & Bryant, 2003), because it possesses two features that affect contagion and communion: Pitch intervals allow harmonious blending, and regularity favours motor synchrony. These features promote simultaneity while allowing some autonomy between voices and bodies (S. Brown, 2000). Music can contribute to group coordination and can increase the effectiveness of collective actions (Roederer, 1984). It may reduce interpersonal conflict compared with speech that may lead to arguments and possible fights (Freeman, 1995; Fukui & Yamashita, 2003) and may have a function as a harmless pastime. This, in turn, may contribute to group solidarity and promote altruism. Music also might have provided a good channel of communication over long periods of time: It is incorporated in everyday activities in pre-literate societies and may enhance the memory capacity in societies with no written records. [3] ***Skill development***: Singing and other music-making activities may supply opportunities for refining perceptual and motor skills (e.g., listening to music might provide a sort of "exercise" for hearing).

This chapter contains three main sections, the first describes the development of music perception, the second focuses on music-syntactic processing (and introduces theoretical models that account for it as well as empirical evidence on this issue), and the third introduces some neural correlates of music perception. As music-syntactic processing is central for the present work, specific emphasis will be put on these processes and their prerequisites.

2.1 Development of music perception

Effortlessly learning to talk and to sing while being exposed to language and music is an example of developmental plasticity. Even during (the last trimester of) pregnancy, sounds in the environment can stimulate the inner ear. These sounds penetrate the tissue and fluid surrounding the head of the foetus and, therefore, rhythmic patterns of music are likely to be detected (D. K. James, Spencer, & Stepsis, 2002). Therefore, newborns show a preference for the voice of their mother and to musical pieces that they have listened to during late pregnancy, indicating a capacity of implicit learning during foetal life (Gerhardt & Abrams, 2000).

Responsiveness to infant-directed singing appears inborn. Masataka (1999) reported this preference in 2-day-old infants who, having been born to congenitally deaf parents, had no previous exposure to singing. Specific to infant-directed singing are a particular timbre, perturbations in fundamental frequency (jitter), and intensity (shimmer) (Trainor, Clark, Huntley, & Adams, 1997; Trehub, Hill, & Kamenetsky, 1997; Trehub, Schellenberg, & Hill, 1997). These parameters may lead to a certain emotional and affective expressiveness. Singing has an arousal-modulating effect and may lead to changes in cortisol level (Shenfield, Trehub, & Nakata, 2003). It is likely that singing promotes reciprocal emotional ties and reduces the psychological distance between singer and listener (Lomax, 1968; Trehub, Hill et al., 1997). For example, lullabies are found in cultures across the world and appear to represent a true music universal. Simplicity (e.g., simple contour, simple tonal schemes) and repetitiveness appear as key features of lullabies together with a generally slower tempo, a higher median pitch, and more descending intervals than in other melodies (Dowling, 1988; Unyk, Trehub, Trainor, & Schellenberg, 1992). Infants showed an enhanced attention to a woman singing to her infant relative to a comparable performance with no infant audience (Trainor, 1996). Men's singing does not generate this different responsiveness (unless the voice pitch is artificially heightened; O'Neill, Trainor, & Trehub, 2001). Infant-directed speaking also has a musical quality but infants demonstrate more sustained attentiveness and engagement during maternal singing than maternal speaking (Nakata & Trehub, 2004; Trehub, 2003c).

Currently, there is no widely accepted and comprehensive model how music perception develops. Initially, infants' resolution of frequency, timing, and timbre is finer than that required for musical purposes (see Trehub, 2001 for a review). Even though, there is a growing body of evidence, confirming infants' disposition to structure or organize the elements of auditory patterns in a adult-like way (Trehub, 1987, 1990, 1993; Trehub & Trainor, 1990).

There are some features that are shared by most (if not all) musical cultures suggesting innately specified auditory mechanisms. One of these features is that most scales consist of a discrete set of five to seven pitches arranged within the octave range (presumably resulting from constraints on short-term memory and categorization, cf. G. A. Miller, 1956). Moreover, most scales are build of unequal intervals leading to a unique set of interval relations that might be encoded more easily (Balzano, 1980, 1982; Shepard, 1982; Trehub, Schellenberg, & Kamenetsky, 1999). Within the scale, intervals with simple frequency relations – such as octave and fifth – are structurally more important: [1] Infants demonstrate octave equivalence (Demany & Armand, 1984), [2] they prefer consonance over dissonance and categorize intervals on the basis of their consonance (Schellenberg & Trainor, 1996; Schellenberg & Trehub, 1996; Trainor & Heinmiller, 1998; Trainor, Tsang, & Cheung, 2002; Zentner & Kagan, 1998), and [3] they more easily detect changes in sequential intervals from simple (consonant intervals) to complex frequency ratios (dissonant intervals) than *vice versa* (Trainor, 1997).

Infants show a strong preference to rely merely on the relationships between pitches than on their absolute values.[2] Use of reference pulses and the induction of rhythmic patterns by the asymmetrical subdivision of time pulses are also evident cross-culturally. The preference for relational processing is assumed to be restricted to human listeners (McDermott & Hauser, 2005). Relational processing operates for pitch structure, spectral structure, and temporal structure (Hulse, Takeuchi, & Braaten, 1992) and

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[2] There is some debate about how far infants make use of absolute pitch information (Saffran, 2003). However, contrasting evidence by Trehub (2003a), and Trehub, Bull and Thorpe (1984) indicated that the use of absolute pitch information might merely rely on short-term memory. Plantinga and Trainor (2003, 2005) also demonstrated a consistent priority for relative pitch processing. Recently, Saffran, Reeck, Niebuhr, and Wilson (2005) found that infants used relative pitch cues in task dependent manner, i.e., if such cues were more easily accessible or if absolute pitch cues were uninformative.

results in [1] the priority of contour over interval processing (see “contour processing” below), and [2] the priority of temporal patterning over specific timing cues (see “processing of metre and rhythm” below), both following Gestalt principles for grouping. These Gestalt principles are important for perceiving and remembering spoken as well as musical patterns (Trehub, 1990; Trehub, Trainor, & Unyk, 1993). Children, thus, focus on relational aspects of melodies, and synthesize global representations from local details (i.e., they encode the melodic contour instead of exact pitches and intervals and extract the temporal structure of the melody; Trehub, 1987).

Contour processing is an important part of relational processing in music. 5-month old infants were found to easily remember melodic contour and to detect invariance in it (Chang & Trehub, 1977; Trehub et al., 1984). The representation of contour appears to be very robust, i.e., children often generalize it across transpositions (Trehub, Thorpe, & Morrongiello, 1987) and are unable to detect changes when the contour is preserved (Trehub et al., 1984). Infants group tones by their similarity in frequency, waveform or intensity (Thorpe & Trehub, 1989; Thorpe, Trehub, Morrongiello, & Bull, 1984) and segregate streams by the same mechanisms (Demany, 1982). This happens in a manner that is very comparable to that in adults (cf. Bregman, 1990). Pitch contour seem to be essential for the identity of a melody, but rhythm also contributes to it.

The ***processing of metre and rhythm*** may rely on some innate mechanism to process temporal patterns (Drake & Bertrand, 2001). Infants are sensitive to changes in temporal groupings (Chang & Trehub, 1977; Trehub & Thorpe, 1989), meter (Hannon & Johnson, 2005), tempo (Baruch & Drake, 1997), duration (Thorpe & Trehub, 1989), and timbre (Trehub, Endman, & Thorpe, 1990). Demany, McKenzie, and Vurpillot (1977) demonstrated that even 2-month old infants habituate to a specific rhythmic structure. Children seem to encode rhythmic patterns on the basis of relative duration. This strategy becomes more salient with age or experience (Morrongiello, 1984). Meter must be inferred from periodic regularities in the music. There seems to be a bias to stretch or shorten complex durations to fit simpler ratios (Essens, 1986; Povel, 1981). This may contribute to the inference of metrical structure and varies as a function of listening experience (Hannon & Trehub, 2005). Since “important” events occur more frequently at strong metrical positions in Western classical music (Palmer & Krumhansl, 1990), this structure may guide the listeners attention dynamically, enhancing the anticipation of future events (Jones & Boltz, 1989). Conversely, the distribution of events and accents helps to converge on similar metrical interpretations (Brochard, Abecasis, Potter, Ragot, & Drake, 2003). The perception of metre is influenced by implicit knowledge whose acquisition may require long-term exposure to culturally typical durations, duration ratios, and metrical structures (Drake & Ben El Heni, 2003). Meter enables to synchronize movements. *Vice versa*, movements influence the auditory encoding of rhythm (Phillips-Silver & Trainor, 2005), illustrating the strong multisensory connection between body movement and auditory rhythm processing.

The ***segmentation of musical phrases*** involves the use of acoustic and structural cues. Acoustic cues as changes in pitch height (mostly falling) and tone duration (mostly increasing) are critical markers for boundaries. Even 4½-month old infants prefer pauses at phrase boundaries (Jusczyk & Krumhansl, 1993). Later, at 8 months, rhythmical cues were also found to contribute to phrase segmentation, i.e., increasing the duration of a element within a isosynchronous sequence results in segmentation, whereas an increase in intensity did not (in both, adults and children, Trainor & Adams, 2000). Structural cues, such as syntactic regularities, may contribute to the segmentation of phrases (e.g., a dominant-tonic progression usually marks the end of a musical phrase). *Vice versa*, the acquisition of these regularities may presuppose basic grouping mechanisms for parsing a sequence of melody notes.

A critical feature of music – central to the scope of this work – is that musical events fulfil different ***structural functions*** beyond the immediate sounding qualities. How these structural functions are patterned through time defines more abstract and complex dynamic organization. This again, may give rise to experiencing particular emotional qualities. Saffran, Loman, and Robertson (2000) demonstrated that 7-month old infants retained music with which they were familiarized over 2 weeks (but only if the passage appeared in the musical context in which it was learned). This suggests that infants are capable of forming sophisticated representations of music and that they learn and remember structured information. Such structural regularities may be acquired by statistical learning mechanisms (Tillmann, Bharucha, & Bigand, 2000). Dowling (1988) proposed that the repetitiveness and the simplicity of lullabies may help children to acquire musical structure. Likewise, musical training may accelerate this sensitivity to musical relations (Dowling, 1999).

Prerequisite to the acquisition of these regularities is a reference system. ***Musical scales*** have a specific interval structure (often consisting of unequal interval steps) that is typical for the music of the culture in which children grow up. This interval structure must be acquired by children which takes place within the first year of life (Lynch & Eilers, 1992). As for language-specific phonemic contrasts (Cheour et al., 1998), infants are initially sensitive to musical scales from different cultures (Lynch, Eilers, Oller, Urbano, & Wilson, 1991). Likewise, Trehub et al. (1999) demonstrated that infants are able to detect perturbations to both diatonic and unfamiliar unequal interval scales whereas adults only detected changes to melodies from a diatonic scale. Infants are able to discriminate changes smaller than a semitone before they internalize the scale structure of their culture (Olsho, 1984). In Western culture, infants, as a next step, acquire the semitone structure, i.e., they show no preference yet for semitone changes that are in accordance with diatonic scale structure. Before they are 4 to 6 years old, they internalize the diatonic scale structure (Trehub, 1987; Trehub, Cohen, Thorpe, & Morrongiello, 1986).

Tonality induction can be regarded as a musical manifestation of the general psychological principle of a cognitive reference point within a category (Rosch, 1975). It enables children (and adults) to encode long sequences of musical information. The induction of tonality requires a variety of perceptual-cognitive abilities: to resolve frequency, to infer the pitch of complex tones, to accumulate chroma categories, to remember auditory events, and to encode harmonic relations between tones. Most of these prerequisites are present during the first year of life (see above). Initially, infants are presumed to process music independently of any particular musical system such as Western tonality (Lynch, Eilers, Oller, & Urbano, 1990; Trehub & Trainor, 1993). As a part of the acquisition of culture-specific parameters of the own musical culture, infants must learn the tonal structure and tonal hierarchy (Krumhansl, 1990; Krumhansl & Keil, 1982). A mechanism to acquire the tonal structure of their culture may be their sensitivity to statistical regularities in tone sequences (Saffran, Johnson, Aslin, & Newport, 1999). Memory constraints may also influence the infants ease of acquisition of such regularities (Cohen, 2000).

Western harmony is a particular cultural elaboration of the sense of tonality. It is assumed that increasing exposure to the music of its own culture attenuates the effects of culture-general factors while amplifying the influence of culture-specific factors (Schellenberg & Trehub, 1999). Before children have acquired the musical regularities of their culture they may perform differently from adults on certain tasks. Trainor and Trehub (1992) found that infants (8 months old) did not differ in their performance when detecting a change in a melody that either went outside the key or remained within the key and the implied harmony while adults more readily detected the change that went outside the key. Comparably, Trainor and Trehub (1993) demonstrated that 9 to 11 months old infants performed equally well in detecting changes in a melody that was based on either major or augmented triads whereas adults performed better in the discrimination task with a melody based on the major triad (i.e., the more prototypical for Western melody). Trainor and Trehub (1994) found that implicit knowledge of key membership seems to be established in 5-year-olds and that of implied harmony in 7-year-olds. Comparable results were obtained by Cuddy and Badertscher (1987) and Speer and Meeks (1985). Sloboda (1985) also reported superior memory for melodic sequences conforming to the rules of normal tonal progressions in children at 7 but not at 5 years of age. Trehub, Thorpe, and Trainor (1990) demonstrated that 7- to 10-month old infants detected a change in typical Western melodies (based on the major triad) more readily compared to a change in non-typical melodies. However, musical regularities may be present even in much younger children, specifically if implicit measures – that are more sensitive than explicit measures – are used (Schellenberg, Bigand, Poulin-Charronnat, Garnier, & Stevens, 2005). Trehub, Thorpe and Bull (1990; cited after Jusczyk & Krumhansl, 1993) showed that 8½-month old infants were more likely to find one-semitone changes in a melody based on the dominant-tonic progression than in other melodies. This indicates a very early sensitivity to phrase structure, since the dominant-tonic progression is a prominent marker for the end of a musical phrase. This sensitivity may help to acquire tonal structure.

The acquisition of tonal and harmonic regularities might also be influenced by coincidence of music-structurally important events with metrical accents (Schmuckler & Boltz, 1994) and acoustical characteristics. The hierarchy of prominence of tones (or chords) within a key is – at least to some degree – related to consonance (i.e., simple frequency ratios and roughness). Successive tones that are related by simple frequency ratios were processed more readily (Schellenberg & Trehub, 1994). Acoustical surface characteristics are also evidenced to influence the acquisition of regularities among nonadjacent elements: Creel, Newport, and Aslin (2004) demonstrated that (adult) learners did not acquire highly consistent statistical regularities among nonadjacent tones when these were similar in pitch range and timbre. In contrast, these regularities were acquired when the tones shared an acoustic property (such as pitch range or timbre). However, listeners may also implicitly learn statistical regularities uninfluenced by acoustical surface characteristics (as different timbre; Tillmann & McAdams, 2004). Moreover, infants and adults might weight conflicting acoustic cues differently and experience with Western music may increase culturally biased responding, thereby decreasing effects of acoustical characteristics.

Music is highly effective in regulating and optimizing mood and conveying ***emotion*** in infants, adolescents and adults (Trehub, 2003d). In children tone quality elicits the strongest early reactions: smooth, treble-registered sounds elicit attention and pleasure. Children below 5 years seem not to differentiate emotionally between music in conventional compared to dissonant harmony (Moog, 1976; Schellenberg & Trainor, 1996; Schellenberg & Trehub, 1994). In Western music, the mood of a certain piece is related to its mode (i.e., pieces in major key are usually perceived as more happy than pieces in minor key); this relation has to be acquired by children (Gerardi & Gerken, 1995). Tempo may further influence the perception of the affective value of musical pieces. Dalla Bella, Peretz, Rousseau, and Gosselin (2001) asked children to determine the affective value of a piece: 5-year-olds responses are only affected by a change of tempo, whereas these of 6- to 8-year-olds evaluated tempo and mode. Rhythm may also influence the emotion conveyed by music, but there is relative sparse empirical work regarding this topic (see Hannon & Trehub, 2005; Kamenetsky, Hill, & Trehub, 1997 for initial accounts).

2.2 Processing musical syntax

Music consists of hierarchically structured sequences that are organized of perceptually discrete elements. The set of principles governing the combination of these structural elements into sequences is denoted as syntax. Syntax may be seen as a set of rules that formalizes the listener's mental representations (Simon & Sumner, 1968). In general, the purpose of such rules is to enable listeners to develop expectations for successive events. The rules operate on a small and well-defined set of elements, can be described by a few operators, and can be applied recursively to produce hierarchical organized patterns (Deutsch & Feroe, 1981). The ongoing context and the listener's expectations influence the perception of the actually occurring event (Bharucha & Stoeckig, 1986; Boltz, 1993; Schmuckler, 1989, 1990; Schmuckler & Boltz, 1994). Listeners progressively extract regularities of their musical style. These are used to build up implicit knowledge which in turn guides future listening experiences (Jones, 1982; Krumhansl, 1990; Schmuckler, 1989, 1990; Tillmann et al., 2000). For example, Western tonal-harmonic music essentially relies on the conventionalized use of certain chords and chord progressions. Musical patterns exist simultaneously in multiple dimensions (metric, rhythmic, melodic, and harmonic) and musical events acquire meaning through their relationship to other events to become part of a larger structure.

Theoretical accounts

Krumhansl and Kessler (1982) were among the first to investigate the cognitive representation of harmonic and tonal structure of Western music. They acquired tone profiles that revealed a hierarchy of prominence or stability: [1] Tonic, [2] tones of the major triad (third and fifth scale tone), [3] remaining scale tones, [4] non-diatonic tones (this hierarchy was compatible with theoretical accounts; e.g., Deutsch & Feroe, 1981; Krumhansl, 1979). These 12 major and 12 minor profiles were subjected to a multi-dimensional scaling procedure (MDS) that revealed a four-dimensional spatial map of distances between keys that are located on the surface of a torus (with neighbouring keys related by the cycle of fifths and parallel or relative major/minor relationships; see Figure 2-1).[3]

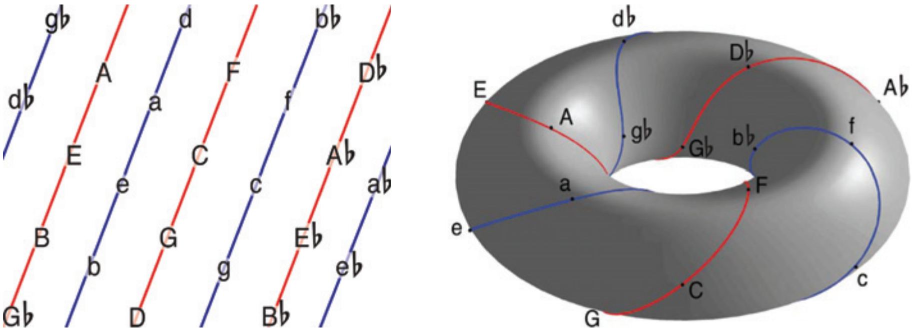

Figure 2-1 Representation of key maps (according to Krumhansl, 1990), either unfolded (left) or on the surface of a torus (right). The matching of the opposite edges of the unfolded map will result in the toroidal representation. Circle of fifths for major (red) and minor keys (blue), each wrapping the torus three times. Every major key is flanked by its relative (e.g., C major – a minor) and its parallel minor (e.g., C major – c minor).

Specific chord types (e.g., major, minor, and diminished) appear at certain positions within a musical scale, indicating the keys in which they appear. The degree of association (i.e., which chord function they have in a particular key) reflects their different functional roles in the hierarchy and supports the simultaneous interpretation of chords in their various harmonic roles. Krumhansl and Kessler (1982) suggested that listeners process the multiple harmonic functions of the chords and integrate this information which gives rise to a sense of key.

Deutsch and Feroe (1981) proposed a hierarchical network involved in the representation of pitch sequences. They assumed that elements are organized as structural units in accordance with Gestalt laws (such as proximity and good continuation) at each level of the hierarchy.[4] The hierarchical representation can be described formally using alphabets (such as “chromatic scale”, “diatonic scale”, and “triad”), elementary operators (“same”, “next”, “predecessor”, etc.), and sequence operators (e.g., “prime” [creating a compound of two sequences], “retrograde”, and “inversion”). Alphabets rely on a small number of highly overlearned structures that act on each other in a hierarchical fashion (e.g., the tonic is contained in the triad which is based on notes from the diatonic scale which is part of the chromatic scale). This allows for the production of melodic segments of enormous variety with a very small set of basic structures. The elementary and

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[3] There are also other geometrical approximations of musical pitch structure, e.g., a conical representation (with the tonic at the apex and the less related tones at different positions in the frustrum) proposed by Krumhansl (1979) or a helical representation (with one dimension representing the position on the cycle of fifths and another dimension for the tone height) proposed by Shepard (1982).

[4] This theory is related to Schenker’s (1956) notion of a mapping from the ornamented musical surface to a hierarchically organized set of reductions.

sequence operators work on these different alphabets. It is assumed that sequence structures and their associated alphabets are retained in parallel at different hierarchical levels. The reference element is first applied to the highest level realizing a sequence of notes at this level. These notes in turn serve as reference elements at the next-lower level. The process is continued until the sequence of notes at the lowest level is realized (for an illustration, see Figure 8 to 11 in Deutsch & Feroe, 1981). For example, chord progressions in Western tonal music are strongly hierarchical and the tonic predominates over other chords in a key and serves as a point of departure as well as goal of a harmonic progression.

Lehrdahl's (2001) tonal pitch space theory is similar to the model of Deutsch and Feroe (1981). In addition, it assumes that the distances between notes or chords of a sequence can be conceptualized as cognitive pitch-space distances. It is also hierarchically organized – a pitch that is relatively stable at a given level also appears at the next larger level. The model assumes five layers: the topmost layer is the tonic pitch, in the second layer the dominant is added, followed by the third scale degree in the third layer (the tones of these three layers form a triad, a chord essential for harmonic tonality). The fourth layer includes the remaining notes of the diatonic scale and the fifth layer consists of the chromatic scale, in which adjacent pitches are a semitone apart (the smallest interval in the tonal system). The taxonomy of a pitch space provides a sense of orientation in melodies: a pitch is heard not just in relation to the tonic but also in relation to the more stable pitches that it falls between in the space. Thus, same pitch may play a different role at different points in the melody. Its role is determined by the context in which it appears. This results in a hierarchical, recursive structure in which each note of the melody is related to more stable notes. The related notes need not be adjacent at the musical surface, but they must be adjacent at some level of abstraction. This kind of organization (in music-theory often called a pitch reduction; Schenker, 1956) results in a tree structure. It plays a role in determining degrees of tension (at a relatively unstable note, attached relatively low in the tree) and relaxation (at relatively stable notes, attached relatively high up in the tree).

Computational modelling

Several musicological and psychological accounts to tonality induction involved the finding of algorithms and of computational models. An early model of key-finding (Longuet-Higgins & Steedman, 1971) examined the musical sample in which diatonic major and minor scales the actual tone was a member. Keys for which this was not the case were eliminated. A tonic-dominant rule was invoked if either all keys are eliminated, or if the end of the sample is reached and more than one candidate key remains.

Krumhansl and Schmuckler (see Krumhansl, 1990) constructed an algorithm that matches the tone duration in the sample to the tonal hierarchies (Krumhansl & Kessler, 1982). Later, Shmulevich and Yli-Harja (2000) proposed an extension to this algorithm directed at smoothing local oscillations in key assignments.

Another influential approach to key-finding was based on modelling with neural networks. Leman's (1995) neural network model takes acoustic information as input which enters a self-organizing network that consists of cognitive schemes for pitch structures including a schema for tone-centre perception that has resulted from long-term learning. However, this model focus' on chords and on tonal centres but does not account for the relationships between tones, chords, and keys.

Bharucha's (1987) connectionist model of key membership (a self-organizing map, SOM; Kohonen, 2006) is organized in three layers (corresponding to tones, chords, and keys). In spite of some simplifications, the model provides a relevant framework for understanding how musical knowledge may be mentally represented and how this knowledge, once activated by a given musical context, may influence the processing of tonal structures. However, the model was based on music theoretic constraints; neither the connections nor their weights resulted from a learning process. In this respect, the model represented the idealized end state of an implicit learning process.

Tillmann, Bharucha, and Bigand (2000) demonstrated how implicit knowledge of tonal structure may be acquired, namely that such knowledge can result from neural self-organization following mere exposure to tone sequences structured according to particular regularities. A SOM, comparable to Bharucha's (1987) connectionist model, was used. It was trained in two steps: First, the layer representing the major and minor chords was learned to detect the tones belonging to these chords. Then, the layer representing the major keys was trained with chord sequences. Four different learning simulations were set up: During the training of the chord layer the input was defined by either a sparse coding (the pitch classes) or a psychoacoustically richer coding scheme (a weighted sum of subharmonics corresponding to the pitch classes, according to Parncutt, 1988). Then, during the training of the key layer, either simple harmonic material (sets of three major and three minor chords for each key presented in random order) or more realistic chord sequences (with the same chords but relying on a probability distribution of these chords in tonal music) were used. The differences in the input coding were essentially for the feed-forward activation while comparable activation patterns were found when the abstracted "knowledge" (i.e., the connection weights) exerted its influence by top-down processes. The model could simulate empirical data from a large number of studies. Taken together, it was possible to model the acquisition of the highly sophisticated regularities of the Western tonal system by an implicit learning process.

Toiviainen and Krumhansl (2003) also used a SOM to represent the developing and changing sense of key with two different models of tonality induction, based either on pitch class distribution or tone-transition distribution (i.e., either the K-K profiles or measures of perceived relatedness of two tones, both in Krumhansl, 1990). Both models equally well predicted listener's key judgements closely matching concurrent probe-tone data ($r \approx 0.90$).[5] This result was somewhat unexpected because it was assumed that listener's judgements might strongly rely on their implicit knowledge of tone transitions for familiar musical styles. The two models, however, fit slightly different aspects of the listener's judgements. Moreover, tension ratings were found related to key distance, i.e., they increased with modulations to relatively distant keys and they decreased for returning to the key of the composition.

Empirical evidence

Apart from the theoretical models described above, a considerable amount of empirical work investigated how tonality and harmony are represented and how they influence the listener's perception. Krumhansl, Bharucha and Castellano (1982) showed that listeners interpreted chords in terms of their harmonic function and perceived these differently, depending on the distance between the key of the actual context and the keys of which the chords are member. Later, Bharucha and Stoeckig (1986, 1987) demonstrated that a prime context activates the listener's knowledge of Western tonal hierarchies, leading the listener to anticipate events belonging to the same key, i.e., judging whether a target was facilitated when in-tune targets shared a parent key with the prime chords. Tillmann, Janata, Birk, and Bharucha (2003) demonstrated that, if a musical sequence establishes a tonal centre, the processing of the tonic chord benefited of priming whereas the processing of other chords was hampered (even chords belonging to the same key, e.g., the subdominant). These observed patterns of costs and benefits can be described as accumulated activation in tonal knowledge structures within a connectionist model.

Bigand and his coworkers showed in some experiments that harmonic priming influenced the perception of other musical and non-musical events. Initially, Bigand, Madurell, Tillmann and Pineau (1999) found that consonance-dissonance-ratings were faster and more accurate when they coincided with harmonically related targets. Bigand, Poulin, Tillmann, Madurell and D'Adamo (2003) tried to disentangle sensory and cognitive priming. They introduced a ''subdominant-in-context'' condition (i.e., the harmonically less related chord occurred in the context and its processing should be facilitated in case of sensory priming) that they compared to a "no-target-in-context" condi-

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[5] A musical context is sounded followed by a certain probe-tone (successively probing all pitches of the chromatic scale) and participants rated how well the probe tone fitted with the musical context.

tion. The processing of the tonic chord was faster in both conditions, demonstrating the predominance of harmonic over sensory priming. The effect of harmonic priming may extend beyond the domain of music. For example, Bigand, Tillmann, Poulin, D'Adamo, and Madurell (2001) found faster phoneme-monitoring for harmonically more related chords and Poulin-Charronnat, Bigand, Madurell, and Peereman (2005) reported that semantic priming was influenced by harmonic priming (i.e., the semantic priming effect was stronger for the harmonically more related chords).

It may be concluded that musical structures are processed in an irrepressible way by automatic processes that occur as fast as those found in linguistic domain. Furthermore, the findings demonstrate the existence of an internal tonal structure with a special role for the tonic as a reference point to which other events are anchored and referred to (cf. Bharucha, 1984; Krumhansl, 1979). Comparable pattern of results were obtained for both musically trained and untrained listeners. It is assumed that these capacities reach such a degree of sophistication that they enable non-musicians to respond to music (in some respect) as musicians. It suggests that the ability to process music according to music-syntactic regularities does not derive from intensive music training (cf. Bigand & Poulin-Charronnat, 2006; Koelsch et al., 2000).

2.3 Neural correlates of music perception

Music processing must generate internal representations of any given input, permitting the stimulus to be segregated from its background, analyzed along several dimensions, recognized, and possibly acted upon. These processes have neural correlates that can be investigated with neurophysiological methods. Music relies on relations between elements, rather than on absolute values of elements. Thus, its representations need to be relatively abstract and perceptually constant. That is, they must be insensitive to superficial variations in stimulus features (loudness, reverberation, spectral filtering, etc.).

Koelsch and Siebel (2005) proposed a model to account for several processing steps in music perception and their neural correlates (see Figure 2-2). A sound reaching the eardrum sets into motion a complex cascade of mechanical, chemical, and neural events in the cochlea, the brain stem, midbrain nuclei, and the cortex that results in a percept.

Feature extraction: In a first cortical processing step, that takes place mainly in the auditory cortex (presumably in primary and adjacent secondary auditory fields), specific information about acoustic features, such as pitch height and chroma, timbre, intensity, and roughness are extracted (e.g., Griffiths, Johnsrude, Dean, & Green, 1999; Tramo, Shah, & Braida, 2002; J. D. Warren, Uppenkamp, Patterson, & Griffiths, 2003). The operations at feature extraction appear to be reflected in ERP components with latencies

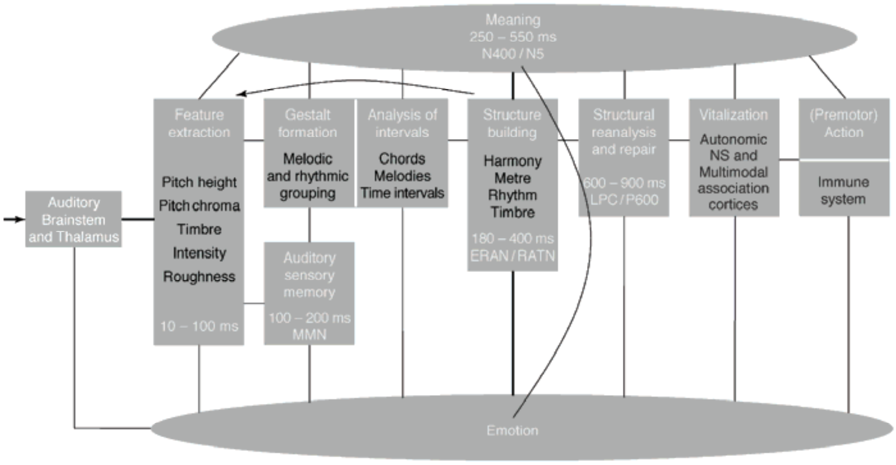

Figure 2-2 Neurocognitive model of music perception (adapted from Koelsch & Siebel, 2005)

of up to 100 ms (mainly the P1 and N1). Pitch information is essential for later processing stages such as tonality induction that in turn influence structure building.

The development of processes underlying feature extraction can be investigated by the evaluation of the ERP responses in this time range. Studies investigating auditory event-related potentials in newborns and infants (P150, N250, P350 and N450; resembling the P1, N1, P2 and N2 components in adults) found these components already identifiable at birth whereas the waveform morphology changes: The latencies of all components shortened with age and the amplitudes of the N250 and the P350 increased up to 9 months and then gradually decreased with age (the latencies of the three latter components further decreased up to 6 years; see Fujioka, Ross, Kakigi, Pantev, & Trainor, 2006; also cf. Jing & Benasich, 2006; Kushnerenko, Ceponiene, Balan, Fellman, Huotilaine et al., 2002). Kushnerenko, Cieponiene, Fellman, Huotilainen, and Winkler (2001) investigated the neural correlates of sound duration, reflected in a change of the N2 amplitude, which was similar in newborns and adults.

Gestalt formation and interval analysis: After auditory features have been extracted, the acoustic information enters the auditory sensory memory, and in a next stage auditory Gestalten are formed (e.g., representations comprising several perceptual elements). This grouping is proposed to rely on Gestalt principles (Deutsch, 1999, Chapter 9). The analysis of intervals might include: processing of the pitch relations between succeeding or simultaneous tones (i.e., the tones of either a melody, or a chord) and processing of temporal intervals. Electrophysiologically, operations of auditory sensory memory are mainly reflected in the mismatch negativity (MMN). It is elicited by the (non-attentive) detection of a deviant stimulus within a series of standard stimuli.

MMN paradigms may be employed to investigate to investigate relations between musical events that differ in their level of abstractness. Firstly, ***simple feature relations*** may be investigated (e.g., tones deviating in frequency). In infants, Kushnerenko, Ceponiene, Balan, Fellman, & Näätänen (2002) demonstrated an MMN in response to the detection of pitch change that develops during the first year of life. Jing and Benasich (2006) found no MMN at 3 months while it became apparent at 4 to 5 months and was robust at 6 months. An MMN may be elicited by violations of an ***abstract regularity*** (such as infrequent tone pairs of descending pitch in a sequence of tone pairs of ascending pitch; see Korzyukov, Winkler, Gumenyuk, & Alho, 2003). Fujioka, Trainor, Ross, Kakigi, and Pantev (2004) investigated the ***processing of melodic contour*** and ***interval structure***. An MMN was evoked by pitch contour and interval deviations demonstrating the automatic processing of abstract changes in both, melody and interval, in the auditory cortex. A recent study by Brattico, Tervaniemi, Näätänen, and Peretz (2006) presented non-musicians with unfamiliar melodies, containing pitch deviants that either went out-of-key (one semitone apart from the preceding pitch) or out-of-tune (a quartertone apart from the preceding pitch). These deviants elicited a MMN indicating a fast and automatic extraction of the relational properties of a musical scale. For contour representation, the right *superior temporal gyrus* (STG) is proposed to be crucial, whereas both the right and left temporal structures appear to be involved when interval information is required (Ayotte, Peretz, Rousseau, Bard, & Bojanowski, 2000; Liegeois-Chauvel, Peretz, Babai, Laguitton, & Chauvel, 1998; Peretz, 1990; Vignolo, 2003). Two types of ***temporal organization*** appear fundamental: rhythmic grouping and metrical regularity. The *cerebellum* and the *basal ganglia* are presumably central for the controlling of motor and perceptual timing (Janata & Grafton, 2003). As for harmony, the metrical organization is (at least to some extent) determined by the abstract knowledge about the Western metrical system (Palmer & Krumhansl, 1990).

Even particular ***aspects of processing polyphonic music*** are processed at this stage: Fujioka, Trainor, Ross, Kakigi, and Pantev (2005) investigated this in a MMN paradigm using four deviations that occurred either in the high or the low voice and either left the key or remained within the key of the melody. A larger MMN was found for deviants in the high voice than in the low voice, suggesting that melodic information of each voice is encoded separately, with the higher voice more salient than the lower. An enlarged MMN was also observed for in-key compared to out-of-key changes which might reflect the size of change (2 vs. 1 semitone for in-key *vs*. out-of-key changes). This indicates that tonality is most presumably processed at subsequent cognitive stages. The brain regions involved in selectively listening to one stream within polyphonic music were investigated by Janata, Tillmann, and Bharucha (2002). They found a similar spatial extent of activation in the STG in global- and selective-listening conditions whereas parietal (*intraparietal sulcus* and *frontal operculum*) and medial frontal structures (*inferior frontal sulcus*, *precentral sulcus* and pre-SMA) were more active when selectively attending to one stream.

Structure building: The analysis of musical structure requires the computation of structural relations, e.g., that of the relation between a chord function and a preceding harmonic context. Similar operations presumably exist for the processing of rhythm and metre. Most of these processes appear to be fairly automatic (Koelsch, 2005). Two processes may be detrimental for the processing of musical syntax: Inducing tonality and building up harmonic relations.

***Tonality induction*:** Pitches are organized along musical scales around a central tone (the tonic) and with a hierarchy of importance of the remaining scale tones (with the fifth and the third scale tone closely related to the tonic). The relations of succeeding pitches do not only define interval size but also evoke a particular scale. Thus, the tonal system mediates perception of musical pitch in an automatic way and without conscious awareness (cf. Tillmann et al., 2000). The brain structures maintaining tonal knowledge are proposed to reside largely outside of temporal lobe auditory structures (Tramo, Bharucha, & Musiek, 1990). Zatorre (2001) suggested a hierarchical view, with right inferior lateral frontal areas that are important for maintenance of tonal information, and dorsolateral frontal areas that are involved in higher-level functions such as monitoring the contents of working memory. Janata et al. (2002) demonstrated that areas in the rostro-medial prefrontal cortex track activation in tonal space and exhibited selectivity for different keys. These brain regions are assumed to underlie the processing of the formal structure that determines relationships within a harmonic or tonal space on which Western tonal music relies.

***Harmonic relations*:** Music unfolds over long periods of time and is highly structured along multiple dimensions. Its processing involves the contribution of different sources of knowledge. Music-syntactic processing requires the processing of long-distance dependencies which may be crucially dependent of the contribution of working memory. The perception of pitch relations in chords seems to operate like the perception of the tonal hierarchy among successive tones. The succession of chords is governed by harmonic principles, whose regularities are assimilated via passive exposure to samples of Western music (Bigand, 2003; Tillmann et al., 2000). A number of studies focused on working memory for tonal information. They converge on the idea that it may rely on interactions between frontal cortical and posterior temporal areas (Griffiths et al., 1999; Zatorre, Evans, & Meyer, 1994).

In a study, employing a harmonic priming paradigm, Tillmann, Janata and Bharucha (2003) found stronger activations for harmonically unrelated targets in the *inferior frontal gyrus* (IFG; *pars opercularis*, extending into *anterior insula*). Specifically, they found an increased number of activated voxels in this region as well as a stronger BOLD response which was more pronounced in the right than in the left hemisphere. It was suggested that these regions are involved in the integration of incoming sounds over time. That is, incoming chords are stored in sensory memory, activate a given key representation and give rise to further events, specifically for these that are harmonically related to the prime context. If the integration demands are more complex, inferior frontal activation increases. Essentially the same results (but restricted to the right hemisphere) were found in a further study by Tillmann et al. (2006) which controlled better for sensory influences and used a more subtle violation of harmonic expectancies.

Krumhansl (2003) investigated the processing of short melodies that were followed by a final tone that was either expected or unexpected. She also found stronger activity in the IFG (*pars opercularis*) and *anterior insula* for unexpected as compared to expected targets. Koelsch, Gunter et al. (2002) presented chord sequences that infrequently contained unexpected musical events (i.e., tones with different timbres, tone clusters, and tonal modulations). Modulations evoked a stronger activation in the IFG (*pars opercularis*) especially in the right hemisphere. Koelsch, Fritz, Schulze, Alsop, and Schlaug (2005) investigated three groups of participants (10-year-olds, adult non-musicians, and adult musicians) with chord sequences ending either on a regular or on an irregular chord. The activation patterns of children were similar to that of adults for the right hemisphere whereas adults showed larger activations in left prefrontal areas, left *supramarginal gyrus*, and left temporal areas. Musical training was correlated with stronger activations in the *frontal operculum* and the anterior portion of the STG. Four of the mentioned studies (Koelsch, Fritz et al., 2005; Koelsch, Gunter et al., 2002; Tillmann, Janata, & Bharucha, 2003; Tillmann et al., 2006) found the activation of *frontal opercular cortex* and the *anterior insula* integrated in an overall neural system that includes frontolateral and orbitofrontal areas, the *anterior insula*, temporal (anterior STG, posterior STG and middle temporal gyrus, MTG) and right parietal areas (in the *supramarginal gyrus*).

Electrophysiologically, a violation of harmonic regularities is mainly reflected in two ERP components: the Early Right Anterior Negativity (ERAN) and the N5. The ERAN is elicited around 150 to 200 ms, most prominent over frontal electrodes, and is taken to reflect fast and automatic processes of syntactic structure building. The N5, peaking around 500 to 600 ms, is also most prominent over frontal electrodes, and was related to processes of harmonic integration (Koelsch et al., 2000). The amplitude of both, ERAN and N5, are influenced by the degree of musical expectancy violation (induced by the preceding harmonic context), and by the probability for deviant acoustic events (Koelsch et al., 2000). The ERAN can be elicited in response to expressive music (Koelsch & Mulder, 2002), its amplitude was found to be enlarged in musicians (Koelsch, Schmidt et al., 2002), and it could be elicited pre-attentively (Koelsch, Schröger, & Gunter, 2002). Despite some similarities with the MMN, the ERAN was shown to be specifically dependent on the degree of harmonic appropriateness and to differ from the MMN with respect to the underlying neural mechanisms (Koelsch et al., 2001). Both components, the ERAN and the N5, were present even in 5-year old children (Koelsch et al., 2003). The neural generators of the ERAN were located in the inferior frontal gyrus (Maess, Koelsch, Gunter, & Friederici, 2001), resembling evidence from (above mentioned) fMRI studies.

Further electrophysiological studies, investigating processing of musical syntax, also found other ERP components. For example, Patel, Gibson, Ratner, Besson, and Holcomb (1998) found both, an early negativity with a right antero-temporal scalp distribution and a late positivity with posterior scalp distribution in response to music-structural incongruities. Another study by Regnault, Bigand, and Besson (2001; see also Janata, 1995) found a larger P300 amplitude in response to a subdominant compared to a tonic chord at the end of a sequence. This study differed from the ERAN studies mentioned above in two important points: firstly, the violation of harmonic expectancies was very subtle, and, secondly, the participants were required to make a judgement on the target chord. Poulin-Charronnat, Bigand and Koelsch (2006) used chord sequences, comparable to those used by Regnault, Bigand, and Besson (2001). They were not able to find an ERAN, and found an N5, but only in participants with musical training.

Sequencing**:** Music can be thought as an interaction between temporal and tonal sequences with a joint accent structure that specifies conjunctions of rhythmic and melodic events (Jones, 1987). This in turn shapes melodic and harmonic expectancies (Boltz, 1993; Jones, Boltz, & Kidd, 1982; Schmuckler & Boltz, 1994) and may influence the emotional connotation (Schellenberg, Krysciak, & Campbell, 2000). Put to a more abstract level, this involves the processing of sequences. Platel et al. (1997) were among the first to suggest a role for left inferior Broca's area (BA 44/6, extending into the *insula*) in the processing of sequential sounds because their rhythm task (detecting irregular note length and intervals) activated this cerebral region. Comparable evidence came from studies on processing temporal structure and predicting future sequential events (Coull, 2004; Fuster, 2001; Rao, Mayer, & Harrington, 2001; Schubotz, Friederici, & von Cramon, 2000), e.g., when participants indicated violations of previously encountered rhythmic patterns and specific event successions (Schubotz & von Cramon, 2001a). Janata and Grafton (2003) run a meta-analysis on brain imaging studies on sequence learning and time-interval production in order to disentangle the influence of temporal (e.g., rhythmical complexity) and ordinal complexity (e.g., complexity of finger movements). They found *anterior cingulate*, *insula*, and *precuneus* influenced by ordinal complexity (with rather less temporal complexity) while the *intraparietal sulcus* was merely responsive to temporal complexity. When both temporal and ordinal complexity was increased, *ventrolateral prefrontal cortex*, *basal ganglia*, and *thalamus* are most sensitive.

In subsequent stages, **structural reanalysis and repair** may be necessary. Electrophysiologically, these processes may be reflected in the ERPs as positive potentials that are maximal around 600–900 ms. Besson and Faïta (1995) found a larger LPC (late positive component) in response to different violations of expectancies (an incongruous note that was either diatonic, non-diatonic, or a change in rhythm). Moreover, they found that both, the tonal structure and the familiarity with the musical pieces, may modulate the amplitude and the latency of the LPC. A comparable ERP component was found by Patel et al. (1998).

Both, **meaning** and **emotion** are assumed to interact with processes of structure building (indicated by the thick lines in the model of Koelsch & Siebel, 2005). The emergence of meaning, based on the processing of musical structure, requires integration of expected and unexpected events into a larger, meaningful musical context (Koelsch, 2005; Koelsch et al., 2004).
Experiencing music is intimately related to its emotional appeal (Juslin & Sloboda, 2001). For example, adult members of a culture mostly agree on the emotional characterization of a musical piece and tend to select the same adjectives to describe it (Hevner, 1936). The outcome of syntactic processing may be important for processing meaning and emotion in music: Mechanisms for representing music are multidimensional and hierarchical. Music is, thus, characterized by points of greater or lesser prominence or distance from one another. The emotion induced by music is strongly affected by the modulation of tension and resolution within a piece. It appears to be a function of cognitive representations of tonality (Krumhansl, 1990; Lerdahl, 2001; L. B. Meyer, 1956; Narmour, 1990). Expression in music is one means to make these structural features more prominent thus heightening the emotional response. Studies investigating the brain correlates of emotion elicited by music (Blood & Zatorre, 2001; Blood, Zatorre, Bermudez, & Evans, 1999; Menon & Levitin, 2005) found activity in some brain regions in the *orbitofrontal cortex*, regarded as interface between cognition and

affect (see, e.g., Nobre, Coull, Frith, & Mesulam, 1999). These brain region were also observed to be activated in studies investigating musical syntax processing (Koelsch, Fritz et al., 2005; Tillmann et al., 2006). Likewise, a recent study by Steinbeis, Koelsch, and Sloboda (2006) demonstrated a strong relation between a violation of harmonic expectancies and subjective ratings of tension and emotionality as well as with psycho-physiological measures.

2.4 Conclusion

It was shown that infants and children effortlessly learn to perceive and to produce the music of their own culture. Starting with some initial constraints they acquire the music's cultural specific regularities. These constraints may be considered as merely domain-general principles that also may be employed for learning in other cognitive domains such as language. Music is structured in manifold ways on several dimensions in which events may coincide: Harmonically important events often correspond to metrically stressed events. This coincidence may contribute to the acquisition of regularities which may be learned even when some structural cues were not noticed. Some shared neural resources underlying the perception of certain aspects of music and language were observed. Specifically, there is strong evidence for similar brain regions underlying the processing of musical and linguistic syntax. Put to a more abstract level, the brain regions may be involved in the processing of sequences that are structured in accordance with specific regularities.

3 Musical Training

Performing a piece of music is regarded as one of the most demanding and complex cognitive tasks and involves a multitude of cognitive processes. It, thus, involves multiple brain systems including the motor, auditory, limbic, and executive systems, and, moreover, requires the integration of information from several cognitive domains (cf. Münte, Nager, Beiss, Schroeder, & Altenmüller, 2003).

This chapter consists of five sections. In the first section, the concept of plasticity – providing a framework to investigate influences of musical training on neural mechanisms – will be introduced. The second section provides an overview on behavioural consequences of musical training. Influences of musical training on neural correlates of music perception are outlined in the third section and the fourth section. Finally, the fifth section reviews studies demonstrating transfer effects to other cognitive domains which are due to musical training.

3.1 Plasticity

The concept of brain plasticity provides a framework to investigate differences between musicians and non-musicians. Human behaviour is enormously adaptive to environmental demands by learning. It implies that the brain is adaptable and changes in response to environmental stimulation and cognitive processes. This can lead to changes in cognition, brain function, and modifications of the human body. Plasticity, defined as tuning of neuronal circuits in response to environmental demands. These adaptations can include strengthening of existing synapses, formation of new synapses, or the additional recruitment of cortical tissue.

Plasticity is a quite old concept. James (1890) presumed the phenomenon of habit formation due to plasticity. Ramón y Cajal (1904) proposed the formation of new neural pathways through ramification and progressive dendritic growth as well as the reinforcement of pre-established organic pathways in order to excel in a demanding task (such as piano playing). Hebb (1949) was the first to experimentally demonstrate that neuronal cortical connections are strengthened and remodelled by our experience. This inspired many scientists to study biochemical, behavioural and morphological effects of experience, learning, activities and specific training (e.g., Bennett, Diamond, Krech, & Rosenzweig, 1964).

Cortical representation areas can be modified by sensory input and training (Buonomano & Merzenich, 1998; Hickmott & Merzenich, 2002; Kaas, 1991; Pascual-Leone, 2001; Robertson & Irvine, 1989). For example, plasticity was demonstrated in the auditory domain after frequency discrimination training (see below). It may also appear as regression of cortical representation when a certain frequency was removed from music (Pantev & Lutkenhoner, 2000; Pantev, Wollbrink, Roberts, Engelien, & Lutkenhoner, 1999). These effects revealed a dynamic form of neural plasticity. It may contribute to skill acquisition and result in structural changes in cortical and sub-cortical networks as the skill becomes more established and automatic (Pantev, 1999; Petersen, van Mier, Fiez, & Raichle, 1998; Raichle et al., 1994).

Musical training involves complex motor, auditory and other cognitive skills. Achieving skilled musical performance relies on extraordinary intense long-term rehearsal. It is based on adjusting ones own movements in response to visual, auditory, and somatosensory feedback which has to be integrated. Musicians are required to translate musical symbols into complex, sequential movements within a strictly defined temporal structure, to memorize long musical phrases, and to identify tones without the use of a reference tone. Due to the multimodal nature and the intensity of musical training, musicians are ideally suited to investigate the various aspects of complex skill acquisition and to study learning and brain plasticity (Münte et al., 2002; Schlaug, 2001). In addition to learning itself, functional differences exhibited by brains of professional musicians may reflect innate abilities, perhaps fostered by early exposure to musical training (Schlaug, 2001).

However, not all training-induced plasticity is beneficial. Some musicians develop a disabling condition, e.g., focal hand dystonia or embouchure dystonia, which is considered as example of maladaptive plasticity.[6]

3.2 Skill improvement due to musical training

Expertise research evidenced that important characteristics of expert's superior performance are acquired through experience and practising (e.g., Ericsson, Krampe, & Tesch-Römer, 1993). Usually, individuals require 10 or more years of preparation to attain international-level performance (Simon & Chase, 1973; Sosniak, 1985). Maximal levels of performance are not attained automatically by mere exposure to a domain, but are a result of deliberate practice. In contrast to skilled activities that can be performed by rote, most types of expertise are mediated by cognitive processes such as monitoring, planning, reasoning, and anticipating.

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[6] For a more thorough discussion regarding: [1] the mechanisms of the development of dystonia, see, e.g., Butterworth et al. (2003); Elbert et al. (1998); Frucht et al. (2001); Hirata, Schulz, Altenmüller, Elbert, and Pantev (2004); McKenzie, Nagarajan, Roberts, Merzenich, and Byl (2003); and Stinear and Byblow (2004); [2] its consequences, see, e.g., Schuele and Lederman (2004); and [3] therapeutical methods to cure this malfunction, see, e.g., Candia, Wienbruch, Elbert, Rockstroh, and Ray, (2003); Zeuner et al., (2002); and Zeuner and Hallett (2003).

Deliberate practise is a highly structured activity with the explicit goal to improve ones own performance. This activity requires effort and is not inherently enjoyable, but individuals might be motivated by its instrumental value in improving performance. It involves careful monitoring and problem solving to attain the desired improvements. Repeated exposure to critical aspects of the task should allow for an incrementally improvement of the own performance in response to feedback (Gruson, 1988; Miklaszewski, 1989).

Ericsson, Krampe, and Tesch-Römer (1993) proposed a framework to account for expert performance. Their central thesis is that expert performance is related to an extended process of skill acquisition, mediated by large, but not excessive daily amounts of deliberate practice (to guarantee for optimal concentration and effectiveness). They observed a highly predictive relationship between the skill level of different groups of musicians (excellent musicians with potential for international careers, good musicians, and music teachers) and the average number of hours of accumulated practise. Moreover, they did show that excellent and good musicians did not differ in terms of their actual amount of practising, but in the accumulated amount of practising over the entire developmental period. However, in the early stages of acquiring musical expertise (i.e., in 7 to 9 year old children), conceptions based on the amount of practice may be inadequate to understand the process of instrumental development. Instead, their (metacognitive) strategies (as, e.g., the amount of self-correction when rehearsing, or beginning with repertoire to be practised before turning to pieces they enjoy to play) were a more powerful predictor than their accumulated practice (McPherson, 2005): Better players had more sophisticated learning strategies (very early in their development), and the general understanding that their performance was tied to the quality of their effort.

Musical skills

In general, experts attain particular skills that circumvent basic limits on working memory capacity and sequential processing. Experts do not only have more, but also better organized knowledge, which enables them to retrieve solution plans as part of their comprehension of problems. This is a result of acquiring – during many years of experience – vast amounts of knowledge and the ability to perform pattern-based retrieval.

Musicians have sophisticated skills for basic aspects of auditory processing, e.g., they effortlessly detected tempo manipulations (Ellis, 1991), changes in the tuning of intervals (Elliot, Platt, & Racine, 1987), or in instrumental timbre (Chartrand & Belin, 2006; Crummer, Walton, Wayman, Hantz, & Frisina, 1994). In addition, employing their knowledge of musical structure, musicians are superior [1] in their processing of consonant *vs.* dissonant target chords following harmonic priming (Bigand et al., 1999), [2] in their short-term-memory performance for notation (Halpern & Bower, 1982; Sloboda, 1976), and [3] in their memory and recognition of musical phrases (Palmer, Blakeslee, & Jusczyk, 1999). However, their memory performance was not superior for randomly rearranged notational information or for phrases of atonal music (Sloboda, Hermelin, & O'Connor, 1985). This highlights the importance of knowledge of a reference system (e.g., Western tonal knowledge) for their improved performance.

Even children's perception of music is fostered by musical training: [1] Children with musical training become more accurate in their judgements about tempo (Madsen, 1979), and are more likely to focus on metric organization (whereas untrained listeners rely stronger on figural groupings; cf. Morrongiello, 1992). [2] Musically trained children outperformed their peers when melody changes had to be recognized: Morrongiello and Roes (1990) demonstrated that musical training enhanced children's perception of melodic features (as pitch and interval information) and the speed at which this information is processed. Moreover, they found a developmental difference with respect to the processing of tonal *vs.* atonal melodies: whereas five-year-olds with musical training showed higher performance than their untrained peers for both kinds of melodies, the performance of nine-year-olds with musical training was further enhanced for tonal (compared to atonal) melodies.

Motor skills

Musical training may lead to physiological adaptations (see, e.g., Ericsson & Charness, 1994) and superior behavioural skills (see, e.g., Ericsson et al., 1993; cf. Hund-Georgiadis & von Cramon, 1999) as well as to changes in the brain correlates of motor processes (see, e.g., Lotze, Scheler, Tan, Braun, & Birbaumer, 2003; Ragert, Schmidt, Altenmüller, & Dinse, 2004; Seitz & Roland, 1992; Slobounov, Chiang, Johnston, & Ray, 2002).

The discussion of motor skills will mainly focus on the processing of sequences which is – in some respect – related to the processing of syntax (Lashley, 1951; for further discussion, see the chapter "Music Perception"). Experts can circumvent basic limits of sequential processing in tasks involving motor performance (e.g., musicians spent considerable time to determining how to hit keys to minimize such constraints on movement) and are, due to their ability to anticipate future events, able to prepare actions in advance (comparable evidence was obtained by Salthouse, 1984, for professional typists). Superior planning abilities, combined with a better anticipation and mastery of temporal constraints, may contribute to the musicians' successful learning of new musical pieces (Drake & Palmer, 2000; Palmer & Drake, 1997). They possess more abstract representation mental plans (in which a particular movement is prepared) which enables them to transfer these plans more easily to other movements (Palmer & Meyer, 2000): At advanced skill levels mental plans for actions become independent of the required movements and can be more easily transferred to other motor acts.

3.3 Brain-anatomical correlates of musical training

Due to the specific challenges that musicians experience, it was expected to find differences specifically for the brain correlates of auditory and motor functions.

Auditory regions: The auditory cortex has a crucial role in the perception of music, speech, and auditory space. A larger grey matter volume of the primary auditory cortex (*Heschl's gyrus*) in musicians, accompanied by larger potentials of their auditory evoked brain activity was demonstrated by Schneider et al. (2002). Both quantities were correlated with musical aptitude.

In secondary auditory regions, differences were found for the *planum temporale* (Schlaug, Jäncke, Huang, Staiger, & Steinmetz, 1995), but mainly for a particular group, namely absolute pitch musicians. Musicians differed from non-musicians in their brain activity when remembering pitch heights (even when they were parallel with regard to their memory performance; Gaab & Schlaug, 2003) and in their processing of complex harmonic sounds and harmony (Rauschecker, 1999; Schmithorst & Holland, 2003). Decreased activation of the auditory cortex (i.e., the *planum temporale*, the *planum polare*, and the *superior temporal sulcus*) was demonstrated by Jäncke et al. (2001) after training in a frequency discrimination task, taken to reflect the facilitated processing of these tones.

Motor regions: Musicians and non-musicians differ greatly in their demands for motor processing. This is associated with a larger extent of motor and somatosensory information to be processed, due to the highly complex movement patterns that are necessary for playing an instrument. These behavioural changes may also manifest themselves in structural changes within the brain. Firstly, this led to changes in brain morphology, e.g., a less pronounced left-right-asymmetry in the motor cortex (Amunts et al., 1997; Bangert & Schlaug, 2006; Jäncke, Schlaug, & Steinmetz, 1997), an enlarged *cerebellum* (Hutchinson, Lee, Gaab, & Schlaug, 2003), or an enlarged *corpus callosum* (Lee, Chen, & Schlaug, 2003; Schlaug, 2001; Schlaug et al., 1995; Schmithorst & Wilke, 2002). The amount of enlargement for both, *cerebellum* and *corpus callosum*, was correlated with the intensity of practice in the musicians. Secondly, these anatomical differences were also reflected in different patterns of brain activity (Hund-Georgiadis & von Cramon, 1999; Jäncke, Shah, & Peters, 2000; Krings et al., 2000; Meister et al., 2005). It is assumed that practising leads to highly efficient movements and to a strong automation that, in turn, leads to a reduction of brain activation.

In addition to the differences in auditory and motor regions further difference may be found in other brain regions. In adults with musical training since early childhood, the brain white matter differed significantly from controls, demonstrating the strong effects of early musical training (Bengtsson et al., 2005; Schlaug et al., 1995).

Gaser and Schlaug (2003) compared the whole brain morphology of musicians, amateur-musicians and non-musicians and observed a significant positive correlation between musician status and increase in grey matter volume in *perirolandic regions* including primary motor and somatosensory areas, premotor areas, and the left *cerebellum*; *Heschl's gyrus*, *anterior superior parietal areas*, in the *inferior temporal gyrus* (bilaterally in all these regions), and the left *inferior frontal gyrus* (IFG). Remarkably, there were no areas with a significant decrease in grey matter volume in musicians. For most of these regions found enlarged, similar results were obtained in earlier studies. However, additional enlargements were also found in *anterior superior parietal areas*, involved in the integration of information from different sensory modalities. These differences might be implicated in the superior spatial-visual processing found in musicians (see below; see also Hetland, 2000), and may contribute to sight-reading which involves the fast integration of multimodal sensory information and motor preparation (Sergent, Zuck, Terriah, & MacDonald, 1992).

Notably, Gaser and Schlaug found differences for the left IFG which contains *Broca's area*: Sluming et al. (2002, 2007) observed an increased grey matter volume of musicians for this brain region. This region is crucially involved in the processing of musical and linguistic syntax. Put to a more abstract level, this region is essential for the processing of ordered sequences. Many skills, required by instrumentalists, are associated with the analysis of sequential sounds and the transformation of musical notation into motor sequences: listening for the accuracy of a musical performance while reading a musical score – a sequence-checking task – activated the left IFG (Parsons, 2001), as did musical syntax processing (Koelsch, Fritz et al., 2005; Maess et al., 2001), processing and organization of sequential sound stimuli (Platel et al., 1997), and sight reading (Sergent et al., 1992).

3.4 Neuronal functional effects of musical training

Koelsch and Siebel (2005) proposed a model of the processing steps involved in music perception (for detailed description and Figure, see chapter "Music perception"). This model is utilized as a framework to structure the evidence of neuronal functional differences between musicians and non-musicians which is reviewed here.

A considerable amount of first, sub-cortical processing of the auditory signal takes place in auditory *brain-stem* and *thalamus*. Differences between musicians and non-musicians can be found even at earliest processing steps, i.e. at the level of signal transduction (Perrot, Micheyl, Khalfa, & Collet, 1999).

Extraction of stimulus features

The first step of cortical processing is related to the extraction of stimulus features. These processes take place within the first 100 ms after stimulus onset. Schneider et al. (2002) demonstrated that the amplitudes of the ***N19-P30-complex*** (reflecting activity in primary auditory cortex) in musicians were twice as large as in non-musicians. Both, the enhanced amplitude as well as an increased grey matter volume in the primary auditory cortex are positively correlated with measures of musical aptitude.

There is also evidence for increased representation areas beyond the primary auditory cortex, reflected in an ***N1*** amplitude that was enlarged by about 25% in musicians (compared to non-musicians) in response to piano tones but not for pure tones (Pantev et al., 1998). Pantev, Engelien, Candia, and Elbert (2001), observed such an enhanced electrophysiological response which was specific for the timbre of the instrument the musicians played. The timbre specificity (in the latter study) and the correlation with the onset of musical training (in the former study) suggested musical training as crucial factor. Regnault, Bigand, and Besson (2001) found the N1 in musicians enhanced to consonant as compared to dissonant chords, whereas non-musicians did not show a different response. Menning, Roberts, and Pantev (2000) demonstrated that the N1 amplitude can be modified by frequency discrimination training. Shahin, Roberts, Pantev, Aziz, and Picton (2007) observed an enlarged DP130 response (assumed to index non-specific sound characteristics) in musicians.

The ***P2*** (reflecting the analysis of spectral and temporal features) was found highly plastic in several studies. For example, Shahin, Roberts, Pantev, Trainor, and Ross (2005) demonstrated an increased P2 amplitude in response to piano tones (varying in the number of their harmonics) in musicians, whereas musicians and non-musicians did not differ in this study in their N1 response. In children with musical training, enhanced amplitudes of the P1, N1, and P2 responses were found; the P2 enhancement was specific for the instrument of training (Shahin, Roberts, & Trainor, 2004). The enlarged ERP responses, found in musically trained children, resembled these of about 3 year older children (without musical training). In accordance, Fujioka, Ross, Kakigi, Pantev, and Trainor (2006) observed an enlarged N250 (comparable to the adult N2b that is related to the of the detection of occasionally occurring target stimuli) in musically trained children and a change in their overall ERP response morphology between 100 and 400 ms after stimulus onset (e.g., an shorter latency of the investigated ERP components). The underlying neural network was associated with sound categorization and auditory attention. Moreover, whereas in musically trained children the change in the morphology of the ERP response was selective for the violin tones, in non-musically trained children changes were found for both, their response to the violin tones as well as to noise stimuli. Shahin, Bosnyak, Trainor, and Roberts (2003) demonstrated that frequency training not only improved behavioural performance in the frequency discrimination task, but also resulted in enlarged amplitudes of the P2, and the N1c responses (which may reflect the recruitment of additional auditory neurons for the processing of spectral pitch).

Gestalt formation and analysis of intervals

During the second processing step the auditory features (extracted in the first step) are combined into auditory Gestalten (as melodic and rhythmic phrases). These processing steps are mainly investigated using oddball-paradigms to study the ***mismatch negativity*** (***MMN***) (Näätänen, 2000; see also Alho, 1995; Csepe, 1995).

Koelsch, Schröger & Tervaniemi (1999) used such a paradigm. They presented sequences of single tones that contained frequency deviants and major triads that were either pure or slightly impure. Even though frequency deviants in the single tone conditions elicited an MMN in both musicians and non-musicians, frequency deviants embedded in the triads evoked an MMN only in violinists. A later study demonstrated that this facilitated processing can be generalized for musicians other than violinists (Tervaniemi, Just, Koelsch, Widmann, & Schröger, 2005). Behaviourally, musicians detected the pitch changes faster and more accurately than non-musicians. Moreover, the study investigated the influence of attention: Musicians and non-musicians either read a self-chosen book or detected sounds with deviant frequency. The ERP responses during attentive listening (N2b and P3 – the latter component reflects the reorientation of attention) had larger amplitudes in musicians whereas during the reading condition the ERP responses (MMN and P3a – the latter component reflects an attention shift to the deviant stimulus) did not differ between musicians and non-musicians. It suggests that musical expertise may exert a stronger influence at attentive levels of processing.

It was also shown that changes in a highly complex auditory patterns – participants learned to discriminate changes in a melodic patterns – can be detected pre-attentively by the human auditory cortex and, further, that this process is facilitated by musical expertise (Tervaniemi, Rytkonen, Schroger, Ilmoniemi, & Naatanen, 2001). Fujioka, Trainor, Ross, Kakigi, and Pantev (2004) compared melody processing using deviants that either violated the expected contour or deviated in interval size. The MMN in both, contour and interval conditions, was significantly larger in musicians compared to non-musicians. Moreover, non-musicians responded with an MMN only in the interval condition (and only in the right hemisphere), while in musicians, an MMN was elicited to both deviants. In a further study, Fujioka, Trainor, Ross, Kakigi, and Pantev (2005) investigated the processing of polyphonic melodies in which the deviant appeared either in the high or the low voice and either went outside or stayed within the key. While the general response patterns to the four deviants was similar, larger MMN amplitudes were elicited in musician compared to non-musicians.

Rüsseler et al. (2001) investigated the response to metrical deviations with tone sequences of different tempo. When tones were omitted or the distance of successive tones was varied, musicians responded with an MMN in all conditions, non-musicians only at larger differences. Another study used a more naturalistic task (a real drum sequence) and found the amplitude of the MMN modulated by musical training (i.e., enlarged in musicians, especially in drummers). Moreover, the MMN in drummers did not decay for subsequent time-shifted beats (Münte et al., 2003). Both studies reflect the larger temporal window of integration in musicians as well as their superior skills to detect metric deviations (especially in drummers).

Another ERP component, the ***negative displacement attention effect*** (***Nd***) is elicited by stimuli not in the focus of attention when two channels with auditory information have to be processed simultaneously (Hillyard, Teder-Salejarvi, & Munte, 1998). Music often consists of several voices to which musicians may have to attend. Thus, professional musicians showed an enlarged Nd indicating superior attentional selectivity to pitch information (cf. Münte et al., 2002). In conductors, characterised by their superior spatial tuning for auditory information and their superiorness in separating adjacent sound sources, this component was larger than in non-musicians and pianists (Münte, Kohlmetz, Nager, & Altenmüller, 2001).

Structure building

In the third processing step the music's structural properties are processed (e.g., chord progressions within a musical phrase). Koelsch, Schmidt, and Kansok (2002) compared musicians' and non-musicians' ERP responses to a harmonic expectancy violation with chord sequences ending either on a harmonically regular or irregular chord. Musicians had an enlarged amplitude size of the ***early right anterior negativity*** (***ERAN***), i.e., a stronger neural response to a violation of musical structure. A similar result was obtained in musically trained (11-year old) children (Jentschke et al., 2005). This reflects their more extensive implicit and explicit knowledge of musical regularities and their stronger expectancies concerning musical structure. Behaviourally, musicians also demonstrated superior performance in detecting harmonically slightly irregular chords (Koelsch, Jentschke, Sammler, & Mietchen, 2007).

Currently, there are only very few studies that investigate differences between musicians and non-musicians at the later processing stages. Moreover, such studies are only briefly mentioned because syntactic processing is the main topic of the present work only these processes and their prerequisites are considered. Some differences between musicians and non-musicians for motor processes will be briefly discussed, because these involve the sequencing of movements which are based on certain regularities. Exceptional musical performance requires an extremely fast control of complex movement patterns which might be reflected in enlarged representations in the motor cortex (Elbert, Pantev, Wienbruch, Rockstroh, & Taub, 1995; Pascual-Leone, 2001). Furthermore, increased sensory-motor integration may be established during musical training, when motor responses are confined in response to auditory feedback (Bangert, Haeusler, & Altenmüller, 2001; Haueisen & Knösche, 2001; Lotze et al., 2003; Schulz, Ross, & Pantev, 2003; Schurmann, Raij, Fujiki, & Hari, 2002).

3.5 Transfer effects to other cognitive domains

It has been assumed that musical training may give rise to transfer effects to other cognitive functions. Whether factors involved in musical training such as bimanual motor coordination, learning to read music, auditory and memory training, attention, concentration, and timing etc. can transfer to non-musical domains such as language, mathematics or spatial reasoning is controversial. Generally, expert performance was demonstrated to remain relatively domain-specific and there is only sparse evidence for a transfer of expert's superior performance to tasks outside their domain of expertise (see, e.g., Ericsson et al., 1993). However, experts acquire certain cognitive skills that may allow them to circumvent the limits of short-term memory and serial processing.

Innate musical talent?

Before discussing transfer effects elicited by musical training the pertinent question of whether the observed differences between musicians and non-musicians are exclusively acquired through training or are at least in part genetically determined should be discussed.

Howe, Davidson, and Sloboda (1998) summarised, there is little or no evidence to assume an innate musical talent. Firstly, musical expertise is better explained in terms of the amount of training (see above): Even crude retrospective measures of practice are predictive of levels of performance, and Ericsson and Faivre (1988) and Simonton (1991) showed that even "talented" individuals do not reach high levels of expertise without substantial amounts of training. Secondly, there is a lack of convincing positive and a substantial amount of negative evidence for innateness of complex cognitive functions: To date, there is no evidence of specific gene systems affecting high-level performance of special skills in a predictive and selective manner. Moreover, genetically influenced traits are expressed in interaction with a particular environment. Thirdly, other measurable factors may contribute to variability in performance: opportunities, preparatory experiences, encouragement, support, motivation, self-confidence, perseverance, and concentration (Howe, 1975, 1980). Moreover, there are less measurable factors as differences in quality of instruction, effectiveness of practice strategy, and degree of enthusiasm. Finally, only weak correlations were found between general intelligence and various specific abilities in many domains (see, e.g., Ceci, 1996; Ceci & Liker, 1986) including music (Shuter-Dyson, 1999). Cognitive ability was shown to merely influence the early performance within a domain whereas final performance is poorly predicted (Ackerman, 1988; Hulin, Henry, & Noon, 1990).

To investigate, whether there are pre-existing neural, cognitive, or motor markers for musical abilities, 5- to 7-year-olds beginning piano or string lessons were compared to children of the same age (Norton et al., 2005). Neither neural, cognitive, motor or musical differences nor any correlation between musical perceptual skills and any brain or visual-spatial measures were found between the groups: Thus, it is highly likely that exceptional abilities are more consistently explained as acquired skill than as innate talent. Moreover, the exceptional performance of musicians is highly predictable by their amount of accumulated deliberate practice and the beginning of musical training (Ericsson et al., 1993).

Influences of musical training on general cognitive functions

Musical training involves long periods of focused attention, daily practice, reading musical notation, memorization of extended musical passages, learning about a variety of musical structures, and mastery of technical (e.g., fine-motor) skills. It is, thus, supposed to have a positive impact on cognition, particularly during childhood years, when brain development is highly plastic and sensitive to environmental influence (P. R. Huttenlocher, 2002).

Winner and Cooper (2000) conducted a meta-analysis on studies investigating the relation between arts education and academic achievement. Even though there seem to be some transfer effect, the effect sizes are relatively small (and, in addition, consistently smaller for experimental than for correlation studies). Correlations, as those found between musical ability and other cognitive and academic abilities, have been observed for many forms of arts training. However, there is no evidence yet that studying arts has a causal effect on academic achievement. It was instead assumed that moderating variables, such as socioeconomic status or familial attitudes to learning, might underlie these associations. Nonetheless, arts training might stimulate motivational and attitudinal changes (as increasing self-confidence and perseverance, developing high standards as well as cooperativeness, and reducing stress). These, in turn, may spill over into academic achievement.

Musical aptitude was correlated with general intelligence in some studies (see, e.g., Hanshumaker, 1980; Lynn, Graham Wilson, & Gault, 1989). However, Helmbold, Rammsayer, and Altenmüller (2005) did not find intelligence differences between musicians and non-musicians. Moreover, they observed a comparable factor structure of intelligence, contradicting the notion of qualitative differences in intelligence between both groups. Schellenberg (2004) examined in a training study, if music lessons enhance IQ. Children were randomly assigned to groups that either received musical training, drama lessons, or no lessons. Increases in full-scale IQ were found in all groups, but these were more pronounced in the musically-trained group. In a further study, Schellenberg (2006) demonstrated a positive association between musical training and IQ (of around 7 IQ point during adolescence and 2 IQ points in early adulthood) as well as with measures of academic achievement. This relation remained significant even when confounding variables (as family income, and parent's education) were statistically controlled. Musical training may be also beneficial for older adults: Bugos, Perlstein, Brophy, and Bedenbaugh (2004) demonstrated improved cognitive abilities (as temporal working memory, planning, concentration, and strategy maintenance) after individualized piano instruction.

Influences of musical training on visual and spatial abilities

Visual-spatial reasoning requires mentally maintaining images, transforming, and combining these images into a meaningful whole – a process which is also used by musicians in the performance of musical tasks (see, e.g., Patel, Peretz, Tramo, & Labreque, 1998). Especially interval analysis of sequential individual notes and pattern recognition of chords are regarded to enhance visual-spatial abilities (Sluming et al., 2002, 2007). There is accumulating evidence for the enhanced performance of musicians in visual-spatial tasks (see, e.g., Barrett & Barker, 1973; Bilhartz, Bruhn, & Olson, 1999; Costa-Giomi, Gilmour, Siddell, & Lefebvre, 2001; Hassler, Birbaumer, & Feil, 1985; Hetland, 2000 [for a review]; Karma, 1979; Nelson & Barresi, 1989).[7] However, the results of

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[7] A (short-termed) improvement in visual-spatial reasoning after hearing an excerpt from a Mozart piano sonata (termed Mozart-effect) was proposed by Rauscher, Shaw, and Ky (1995). However, studies that are well-controlled tended to report non-significant findings (see, e.g., Chabris, 1999; see, e.g., Steele,

such studies should be considered equivocal (due to the variety of tasks and the small number of studies) and the enhanced visual-spatial performance may be transient (see, e.g., Costa-Giomi, 1999).

Influences of musical training on language processing

A strong relation between music and language is proposed by some researchers (see chapter "Music and Language"). Therefore, it seems likely that skills acquired by musical training might transfer to language. This expectation is strengthened by evidence of some shared neural resources for language and music (see the chapter on "Music and Language").

Timbre: Especially for basic processing steps (evaluating the features of the acoustic signal) comparable processes might underlie both, language and music perception. This was observed for timbre discrimination: musicians were found to perform better than the non-musicians for discriminating voice timbre as well as instrumental timbre (Chartrand & Belin, 2006).

Prosody represents the "musical" aspects of language. It is of special importance during language acquisition, paving the children's way to the acquisition of language's syntax and semantics (see the chapter on "Music and Language"). Prosody and music processing rely on similar neural resources in the right *inferior frontal cortex* (cf. Friederici & Alter, 2004; Koelsch, Fritz et al., 2005). This makes it very likely that musical training might influence prosody processing. In accordance, musicians and non-musicians differed in their processing of musical phrase boundaries (Knösche et al., 2005; Neuhaus, Knösche, & Friederici, 2006): While musicians showed a closure positive shift (CPS), reflecting the processing of a phrase boundary, non-musicians exhibited an early negativity and a less pronounced CPS. Musicians are, thus, hypothesized to process musical phrases similar to language in a structured manner while non-musicians may primarily detect the discontinuity in the melodic line.

Likewise, there is evidence that musical training enhances the prosody perception in speech (Schön, Magne, & Besson, 2004; Thompson, Schellenberg, & Husain, 2004). These differences were also reflected electrophysiologically: The positivity in response to a prosodic incongruity (similar to a P600) had shorter onset latencies in musicians than in non-musicians, and musicians showed a bilaterally distributed early negativity whereas this component was left lateralized in the non-musicians (Magne, Schön, &

2000; Steele, Brown, & Stoecker, 1999; Steele, dalla Bella et al., 1999), or have shown that the Mozart effect is an artefact of improved arousal and mood (Thompson, Schellenberg, & Husain, 2001). In addition to the generally weak empirical support for the Mozart effect, there is a lack of positive findings, particularly in children.

Besson, 2006; Schön et al., 2004). Moreno and Besson (2006) investigated in children the influences of relative short-termed (8 weeks) musical training compared to painting lessons on the processing of prosody. No behavioural differences were found. Electrophysiologically, the late positive component in response to a strong prosodic incongruity had a reduced amplitude in musically trained children.

Verbal memory: Musical training enhanced verbal memory performance (Kilgour, Jakobson, & Cuddy, 2000), presumably due to the strengthened auditory temporal-order processing in musicians. Two further studies (Chan, Ho, & Cheung, 1998 [adults]; Ho, Cheung, & Chan, 2003 [children]) demonstrated improvements in verbal, but not in visual (short-term) memory (with retention intervals of 10 to 30 min) whereas no significant correlations of verbal memory scores with age, IQ, and socioeconomic factors were found. Brandler and Rammsayer (2003) also found reliably higher performance in verbal memory in conservatory students.

Reading: It seems reasonable to hypothesize that musical training may help children to acquire reading skills, since both, music and language, involve formal written notation which maps onto a specific sound (requiring phonological or tonal distinction). Butzlaff (2000) ran a meta-analysis of six experimental and 25 correlation studies: A strong and reliable association between music and reading was found in the correlation studies, whereas heterogeneous and non-robust results were observed in the experimental studies. It was, thus, summarized that the relationship of these two variables is neither large, nor robust, nor reliable. In contrast, a recent study on early reading ability found music skills correlated with both phonological awareness and reading development, further showing that music perception skills were a good predictor of reading ability, even when variance due to phonological awareness and other cognitive abilities (mathematics, digit span, and vocabulary) were statistically controlled for (Anvari, Trainor, Woodside, & Levy, 2002).

3.6 Conclusion

Neurophysiological as well as behavioural evidence indicates that musical training may lead to improvements in certain cognitive functions. Such improvements are consistently found especially for music perception and motor performance. They range from very basic, perceptual processes (e.g., an enhanced neural activity when perceiving of instrumental timbre) to more complex, cognitive functions (as the improved processing of musical syntax). Because these differences are mainly found for neural processes that related to music perception and performance, it seems highly likely that differences between musicians and non-musicians are induced by learning and due to neuronal plasticity. Moreover, children who start to learn an instrument were not found to differ with regard to their cognitive, motor, and musical skills from children not commencing musical training (Norton et al., 2005).

In addition to differences that are related to music processing, there is evidence of some transfer to other cognitive domains. For transfer effects to cognitive functions that are rather closely related to music (such as processing of language prosody) the empirical findings are relative consistent whereas for transfer to less closely related domains (e.g., visual-spatial functions or general cognitive skills) the findings are often controversial. A number of studies observed transfer effects from music to language (e.g., increased verbal memory or reading ability).

4 Music and Language

Music and language are acoustic systems with strong similarities. Music and language consist of a limited number of discrete units, chosen out of an indefinite number of possible acoustic elements. Whereas the sound elements themselves are characterized by the same parameters (pitch, duration, articulation, timbre, and loudness), their dynamic ranges and resolutions are certainly different between music and speech. Both unfold in time with phrases as their basic units of structure and function. Phrases are generated through sequential, combinatorial arrangement of their basic elements (e.g., phonemes, notes) and are melodic-rhythmic structures (in music as well as in language). Expressive phrasing is employed to convey emphasis, emotional states, and emotive meaning, which is achieved by modulating basic acoustic properties of the phrases (e.g., pitch, intensity, duration). Music and language involve multiple levels of representation: For music, one usually differentiates temporal (meter and rhythm), melodic (contour, pitch, and interval), and harmonic (chords) aspects. For language there are at least five different levels of processing: the phonetic-phonological level (including both, segmental – phonetic – and suprasegmental – prosodic – levels); the morphosyntactic level (encompassing the combination of phonemes into morphemes and these into words); the syntactic level (governing the relations between words); the lexico-semantic level (accessing the meaning of words and sentences); and the pragmatic level (comprising discourse organization and contextual influences).

Three main topics are described in this chapter: In the first section some evolutionary considerations regarding a common origin of music and language are outlined, in the second section, similarities in the acquisition of music and language processing are described, and in the third section similarities in the processing of music and language are summarized.

4.1 Evolutionary considerations

The idea of far-reaching similarities of music and language is quite old. Rousseau (1781/1998) was a strong advocate of the view that music and language share some common ancestor and that language evolved out of music for the sake of a rational organization of human societies. Darwin (1871/1989) also argued for a common origin, but considered language as precursor of music. During the 20th century, this idea was further proposed and elaborated by some musicologists, ethnomusicologists, and music psychologists (e.g., Bright, 1963; Chandola, 1970; Feld, 1974; Ruwet, 1967; Sloboda, 1985).

Brown (2000) proposed a model to account for how music and language might have developed (see Figure 4-1). He argued, music and language could be seen as reciprocal specializations of a dual-natured referential emotive communicative precursor, whereby music emphasizes sound as emotive meaning and language emphasizes sound as referential meaning. This precursor is assumed to contain two stages. A first evolutionary stage, the referential emotive vocalization system, incorporates sound both, emotive and referential meaning. It relies upon a class of vocalizations (well-described in primates) that serves as emotive response to some objects in the environment and are semantically specific to a class of objects.

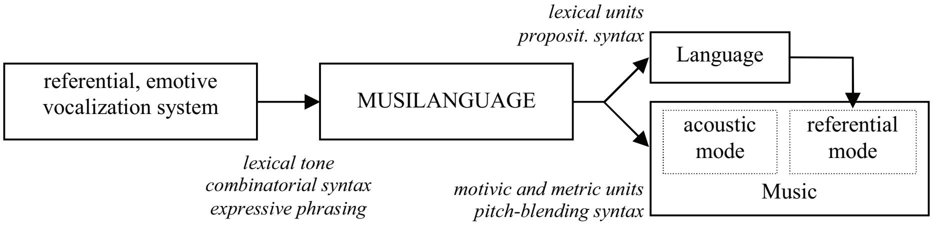

Figure 4-1 “Musilanguage Model” (adapeted from S. Brown, 2000)

Then, another ancestral stage, the “musilanguage” stage, is hypothesized. It embodies shared features of music and language, such that from this stage the two domains might have arisen. In its development, a two-step process is assumed, with the occurrence of unitary lexical-tonal elements as primary stage. A later stage introduced the combinatorial arrangement of these elements, i.e. phrase formation based on combinatorial syntax and expressive phrasing principles. At least three essential features are necessary to qualify this common “musilanguage” stage as a precursor and scaffold for both domains: [1] Lexical tone refers to the use of pitch as a vehicle for semantic meaning.[8] [2] Combinatorial formation refers to the ability to form small phrases from different tonal elements. This gives rise to two levels of meaning: firstly, to relations between the individual units (compound) and, secondly, to categorical formulas that characterize the phrase as a whole (global). These phrases must be able to exhibit melodic, rhythmic, and semantic variations. Later, hierarchical organization emerged in a modality-specific fashion, leading to specific grammars of language and music. [3] Phrasing is the device by which expressive emphasis can be added to the phrases. This can happen in numerous ways (e.g., by tempo, dynamics, or rhythmic modulation). Speech and musical

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[8] Nowadays, still the majority of the world’s languages are tonal (Fromkin, 1978). Nontonal, or “intonation” languages which do not depend heavily on pitch for lexical meaning are seen as evolutionary latecomers which have discarded their dependence on tone. Intermediate states (pitch-accent languages) exhibit some lexical dependence on tone, but also depend heavily on intonation.

phrasing often relies on the same processes. Thus, it seems inadequate to dichotomize expressive phrasing in speech and music.

From the "musilanguage" stage, an evolutionary divergence might have led to the formation of two distinct, specialized functions whereas the retention of some shared features conferred by the joint precursor is also hypothesized. This specialization results from the reciprocal elaboration of sound, becoming either referential or emotive meaning. In language, a large semantic system with greatly specific, referential meanings might have led to the development of a propositional syntax. It specifies the temporal and behavioural relationships between subjects and objects in a phrase (and involves hierarchical organization and recursiveness). In music, the acoustic range and pitch repertoire greatly expanded. This also led to a complex and hierarchical syntactic system based on pitch patterning and blending. Pitch blending and isometric rhythm are highly effective means in promoting cooperative group performance, and may have played an essential role in group coordination, cooperation, and cohesion.

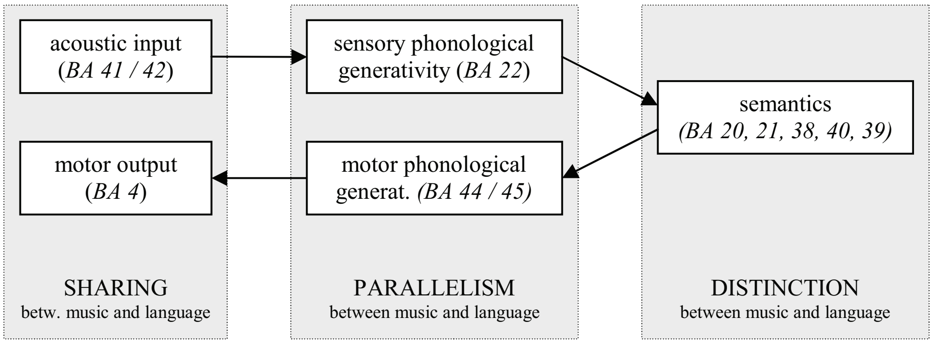

Figure 4-2 Model specifying three levels of interaction between music and language in the brain: sharing, parallelism, or distinction. Adapted from Brown, Martinez, & Parsons (2006).

Later, Brown, Martinez, and Parsons (2006) elaborated this idea and introduced neural correlates of particular aspects of music and language processing in their model. They proposed certain features of music and language as either "shared", "parallel", or "distinctive" (see Figure 4-2) and determined their neural correlates. "Shared" resources and overlapping activations may be found for primary auditory processing and vocal motor-somatosensory processing in both domains. "Parallel" and partially overlapping representations – e.g., for combinatorial generativity for sound sequences (phonology) – are assumed to rely on homologous brain regions. On the perceptual side, the *superior temporal gyrus* (Brodmann area (BA) 22), especially its posterior region (the planum temporale, an auditory association area; see, e.g., Griffiths & Warren, 2002) is involved in the perceptual processing of complex sound patterns, including speech and music. The role of BA 22 in phonological processing for speech seems well founded in the literature (for a review, see Scott & Wise, 2004). In music, it may have relevance for processing pitch, interval, and scale structure (Griffiths & Warren, 2002; Peretz & Zatorre, 2005). On the production side, the *inferior frontal gyrus* (BA 44 / 45) is regarded as an interface between phonological generativity and syntactic functioning. This region is assumed to be a large functional region, with sub-regions supporting syntactic, semantic, and phonological operations (see below and the chapter on "Language perception").

Finally, "distinctive" domain-specific and non-overlapping representations for information bearing (semantic) functions of music and language are mainly found in extrasylvian, temporal areas. In addition, music employs isometric rhythms and pitch blends and language utilizes words and propositional syntax which may also be regarded as distinct features (S. Brown, 2001). Key semantic areas for language (for reviews, see Bookheimer, 2002; Indefrey & Levelt, 2004; Price, 2000) are found in the left middle and inferior temporal gyrus (BA 21 / 20), bilateral ventral temporal pole (BA 38v), left inferior parietal cortex (BA 39 ⁄ 40), and inferior frontal gyrus (BA 47). Brown, Martinez, and Parsons (2004) claimed the superior temporal pole as a plausible candidate area for representing semantics in music, which might be related to the processing of motives.

4.2 Similarities in music and language acquisition

Linguistic and musical knowledge are the most complex systems universally acquired by humans early in life. However, children acquire musical and linguistic rules in a similar, effortless way and are early able to create new musical and verbal sentences by applying a rule system that they have been capable to abstract without conscious intentions. To this end, infants must derive structure amidst the information in their environment (for a more detailed discussion of the acquisition mechanisms, see the chapters on "Language perception" and "Music perception").

McMullen and Saffran (2004) propose that similar mechanisms of learning and memory may be utilized in the acquisition of knowledge in both domains. In particular, they assume that while adult musical and linguistic processes are modularized to some extent as separate entities, there may be similar developmental underpinnings in both domains. This suggests that modularity is an emergent property (acquired with mere exposure). McMullen and Saffran (2004; p. 290) assume that "knowledge of music [is] gained implicitly from the musical exposure […] this process involves inducing structure from environmental input".

Some of the perceptual, computational, social and neural constraints that are proposed by Kuhl (2004) to be essential for language acquisition may also apply for the acquisition of the regularities of the own musical culture. Some *perceptual constraints* are described in the section on relational processing (e.g., grouping according to Gestalt laws). The infant's learning is constrained by its perceptual abilities. The comparability of the mechanisms, involved in the acquisition of music and language suggests that at least some aspects of music and language are acquired via the same learning mechanisms. Presumably, these mechanisms are utilized to avoid "blooming buzzing confusion" (W. James, 1890) by virtue of a perceptual system that weights some cues more than others and a learning system flexibly adaptable to the actual task. Categorical perception is an example for such a perceptual constraint and infants employ categorical perception for speech and non-speech sounds. For example, in language categorical perception is applied to phonemes, whereas in music tones or chords may be categorized according to their frequency spectrum.

Computational constraints like pattern detection or satistical learning may be involved in the segmentation of musical phrases and the abstraction of the regularities that enable the processing of musical structure. Categorical knowledge may enable children to track consistent patterns in the input and to detect the probabilities of particular tones to co-occur to locate the boundaries between both, words and tones (Saffran et al., 1999). Infant learners can detect structure employing either rule-based or statistical learning (cf. Perruchet & Pacton, 2006). While rule-based learning relies on chunking, statistical learning relies on frequency distributions. Both principles abstract from the particular elements in the input to recognize "grammatical" sequences and involve the detection of sound patterns that cue underlying structure. These mechanisms might not be dedicated solely to language learning but might also be used for learning in other domains. For example, infants may use such mechanisms to acquire knowledge about musical scale structure and Western tonal conventions (exploiting their distributional properties, see Krumhansl, 1990; Tillmann et al., 2000).

Suprasegmental cues (which are similar for music and language) are probabilistically related with structural boundaries and, thus, are assumed to play a role in delineating structural information: Infants are shown to listen longer to music when pauses are placed on appropriate rather than random positions (Jusczyk & Krumhansl, 1993; Krumhansl & Jusczyk, 1990). These prosodic cues are highly salient to infants and drive much of the early processing in both domains. This might rely on their earliest learning experiences – the filtering properties of the uterus leave rhythmic cues intact relative to high frequency information.

Social constraints may channel what information will be focused when infants were familiarized with music of their culture and with language. The emphasis, introduced by specific musical properties in infant-directed singing and speech may help to focus the attention on these properties.

Neural constraints help to channel information to be acquired by information which was learned before. That is, as soon as regularities of the music of the own culture are acquired, abilities to perceive the music of another cultures may disappear. Such processes may apply to the acquisition of musical scales, tonality, and harmony. That is, infants perceive and remember music which is structured in accordance to the rules of their musical system as their experience with that music increases (Schellenberg & Trehub, 1999; Trehub, 2000; Trehub et al., 1987). *Vice versa*, they simultaneously loose the ability to perceive the music of any culture (Lynch et al., 1991; Trehub et al., 1999). Comparably, in language they lose their ability to discriminate phonemes of any language (Cheour et al., 1998).

4.3 Similarities in processing music and language

Whereas some researchers favour a modular view of music processing with music-specific neuronal networks (Peretz & Coltheart, 2003; Peretz & Zatorre, 2005), an alternative view points to significant overlap between neuronal structures utilized in language and music processing (Koelsch, 2005; Patel, 2003). This view is strengthened by studies like Koelsch et al. (2002) demonstrating that important language areas are involved in processing music.

However, while speech is highly dependent on rapidly changing broadband sounds, small and precise changes in frequency have to be differentiated in order to process tonal patterns in music: Whereas temporal differences as small as 20 ms are needed to process rapidly changing energy peaks characteristic of many speech consonants in language (Tallal, Miller, & Fitch, 1993), melodies with note durations shorter than about 160 ms are difficult to identify (R. M. Warren, Gardner, Brubaker, & Bashford, 1991). Since there is a trade-of between spectral and temporal resolution there is some functional specialization of the primary auditory cortex (cf. Liegeois-Chauvel, Giraud, Badier, Marquis, & Chauvel, 2001; Poeppel, 2003; Zatorre, 2001; Zatorre & Belin, 2001; Zatorre, Belin, & Penhune, 2002): Left auditory areas preferentially extract information from short (20 to 50 ms) integration windows and are, therefore, superior in temporal processing. In contrast, their right homologues are preferentially involved in spectral processing (pitch, prosody) with longer (150 to 250 ms) integration windows.

Language prosody and music

In accordance with these ideas, Friederici and Alter (2004) hypothesized a rough distinction of processing segmental *vs.* suprasegmental speech information related to the distinction between the two hemispheres: While segmental, lexical and syntactic information is processed in the left hemisphere, sentence level suprasegmental information (as accentuation and boundary marking) is processed by the right hemisphere (specifically, the frontal operculum and superior temporal areas; cf. M. Meyer, Alter, Friederici, Lohmann, & von Cramon, 2002). Music is also mainly processed in the right hemisphere, strengthening assumptions of a strong interrelation of these two domains. Nonetheless, the comprehension of linguistic prosody is not exclusively right-lateralized and the left hemisphere may contribute whenever prosody is segmentally bound (stress, lexically relevant tone). This hemispheric specialization is demonstrated even in four year old children (Wartenburger et al., 2007): processing prosody in isolation elicits a larger right fronto-temporal activation whereas a more left-lateralized activation is elicited by perceiving language with full linguistic content.

Prosody is proposed to be especially important during the first steps of language acquisition, since infants seem to posses an inborn capacity to communicate on the basis of musical, pre-linguistic elements (Papoušek, Jürgens, & Papoušek, 1992). Prosody can convey emotional messages. Prosodic structure describes how duration, pitch and intensity create structured rhythmic and melodic patterns in speech and music (Jusczyk & Krumhansl, 1993). The infants' attention and communicative approval are heightened by salient intonational pattern (Fernald, 1985, 1993). This exaggerated intonation, characteristic of infant-directed-speech and found cross-culturally, seems specifically helpful to children in order to figure out the sender's communicative intents (Fernald, 1989). Likewise, in music, a preference for high-pitched music (Trainor & Zacharias, 1998) and consonance (Trainor & Heinmiller, 1998) was observed in infants. The latter was often related to positive emotional judgements (cf. Juslin & Laukka, 2003).

Speech prosody can be decomposed into three features: variations in amplitude, pitch (contour), and timing (rhythm). Contour and rhythm will be described in more detail.

Contour is a salient feature of music (melody) and language (intonation). Local acoustic cues, such as pause insertion and pre-final lengthening, and global structural traits, such as contour, are an important marker for phrase boundaries. Thus, phrasing in music bears some striking similarities to the same phenomenon in speech. Neurophysiologically, the offset of a phrase boundary in music (Knösche et al., 2005) as well as in language (Steinhauer, Alter, & Friederici, 1999) was reflected by a very similar, centroparietally distributed positive ERP component, maximal around 550 ms (closure positive shift; CPS).

Intonation further has the capability to convey emotional messages, as intention and affect. Register was shown to be the first component of intonation to stabilize (Snow & Balog, 2002): infants must get independent of absolute frequencies in order to process contour. For music, there is evidence of a generalisation of contour across different pitch registers (Trehub et al., 1987). For language, children are shown to control some core features of intonation before they produce two-word combinations (Snow & Balog, 2002). For example, children demonstrate a change in the proportion of their use of falling *vs*. rising contours in accordance with the directions in ambient language which indicates their acquisition of the boundary-marking function of intonation (Snow & Balog, 2002). Thus, intonation represents the first expressive grammar-like feature that children use in their single-word utterances. Some core aspects of intonation seem to aid the perception of structural information (syntax).

Rhythmic organization, the temporal and accentual patterning of sound, is also regarded as an essential feature of music (Gabrielsson, 1993) and language (Cutler, 1991). [1] Tempo modulations play a significant role in musical communication (e.g., marking melodic phrases by a systematic pattern of speeding up and slowing down; Gabrielsson, 1987) as well as in language (e.g., communication of emotion or avoiding interruption; Murray & Arnott, 1993). [2] Metrical schemata provide listeners or performers with a stable pattern, and can be regarded as an organizational principle optionally applied across domains. Rhythm may apply to several domains, such as music, language (e.g., for poetry, or in stress-timed languages), and movement (e.g., dance). Some studies observed a considerable influence of the rhythm of the composer's language on this of its compositions (Huron & Ollen, 2003; Patel & Daniele, 2003).

Evidence from some studies demonstrated a marked influence of musical training on processing of linguistic prosody (for a more detailed overview, see the chapter on "Musical training", but see also Magne, Schön, & Besson, 2003; Magne et al., 2006; Moreno & Besson, 2006; Schön et al., 2004; Thompson et al., 2004). Likewise, some forms of music therapy exploit this relationship to treat, e.g., aphasics (Jungblut & Aldridge, 2004; Racette, Bard, & Peretz, 2006) or dyslexic children (Overy, 2003). Conversely, patients with right-hemisphere lesions are impaired in their performance for both, prosody and music (Patel, Peretz et al., 1998) and in their syntactic processing, likely due to problems in utilizing prosodic cues for disambiguation (Hoyte, Brownell, Vesely, & Wingfield, 2006; Hoyte, Kim, Brownell, & Wingfield, 2004).

Brain mechanisms for processing linguistic and musical syntax

Both music and language build upon the ability to infinitely combine perceptual elements in different ways. This ability seems to be unique to humans (Fitch & Hauser, 2004). However, in addition to such basic similarities, differences exist in the form, purpose, and use of musical and linguistic syntactic structures: Whereas the rules of musical syntax apply to two dimensions – horizontal (melody) and vertical (harmony) – linguistic syntax is primarily a framework for the relations between meaningful symbols (words). Words in sentences are rather hierarchically structured whereas musical tones and chords are rather linked by probabilistic dependencies. The regularities in language are stricter in order to allow for a clear transmission of semantic messages. That is, in music the structural rules seem to be much less rigid than syntactic and even prosodic rules in speech and one may, thus, more readily violate syntactic conventions for structural or aesthetic reasons (Sloboda, 1991).

Nonetheless, there may be an even larger amount of similarity: Both, music and language, crucially depend on integration and memory when perceiving the structural relations between elements. Predictability is based on knowledge of either what word categories are required to complete a sentential phrase, or what tone or chord could be appropriately follow in the actual musical phrase. Integration is the other side of prediction: each new word or tone has to be integrated within the current structure while integration costs increase with the distance between the current element and prior dependent elements. These ideas are elaborated by Patel (2003) proposing a “shared syntactic integration resource hypothesis” (SSIR). He assumed an overlap in the operations and their neural correlates that provide syntactic integration. More specifically, he proposed that frontal regions supply the resources for computations whereas the representation of syntactic regularities may reside in posterior regions. In accordance with this assumption, the processing of musical and linguistic syntax was demonstrated to take place in rather anterior brain regions. In these regions, the sources of the ELAN (early left anterior negativity) and the ERAN (early right anterior negativity) were localized. The sources of the P600 (and the LPC in music), proposed to reflect processes of syntactic integration are assumed to be generated in posterior representation regions. These late positivities in response to the structurally incongruous elements in language and music were observed to have comparable amplitude sizes and scalp distributions (Patel, Gibson et al., 1998).

Some studies provided evidence for Patel’s SSIR hypothesis: Patel, Iversen, and Hagoort (2004) showed that Broca’s aphasics are lacking of the facilitative effect of harmonic priming (i.e., of a strong music-structural relationship of context and target), indicating that their syntactic processing of both language and music is impaired. Interference effects were expected for tasks that combine linguistic- and music-syntactic processing. Koelsch, Gunter, Wittfoth, and Sammler (2005) presented synchronously music-syntactically regular and irregular chord functions and syntactically correct or incorrect words. Music-syntactically irregular chords elicited an ERAN. Syntactically incorrect words elicited a left anterior negativity (LAN) which was clearly reduced when words were presented simultaneously with music-syntactically irregular chord functions. This indicates an interaction of music-syntactic and of linguistic-syntactic processing and a strong overlap in the involved neural resources.

Taken together, there is considerable evidence for shared neural correlates underlying the processing of linguistic and musical syntax. Specifically, the ERP components in response to a violation of musical (ERAN) and linguistic syntax (ELAN) share a number of characteristics. Functionally, both, ERAN and ELAN, are taken to reflect a violation of expectancies concerning syntactic regularities (cf. Hahne & Friederici, 1999; Koelsch et al., 2000), based on contextually independent, automatic structure-building processes. Further, they are comparable with respect to polarity (both are negativities most prominent over frontal leads), and latency (with a maximum amplitude size around 150 to 200 ms after stimulus onset). They differ, however, slightly in their hemispheric weighting with a predominant left lateralization for linguistic syntax and a mainly right lateralization for musical syntax.

There is some evidence to suggest that both, ERAN and ELAN, are, at least partly, generated in the same brain regions (especially inferior and lateral parts of the inferior frontal gyrus (IFG) and in the anterior superior temporal gyrus). This view is strengthened by findings of a MEG experiment localizing the sources of the ELAN in inferior frontal as well as anterior temporal areas (Friederici, Wang, Herrmann, Maess, & Oertel, 2000). The direct involvement of this area into the generation of the ELAN was also demonstrated in patients with left anterior cortical lesions (Friederici, Hahne, & von Cramon, 1998; Friederici & Kotz, 2003; Friederici, von Cramon, & Kotz, 1999). Likewise, the sources of the ERAN were localized in the IFG (Maess et al., 2001) with additional contribution of the anterior superior temporal gyrus (Koelsch, personal communication). In the same vein, fMRI evidence demonstrates an overlap in the neural substrates when processing musical and linguistic syntax: The IFG was activated during the processing of musical syntax (Koelsch, Fritz et al., 2005; Koelsch, Gunter et al., 2002; Tillmann, Janata, & Bharucha, 2003; Tillmann et al., 2006) as well as for linguistic syntax (Caplan, Alpert, & Waters, 1998; Friederici, Meyer, & von Cramon, 2000; Friederici, Opitz, & von Cramon, 2000; Friederici, Rüschemeyer, Hahne, & Fiebach, 2003; Just, Carpenter, Keller, Eddy, & Thulborn, 1996; Stromswold, Caplan, Alpert, & Rauch, 1996). Activation in the IFG (BA 44 / 45) was also found for violations of the learned syntactic rules of an artificial grammar (Friederici, Bahlmann, Heim, Schubotz, & Anwander, 2006; Opitz & Friederici, 2003). Similarly, the contribution of temporal regions to the processing of linguistic syntax is documented by fMRI experiments (Friederici et al., 2003; M. Meyer, Friederici, & von Cramon, 2000) and lesion studies (Friederici & Kotz, 2003).

Nonetheless, the parts of this network are not necessarily specific to the processing of syntax: e.g., the inferior part of the right IFG was found to be involved in prosody processing (cf. Friederici & Alter, 2004; see also M. Meyer et al., 2000; Wartenburger et al., 2007). Vice versa, the left IFG was found to subserve a variety of musically relevant activities, e.g., music discrimination (Platel et al., 1997), processing and organization of sequential sound stimuli (Platel et al., 1997), sight reading (Sergent et al., 1992), and score reading while listening to the accuracy of a performance (Parsons, 2001). Similar brain regions were involved in the processing of rhythmic information (interval length, Schubotz & von Cramon, 2001b) and in the perception and reproduction of rapid temporal pattern (Fiez et al., 1995; Platel et al., 1997; Rao et al., 1997; Schubotz et al., 2000).

Put to a more abstract level, the functional significance of the inferior frontal cortex may be related to sequential operations in order to process and integrate structured information (see Bornkessel, Zysset, Friederici, von Cramon, & Schlesewsky, 2005; Gelfand & Bookheimer, 2003; Janata & Grafton, 2003; Mesulam, 1998).

Lashley (1951) proposed that sequencing and coordination of behaviour may be regarded as a form of grammar. In accordance, the ability to reproduce arbitrary sequences of 5 gestures was predictive for later grammatical development (around 28 months of age; Bauer, Hertsgaard, Dropik, & Daly, 1998). Since movements can be considered as communicative gestures there might be a relation to language. The inferior frontal cortex (especially the *pars opercularis* and the adjacent *ventral premotor cortex*) were involved in a wide range of motor functions (for a review, see Binkofski & Buccino, 2004). For example, this brain area was shown to code motor schemas relevant for grasping objects (Jeannerod, Arbib, Rizzolatti, & Sakata, 1995; Rizzolatti et al., 1996; Rizzolatti, Fogassi, & Gallese, 2002) and to have complementary cognitive functions, involved in representing, imagining and understanding observed actions (Binkofski et al., 2000; Hamzei et al., 2003; Rizzolatti & Craighero, 2004; Rizzolatti et al., 2002; Schubotz & von Cramon, 2002).

4.4 Conclusion

It was shown, that language and music may have evolved from a common ancestor. This might be the reason why strong similarities between these two domains can be observed. Moreover, some processing mechanisms and constraints may be involved in both, the acquisition of music and language. Moreover, prosody – representing the musical aspects of language – is assumed to pave the infant’s way into the acquisition of semantics and syntax. With respect to the neural correlates, there is considerable evidence for a strong overlap of these between language and music processing: it was found from very early processing steps up to complex properties as prosody or musical and linguistic syntax. Specifically syntactic processing, crucial for the present work, was observed to involve strongly overlapping neural networks.

5 Language Perception

Language is the prime means of communication in humans. It may have evolved from the need for social bonding between individuals belonging to the same group and is thought to be necessary for the organization of human societies. Language has a very strong semantic component and is, thus, a means for expression of rational thought and for the transmission of knowledge as well as it permits projections into the past and the future. Complex syntactic regularities are proposed to be specific to the human language faculty (Fitch & Hauser, 2004). The processing of syntax is central for the present work. Thus, in this chapter special emphasis on its development and its processing. The chapter is organized in two main sections, describing empirical findings related to language acquisition and language processing.

5.1 Language acquisition

Before the development of language perception will be outlined, two theoretical accounts to language acquisition will be introduced, that mainly reflect the nature-nurture debate. Secondly, an overview of the development of language perception by demonstrating when specific ERP components that reflect particular processing stages can be observed for the first time will be provided. Thirdly, constraints which are utilized to acquire linguistic knowledge are described. As the present work is mainly focused on syntactic processing, mainly later stages of language acquisition will be focused, that is, semantics and syntax. Semantics will be discussed as it provides the basic building blocks to syntax. Finally, there will be a section focusing on the development of syntactic processing in children.

Theoretical accounts on language acquisition

In linguistics, two main classes of theories exist to account for language acquisition. The generative perspective assumes some innate knowledge of language structure which does not change over time (cf. Pinker, 1984) and proposes “modularized” sub-systems for different components of language. According to Chomsky (1981), speech by adults is so full of hesitations, false-starts, mispronunciations, and ungrammaticalities this could not be an adequate model to abstract complex and subtle linguistic regularities. In addition, Gold (1967) hypothesized that children can not induce grammar of certain types from only “positive evidence”. The complexity of language and the indeterminacy of input to children (i.e. the “poverty of the stimulus”) is taken as further evidence that grammar cannot be learned (cf. Pinker, 1984). However, a considerable amount of cross-language variation makes it difficult to maintain the belief in one "universal stage" of grammatical learning (Bates & Marchman, 1988). Moreover, obvious developmental progress when acquiring language can be observed in children (proposed to have full grammatical competence). Generativists consider this development as biologically driven with three possible scenarios that may account for it: [1] it may result from improvements in other domains; [2] it may also result from maturation (e.g., of the brain); or [3] even though the basic principles of grammar are innate, the child has to adapt gradually to the grammar of its particular language (cf. Clahsen, 1996).

The other main class of theories, the interactionist view assumes that children acquire their linguistic knowledge by interactions with their environment. It proposes language development as the product of domain-general learning mechanisms. "Usage-based" theories assume that children develop linguistic competence gradually, learning to produce new constructions item by item rather than triggered by pre-specified grammatical rules (see, e.g., Tomasello, 2000). The acquisition is assumed to be mainly based on statistical regularities in the input. Accumulating evidence suggests that linguistic facts can be learned by this way without relying on the abstract or implicit principles proposed in the theory of universal grammar. The language input was found to contain relevant features in sufficient abundance to support statistically based acquisition of several seemingly complex facts about language.[9]

Neurophysiological correlates of language acquisition

Neurophysiologic measures may also provide an important additional source of information for a better understanding of language acquisition. Friederici (2005) reviewed such evidence from ERP (event-related potential) studies (see Figure 5-1). She proposed that the similar brain response patterns can be observed in children and adults, which support the view that language develops in a continuous manner.

In order to understand language, it is an important task to segment the stream of speech into meaningful units. Even though conversational speech provides acoustic breaks these do not reliably signal word boundaries. The infant's task is to figure out the elementary phonemic categories of its language, before it can try to acquire words, composed of these phonemes. Some innate skills seem to lead the acquisition of the phonemic categories. Thus, within the first 2 months of life brain indices for the ability to

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[9] The many opportunities to entrench the most frequent elements of one's own native language is illustrated by an example from Bates, Thal, Finlay and Clancy (2003): One may assume a child that hears approximately 5 hours of speech input per day, at a mean rate of 225 words per minute. Thus, an average 10-year-old child heard 1,034,775,000 English phonemes (at an average of 25,869,375 trials per phoneme), up to 250 million words (including 17,246,250 renditions of the most common function word) and 28 million sentences.

discriminate different phonemes can be observed (Friedrich, Weber, & Friederici, 2004). Together with knowledge of word-stress patterns, this enables the identification of word boundaries. Knowledge about stress patterns and phonotactic rules become established between 5 and 12 months (Weber, Hahne, Friedrich, & Friederici, 2005). Similarly, Cheour et al. (1998) demonstrated that 6 month old infants discriminate native and non-native language contrasts while the ability to discriminate non-native contrasts is disappeared in 12 month olds.

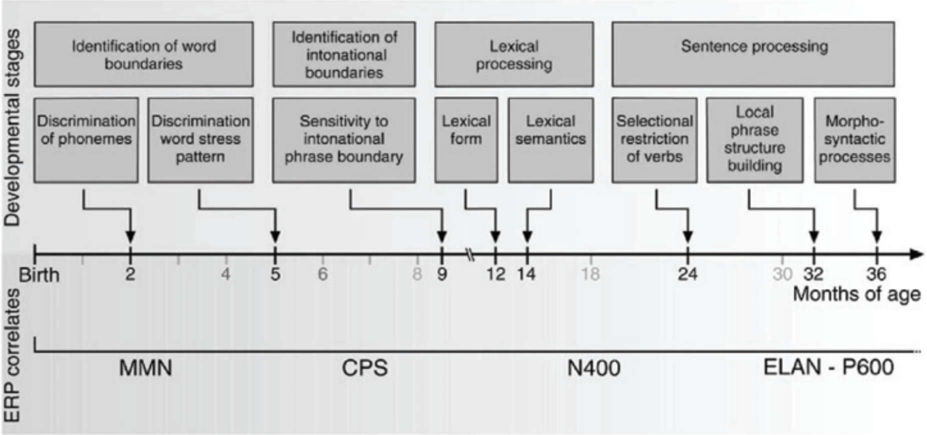

Figure 5-1 Schematic overview of the developmental stages of auditory language perception and the ERP correlates that provide the possibility to investigate phonological, semantic and syntactic processes (modified after Friederici, 2005).

Infants also have to identify intonational boundaries in order to perceive phrases (regarded as a basic unit of language's structure). Pannekamp, Weber, and Friederici (2006) demonstrated sensitivity to intonational phrase boundaries in 8 month old children. They used delexicalized sentences with hummed intonation contour, removing all segmental content and observed a CPS. This ERP component indicates the perception of major intonational boundaries. The ability to detect of phrase boundaries may enable the infant to infer syntactic regularities regarding the legal word order within the phrases.

Because words often appear at a particular position within a phrase, the ability to segment phrases may facilitate the acquisition of a words meaning. Children first acquire knowledge about lexical form (i.e., which words are phonotactically legal) and thereafter knowledge about lexical semantics. Phonotactic knowledge was demonstrated to begin to interact with lexical-semantic processes between 12 and 14 months. The latter processes are present at 14 months (Friedrich & Friederici, 2005). This was demonstrated in a paradigm that concurrently presented a picture and a word. If there was a mismatch between picture and word an N400 was elicited; an ERP component, indicating that a word is semantically incongruent to the context (the picture). An N400 was also observed in 30-month-olds when a word is incongruent to its sentential contexts (Silva Pereyra, Klarman, Lin, & Kuhl, 2005). Children that are at-risk for language impairment often late acquire their first words. In accordance, Friedrich and Friederici (2006) demonstrated that the presence of an N400 at 19 months – as an indicator of intact semantic processing – was associated with later age-adequate expressive language skills while its absence was linked with later poor expressive language skills.

Later, children start to process phrases and sentences, and begin to acquire syntactic regularities. Syntactic violations often elicit a biphasic ERP pattern in adults: An ELAN appears around 200 ms and is taken to reflect early and fairly automatic processes of initial syntactic structure building. It is usually followed by a P600 that has a higher latency and is related to processes of syntactic reanalysis and repair. Such an adult-like ERP response was found in 32 month old children (Oberecker, Friedrich, & Friederici, 2005). In this experiment children were presented with syntactically correct or syntactically incorrect sentences (with active mode construction). The syntactically incorrect sentences contained a phrase structure violation (a preposition not followed by a noun phrase). In younger children only a P600 is found while an ELAN-like response seems absent (Oberecker & Friederici, 2006 [at 24 months]; Silva Pereyra et al., 2005 [at 30 months]). For syntactically more complex, passive sentences, Hahne, Eckstein and Friederici (2004) demonstrated a comparable developmental pattern with a P600 that can be observed even in six-year-olds. Instead of ELAN in children between 7 and 13 years a sustained syntactic negativity (that has a higher latency than the ERAN and a more sustained time course) was found. It gradually develops into the ELAN which is usually observed in older children and adults.

Regarding the functional-anatomical organization of infants' language perception, Dehaene-Lambertz et al. (2006) provided evidence that 3 month old infants' language processing is confined to regions that are similar to those observed in adults in both their localization and their lateralization. They further investigated the time course of this processing, and observed the fastest responses in the vicinity of *Heschl's gyrus*, whereas responses became increasingly delayed toward the posterior part of the *superior temporal gyrus* (STG), and toward the temporal pole and the inferior frontal regions. The activity in the inferior frontal region was sensitive to the immediate repetition of the sentence. Imada et al. (2006) investigated discriminative responses to pure tones, harmonic tones, and syllables with MEG in neonates, 6-month-old infants, and 12-month-old infants. They found evidence for a contribution of the inferior frontal cortex to speech-sound discrimination that was present in 6 and 12 month old infants.

Both, Deheane-Lambertz et al. (2006) and Imada et al. (2006) related this activity to an emerging link between phonetic perception and activation of the motor system. Regarding activity in frontal lobe structures, Bates et al. (2003) suggested that infants cannot succeed in so-called frontal lobe tasks until they have made enough progress (perceptual, motor, mnemonic) to realize that a new set of strategies is required. Such strategies are, in turn, only possible with the involvement of the frontal lobes. The evidence from the studies of both, Deheane-Lambertz et al. (2006) and Imada et al. (2006) indicate that such processing is established quite early in life. Two brain regions, observed in that studies, namely the *superior temporal gyrus* and the *inferior frontal gyrus*, are also of specific importance for syntactic processing and will be discussed in more detail in separate sections (see below).

Constraints and learning mechanisms in language acquisition

At first glance the acquisition of language seems deceptively simple, and children learn quite fast to understand and to produce language. However, on a more precise inspection it becomes obvious that language acquisition is a tremendously complex task. It is, thus, likely that infants approach language with a set of initial constraints, necessary for its acquisition. Kuhl (2004) proposed four main classes of such constraints: [1] perceptual, [2] neural, [3] computational, and [4] social constraints. These constraints enable an infant to acquire knowledge of phonetic categories, which words are phonotactically legal that enables the segmentation of the speech stream into meaningful units and allows for the extraction of meaningful words.

Perceptual constraints: A basic perceptual mechanism is categorical perception. It denotes the ability to classify stimuli into different categories according to certain properties. This may be acoustic properties that discriminate phonetic units, e.g., voice-onset time (Eimas, Siqueland, Jusczyk, & Vigorito, 1971), or place of articulation (Eimas, 1974; Moffitt, 1971; Morse, 1972). Infants were able to detect contrasts not only at the begin but also at the end of syllables (Jusczyk, 1977). They discriminate vowel contrasts, like adults, in a continuous and not in categorical fashion (Kuhl & Miller, 1982; Trehub, 1973). Categories may extend beyond the classification according to basic perceptual features. For example, infants are able to form categories of objects based both on form and, to some extent, on function (Mandler, 2000). Thus, Bloom and Markson (2001) argue, word acquisition might be more easily explained in terms of general cognitive systems (as those involved in concept formation and intentional reference). Therefore, it may be not necessary to propose linguistic constraints (Markman, 1994), which guide the acquisition of new words (e.g., the mutual exclusivity assumption, proposing that children to avoid two labels for the same object).

Perceptual grouping of different sounds is a prerequisite for categorical perception. This involves the ability to categorize sounds despite changes in many dimensions (e.g., talker rate and phonetic context). Infants show some capacity for perceptual normalization in order to cope with variability in speech (Kuhl, 1979, 1983). There seems to be a "perceptual magnet" effect (with prototypical sounds behaving like magnets for similar sounds; Kuhl, 1991). Such an effect is reflected in a study by Maye, Werker, and Gerken (2002). They familiarized infants with stimuli from a phonetic continuum (da-ta) with either a 'bimodal' (frequent presentations of stimuli at the ends of the continuum) or a 'unimodal' mode of presentation (frequent presentations of stimuli from the middle of the continuum). Infants in the bimodal group discriminated the two sounds, whereas those in the unimodal group did not. Equipped with these perceptual abilities, children have to adapt to the linguistically relevant categories of their native language.

Neural constraints denote that exposure to language instigates a mapping process for which infants are neurally prepared, and during which the brain's networks commit themselves to the basic statistical and prosodic features of the native language. This again, permits phonetic and word learning (Kuhl, 2000). Simply experiencing a language early in development, without producing it themselves, can have lasting effects on infants' ability to learn that language as an adult (Au, Knightly, Jun, & Oh, 2002; Knightly, Jun, Oh, & Au, 2003; Oh, Jun, Knightly, & Au, 2003). By contrast, when language input is substantially delayed, native-like skills are never achieved (Mayberry & Lock, 2003). For the ability to discriminate phonemic contrasts prior experience appears not to be a significant factor (Cheour et al., 1998; Streeter, 1976; Trehub, 1976). With increasing familiarity with native speech contrasts there is a decline in sensitivity to non-native speech contrasts (Cheour et al., 1998). Knowledge of legal phonemic categories may be employed to discover higher-order elements in spoken language.

Computational constraints involve statistical learning as a basic mechanism to abstract regularities from distributional features of the own language (Maye et al., 2002). The statistical distribution of sounds in ambient language – which infants analyze – provides clues about its phonemic structure. It seems likely that the mechanisms of statistical learning and their constraints were not tailored solely for language acquisition. They may also apply for learning regularities in other domains, e.g., "tone-word" boundaries (Saffran et al., 1999) or visual pattern sequences (Fiser & Aslin, 2002). By at least 9 months, infants are sensitive to frequency, distribution, and other statistical properties of their perceptual input, e.g., frequent phonetic contrasts and phonotactic patterns (Jusczyk, Luce, & Charles-Luce, 1994; Saffran, Werker, & Werner, 2006).

The pattern detection mechanisms just described can be regarded as a pre-requisite for recognizing words. Infants are sensitive to adjacent transitional probabilities in speech were shown to use this sequential statistics to discover word-like units in absence of other acoustic cues to word boundaries (Saffran, Aslin, & Newport, 1996). After repeated exposure to nonsense words with recurring sound patterns, infants can make generalizations about syllable structure (Saffran & Thiessen, 2003), stress (Gerken, 2004) and phonotactic patterns (Chambers, Onishi, & Fisher, 2003). Infants exploit such knowledge to segment words from fluent speech. Thus, they are able to parse speech and discover potential words, presumably before they understand their meaning (Saffran, 2002; Saffran et al., 1996).

Saffran (2001b) demonstrated that statistical learning mechanisms can generate word-like units. She familiarized eight-month-old infants with nonsense words, and tested the infants' responses to words versus part-words that were embedded either in simple English sentences, in matched nonsense frames, or non-linguistic frames generated from tone sequences. Infants’ listening preferences were affected by the context in which the learned items were embedded. Saffran and Wilson (2003) demonstrated that the same learning mechanisms can be exploited for several learning stages: the mental representations produced by a statistically based word segmentation procedure are represented not as sets of syllables, but form new units that are available to serve as the input to subsequent learning processes.

These statistical learning mechanisms may interact with prosodic cues. Jusczyk and Aslin (1995) found that 7½ month old infants successfully segmented words with the more common stress pattern, but they missegmented words with uncommon stress pattern. In contrast, 10½ month old infants segmented words with both kinds of stress pattern appropriately. That is, infants use prosodic as well as statistical strategies to identify words, but the reliance on these change with age: up to 7 months they rather use statistical than prosodic cues, and around 9 months they start to identify words predominantly on the basis of initial word stress (Thiessen & Saffran, 2003). When conflicting with statistical cues 8 to 9 month old infants seem to favour prosodic stress cues (Johnson & Jusczyk, 2001) or phonotactic cues (Mattys, Jusczyk, Luce, & Morgan, 1999). Recently, research on adult speech processing focused on how listeners integrated probabilistic information from numerous sources (Seidenberg, 1997). The use of language-specific phonetic and phonotactic cues together with prosodic cues (as word-stress) was demonstrated to improve performance in computational models of word segmentation (Swingley, 2005). Moreover, certain prosodic features in continuous speech, such as stress pattern, pauses or vowel lengthening may cue boundaries between words and phrases (Gleitman, Gleitman, Landau, & Wanner, 1988; Morgan, 1996; Morgan, Meier, & Newport, 1987).

Social constraints: Computational learning mechanisms – even though they are powerful – may not provide an exclusive explanation to language acquisition. Language learning may also be grounded in children's appreciation of others' communicative intentions, their sensitivity to joint visual attention and their desire to imitate (e.g., K. Bloom, 1975; R. Brooks & Meltzoff, 2005; Dunbar, 1998; Goldstein, King, & West, 2003; Tomasello, 2003). Social interaction seems to protect infants from meaningless calculations and focuses learning to speech (Kuhl, 2003; Kuhl, Tsao, & Liu, 2003; Thiessen, Hill, & Saffran, 2005). Moreover, there are connections between social awareness and other higher cognitive functions (Dunbar, 1998): People engaged in social interaction are highly aroused and attentive which might enhance the ability to learn and remember.

Semantics

Lexical processing and the acquisition of word semantics may be regarded as an entrance to sentence processing (see Figure 5-1). First signs of word comprehension appear around 8 to 10 months. At 18 months the vocabulary comprises already approximately 250 words (Fenson et al., 1994). Even at 8 months, infants are able to link novel words to novel objects after only a few repetitions, but they require cross-modal synchrony between the presentation of the word and movement of the object (Gogate, Walker-Andrews, & Bahrick, 2001). The ability to form word-object links on the basis of co-occurrence, without facilitating social or temporal cues is evident by 13 to 15 months in laboratory tasks (Schafer & Plunkett, 1998; Werker, Cohen, Lloyd, Casasola, & Stager, 1998). However, at this age, infants' ability to associate novel words with novel objects is still dependent on the contrastive saliency of the words themselves, i.e., they fail with minimally contrastive words (as 'bin' and 'pin') while 17 months olds are able to learn novel pairings even with minimal phonetic contrast (Werker & Fennell, 2004).

During the first months, words will be learned step-by-step before a "vocabulary burst" starts. It denotes a sudden and marked increase in how many words children use, and is proposed to be an emergent function of the processing and a natural consequence of previous processing limitations. Usually, the "burst" occurs when the children acquired a vocabulary of around 50 words. It is coupled with a reorganization of vocabulary composition: Whereas the vocabulary up to this time mainly consisted of content words, a proportional increase of words that serve as predicates (verbs, adjectives) can be observed (Bates et al., 2003; Dromi, 1987). Further, there is a shift from reference (i.e., single-word meaning) to predication (i.e., relational meaning). The acquisition of relational meaning might put forth the first word combinations that typically emerge between 18 to 20 months. In general, the early lexical development is quite gradual and involves not only building-up “adult-like” meaning representations, but also learning to use words in more and more contextually flexible ways and challenging contexts (cf. Bates et al., 2003). During the acquisition of children’s early receptive and expressive vocabulary considerable inter-individual differences may be found. There is a group of “late talkers” which is delayed in language development. Some of these children catch up, others remain late and may suffer from language impairment (see chapter “Specific Language Impairment”).

In the second year of life a considerable improvement in processing efficiency can be observed that enables infants to identify words more quickly and based on partial phonetic information. Frequent word forms, once learned, facilitate segmentation of new words (Bortfeld, Morgan, Golinkoff, & Rathbun, 2005), words that are already known may influence how words in fluent speech are recognized and competition between lexical items may become a significant factor as the lexicon develops (Hollich, Jusczyk, & Luce, 2002). Furthermore, Tsao, Liu, and Kuhl (2004) demonstrated that advanced phonetic abilities may “bootstrap” language learning propelling infants to more sophisticated levels; speech-discrimination skills at 6 months can therefore predict later language development. Moreover, children become attentive to prosodic and syntactic regularities helping them to anticipate upcoming content words in the sentence (Fernald & Marchman, 2006). In general, they develop an increasing efficiency in integrating distributional, lexical, prosodic, and other available sources of information, enabling them to make sense of words that are known while avoiding costly interference from unfamiliar words in the sentence that are not yet known (cf. Fernald & Marchman, 2006).

Morphology is regarded as the rule system governing the construction of complex words. Its acquisition mainly utilizes statistical learning mechanisms. Morphology involves derivational morphology rules, i.e. how to form complex content words from simpler components. Children learn the morphology of their language at different tempi, depending on the type and token frequency in the input (e.g., the relative frequency of different surface forms, and if lexemes are inflected in the same way); perceptual saliency; transparency of meaning; formal complexity (one or more meanings); and the regularity and distributional consistency of the inflectional paradigm (cf. Peters, 1997). For example, children in languages with a very rich and salient morphological system are demonstrated to begin with inflections before they produce any word combinations. The other aspect of morphology – inflectional morphology – comprises rules for modulations of word structure that have grammatical consequences (e.g., to signal grammatical agreement between subject and verb). It can be regarded as a bridge between semantics and syntax.

Syntax

After segmenting words children focus on phrase and sentence level in order to acquire more complex linguistic rules (e.g., the word order within particular phrases). During the second year of life, children become increasingly attentive to the regularities in speech relevant to the grammatical structure of the language they are learning (Friederici, 2005; Gerken, Wilson, & Lewis, 2005; Gomez, 2002). Before they are 3 to 4 years old, children typically acquired most grammar of their native language, including many apparently arbitrary and abstract contrasts (e.g., grammatical gender), and some fairly complex syntactic devices (e.g., passives, relatives). An index of early grammatical development in English is Mean Length of Utterance (MLU). It can be used to break development down into epochs (R. Brown, 1973): MLU ranges from 1.05-1.50 in Early Stage I (single words to first combinations), from 1.5-2.0 in Late Stage I (first inflections), from 2.0 -2.5 in Stage II (productive control over grammar begins), 2.5-3.0 in Stage III (grammatical development well underway), from 3.0-3.5 in Stage IV (complex sentences begin), and so on.

Syntax denotes the principles that govern the word order within a sentence. As outlined above, there are two opposite views dominating the discussion on grammar acquisition: Generativists assume that children, due to the highly complex nature of grammar, can master it only by means of a language-specific learning device and by innate knowledge about certain aspects of the formal structure of language (Universal grammar). In contrast, interactionists argue that grammatical abstraction emerges from interaction between the input and innate learning mechanisms and that these are not restricted to the domain of syntax. These approaches maintain that children start by learning low-scope constructions based around specific words or morphemes. Initially, a child may lack understanding of the internal structure of a construction, but use it as a whole with a specific meaning.

One interactionist theoretical account, provided by Tomasello (2003), will be described in more detail. It assumes, that in the early stages, some utterances are rote learned as a whole (e.g., what's that?), and others may be slot-and-frame patterns (e.g., "Where's X gone?" or "More X"). Thus, many of children's early utterances are characterized by missing features (e.g., subjects or function words are frequently omitted, and utterances often lack finiteness marking). These early utterances reflect features of the input very closely. Thus, children's' early verbs are those that occur most frequently, these verbs are marked in accordance with the most frequent marking, and used in argument structures that appear most frequently. Initially, processing constraints likely limit the length of these utterances. As development proceeds, functional distributional analysis based on the relation between a form and (child-identified) functions leads to more complex and abstract representations of constructions developing internal structure. Then patterns of relationships build up between constructions and their parts, leading to increasing complexity and schematization. Thus, recent constructivist accounts suggest that the abstract transitive construction builds up from a number of different sources: pre-verbal knowledge of causality, the ability to match arguments in an utterance to referents in the environment, the development of other lexically specific constructions around pronouns, and high-frequency items. For example, Fernandes et al. (2006) demonstrate a receptive understanding of argument structure in two-year olds. These were able to map a single scene onto two distinct syntactic frames (transitive and intransitive).

A fundamental mechanism for the acquisition of syntactic regularities is statistical learning (see above).[10] Gomez and Gerken (1999) exposed 12-month-olds to strings of syllable-words produced by one of two complex grammars, leading to considerable variability in the order of the words within the sentences (i.e., a certain word could occur in different positions in the sentence). After a brief exposure (50 up to 127 seconds) to a subset of strings, generated by a training grammar, infants were tested for discrimination of new strings from the two different grammars. Infants listened longer to new strings from their training grammar than to strings from another grammar. Although they were never tested on the exact strings encountered during training, the constraints placed on word ordering were the same during training and test. This demonstrates that learning generalized to novel strings with familiar co-occurrence patterns. Likewise, Marcus, Vijayan, Bandi Rao, and Vishton (1999) demonstrated that infants can abstract beyond specific word order and acquire algebra-like rules (involving substitution of arbitrary elements in a sequence of abstract variables): Seven-month-olds were familiarized with syllable strings based on a certain underlying pattern (ABB vs. ABA) that was the same for training and for test, however with a different vocabulary of syllables (e.g., wi-di-wi *vs.* ba-po-ba). Infants discriminated strings with the training patterns from those with a different pattern despite the change in vocabulary. Very likely operations over abstract (rather than perceptually bound) variables are the basis for the acquisition of algebra-like rules. Such rules may be a basis for linguistic productivity (e.g., children have to learn that determiners precede nouns, etc.).

Although sensitivity to word order is necessary for tracking sequential information in sentences, learners must ultimately abstract beyond the ordering of specific words. The experiment of Gomez and Gerken (1999) outlined above suggests that infants had abstracted some aspect of grammatical structure. The detection non-adjacent dependencies might be a first step into grammar (Bonatti, Pena, Nespor, & Mehler, 2005; Gomez,

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[10] Such learning mechanism are only proposed by interactionist accounts.

2002; Newport & Aslin, 2004; Pena, Bonatti, Nespor, & Mehler, 2002). However, these kinds of distributional relations are almost impossible for learners to acquire, i.e. they do not learn the dependencies between classes (Braine et al., 1990; P. J. Brooks, Braine, Catalano, Brody, & Sudhalter, 1993; Frigo & McDonald, 1998). This difficulty is ameliorated, either when category members are marked with salient conceptual or perceptual cues (Frigo & McDonald, 1998), or when segmentation cues are introduced. These can improve the detection of the non-adjacent dependencies (Gomez, 2002) and help to extract the structural regularities in the stream (Pena et al., 2002). This demonstrates that humans are not unconstrained learners. Instead, abstraction results only when there is sufficient evidence to distinguish the categories in question. In fact, many of the categories found in natural language (such as gender, declension and conjugation classes) are rich in systematic cues to class membership (e.g., verbs tend to have fewer syllables than nouns, a cue used even by 4-year-olds, cf. Cassidy & Kelly, 1991).

The acquisition of abstract structure (e.g., phrase boundaries) is, however, often not obviously and unambiguously mirrored in the surface statistics of the input. There are particular ubiquitous structures, found cross-linguistically, for which the most learning-oriented theories can not provide a transparent explanation. Thus, it is conceivable that some nearly universal structural aspects of human languages may result from certain constraints. Prosodic breaks, function words and concord morphology are effective at promoting hierarchical packaging of word strings in an artificial grammar when they occur consistently with the hierarchical structure (Morgan et al., 1987). An even stronger claim is made by Frazier, Carlson, and Clifton (2006), proposing that prosody may provide the structure within which utterance comprehension takes place, i.e., it might supply the basic skeleton that allows humans to hold an auditory sequence in memory. Gerken, Jusczyk, and Mandel (1994) provide further evidence for the assumption of prosody helping to step into syntax. They demonstrated that the listening preferences of 9 month old infants are more in accordance with prosodic, rather than syntactic, organization. It was demonstrated that statistical cues to phrasal units can be used to locate phrase boundaries (Saffran, 2001a). The statistical and the prosodic account may present different sides of the same coin and do not exclude each other, i.e., the segmentation of phrase boundaries may be especially facilitated when both kinds of cues concur.

The acquisition of syntax was observed to interact with the development of lexical semantics: Fisher, Hall, Rakowitz, and Gleitman (1994) demonstrated that verb acquisition might be mediated by syntactic constraints. Likewise, Fernald, Perfors and Marchman (2006) found that the efficiency of spoken language understanding was related to indices of lexical and grammatical development. Grammatical complexity and vocabulary size were linked by a continuous and accelerating function (Bates & Goodman, 1997). The size of verb vocabulary was concurrently related to the number of reported over-regularizations, an indicator for the acquisition of grammatical morphology (Marchman & Bates, 1994).

Language is a form of communication, a tool that we use to accomplish certain social ends. Children are immersed in communicative interaction with others from infancy, but there are many skills that take years to develop. For example, coordinating reference across speaker and listener roles involves manipulating and understanding given and new information, deictic and anaphoric pronouns, temporal information, and so on.

During development, children gradually become able to consciously reflect on language, to correct their own and others' utterances, and to notice features of language at all levels. Karmiloff-Smith (1992) proposes a developmental progression with an early period of language learning followed by a period of skill automatization: Children have to learn the forms of the language and to use them relatively effortlessly. Once language becomes relatively fluent and automatic, it can become an object of reflection.

5.2 Language processing

In the current section three main issues will be discussed. Firstly, a brief overview of (mainly linguistic) accounts to syntactic processing will be given. The second part introduces a model to describe particular stages of syntactic processing and the brain correlates of these steps. In the third part the function of two brain regions that are involved in language processing, specifically in the processing of linguistic syntax, will be discussed.

Processing syntactic structures

Syntactic information is, among other types of information, used, to determine the meaning of a sentence. Syntactic processes include: [1] Structure building (combining words into larger units on the basis of word category information and grammar rules); [2] checking agreement (i.e. for inflectional features that establish a relationship, e.g., between verb and noun); [3] mapping thematic roles (such as agent and patient) onto certain positions in the sentence; and [4] complexity (e.g., dealing with non-canonical word order).

Complex syntax involves recursion.[11] Recursion is proposed by Hauser, Chomsky and Fitch (2002) as key component of human language. They propose, while other prerequisites may be shared with other animals, no other species has a comparable capacity to recombine meaningful units into an unlimited variety of larger structures: While finite-state grammars can be learned by primates, phrase-structure grammars can not (Fitch & Hauser, 2004).[11]

In linguistics, there are two main accounts to theorize about syntactic parsing: two-stage accounts and interactive accounts. Two-stage accounts assume initial processing (usually modular) and subsequent processing (usually not modular), e.g., the influential "Garden-Path" theory established by Frazier (cf. Frazier, 1987). A first analysis is chosen on the basis of certain assumptions (e.g., "Minimal Attachment"). Alternative two-stage accounts propose that the processor initially adopts an analysis in which a thematic role can be assigned to a new constituent (e.g., Abney, 1989; Pritchett, 1992).

Interactive accounts assume that all potentially relevant sources of information are immediately used and affects further processing (e.g., Bates & MacWhinney, 1989; Taraban & McClelland, 1988; Tyler & Marslen-Wilson, 1977). They generally hypothesize that the processor activates all possible sentence analyses in parallel and these which receive support stay activated. Thus, processing is easy when only one analysis receives support while processing difficulties occur when two or more analyses receive equal support. For a more in-depth discussion of these theories, see e.g., Pickering and van Gompel (2006).

It is often assumed that working memory plays an important role in sentence processing. Memory limitations may affect the ease with which sentences are processed. For instance, Gibson (1998) proposed the syntactic locality prediction theory which claims that two factors – storage costs and integration costs – contribute to sentence complexity because both draw on the same memory resources. Storage costs occur with a dependency between two syntactic elements when one element has to be stored in memory before it can be integrated with a later element. Thus, both costs increase as more new discourse referents have to been processed.

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[11] In general, two types of grammar rules can be distinguished: a ***finite-state grammar*** involves the processing of a simple, local rule (e.g., $(AB)^n$ generating local transitions between As and Bs, i.e., ABABAB), the ***phrase structure grammar*** the processing of a complex, hierarchical rule (e.g., A^nB^n, i.e. AAABBB). Phrase-structure grammar is based on ***recursion***. It denotes an embedding of sentences in sentences. This enables an unlimited extension of a language. The linguistic doctrine that recursion is the only trait which differentiates human and animal communication and is currently under intense debate.

Neurophysiological-functional correlates of language processing

The present section introduces a model on language processing which mainly focus on syntactic processing (Friederici & Kotz, 2003). The present section will mainly introduce neurophysiological-functional aspects of language processing, i.e. the time course and the succession of particular ERP component, reflecting certain processes during language perception. Another section describes two brain regions involved in many processing stages, namely the *superior temporal gyrus* (STG) and the *inferior frontal gyrus* (IFG).

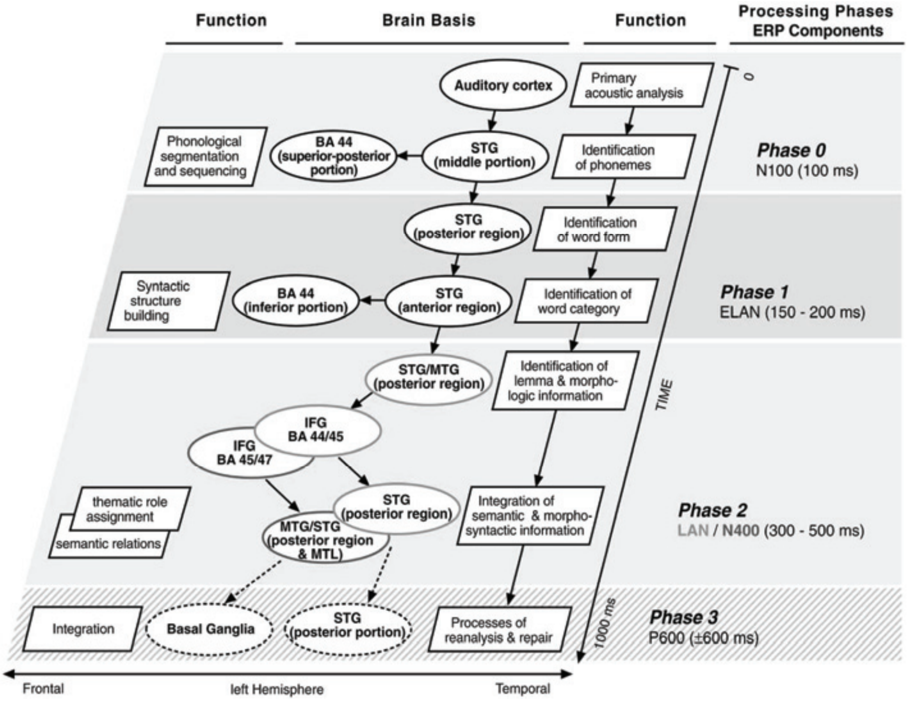

Figure 5-2 Neurocognitive model of auditory language comprehension (adapted from Friederici & Kotz, 2003).

Friederici and Kotz (2003) proposed that language comprehension contains three processing steps: initial syntactic structure building (Phase 1), semantic integration (Phase 2), and late syntactic integration (Phase 3). They argue that their model is compatible with two-stage accounts (syntax-first models) as well as with interactive accounts assuming a late interaction of syntax and semantics, but not with those claiming immediate interaction. It is assumed that language processing is organized into a large number of relatively small, but tightly clustered and interconnected modules with unique contributions. The model presents assumptions about the time course of the processes in which these modules are involved as well as of neural correlates. These different phases will be described in the next sections. Further, the model shall be utilized as a framework to integrate findings from some recent studies.

Primary acoustic analyses (involving the auditory cortex), the identification of phonemes (in the middle portion of the STG), and phonological segmentation and sequencing (in the superior-posterior portion of BA 44 in the IFG) take place during phase 0 (around 100 ms). They are a prerequisite for later processing stages. Electrophysiologically, these processes may be reflected in an N100.

Phase 1: Early syntactic analyses

Phase 1 (150 to 200 ms) is assumed to involve the identification of word form (in posterior regions of the STG) and word category (in anterior regions of the STG) in order to perform an initial structure building (in the inferior portion of BA 44). Processes of very fast and highly automatic initial structure building (i.e., so-called first-pass parsing processes) may be reflected (electrophyiologically) in an ELAN. It is usually elicited by violations of phrase structure, e.g. word category violations (e.g., Friederici et al., 1993; Hahne & Friederici, 1999; Neville, Nicol, Barss, Forster, & Garrett, 1991). Structural expectations were suggested to play a crucial role for these fast syntactic diagnosis processes (see, e.g., Hahne & Friederici, 1999; Lau, Stroud, Plesch, & Phillips, 2006).

The brain areas supporting the early syntactic structure-building processes can be specified in different ways. Friederici, Wang, Herrmann, Maess, and Oertel (2000) localized the sources of the ELAN in a MEG experiment in the anterior portion of the STG and in the inferior frontal region. Studies with patients suffering from localized brain lesions can also contribute to identify which brain regions are involved in these processes: in patients with lesions in the left frontal cortex and in the left anterior temporal lobe no ELAN was found (Friederici et al., 1998; Friederici et al., 1999; Kotz, Frisch, von Cramon, & Friederici, 2003; Kotz, von Cramon, & Friederici, 2003). Similar brain regions were activated in a number of fMRI experiments (e.g., Friederici et al., 2003) demonstrating a crucial involvement of the left anterior STG and the left frontal operculum in these processes.

Phase 2: Building semantic relations and thematic role assignment

Processes that are related to building semantic relations and thematic role assignment can elicit an N400 or a LAN. These processes are supported by a temporo-frontal network involving the middle and possibly the posterior portion of the STG and MTG and BA 45/47 in the IFG. In accordance, Friederici, von Cramon and Kotz (1999) observed an attenuated N400 in patients with left frontal cortical lesions.

An N400 may be elicited when a word rendered a sentence semantically incongruent (Holcomb & Neville, 1991; Kutas & Hillyard, 1980), when the verb argument structure is violated (Friederici & Meyer, 2004), when an unexpected but correct word category appeared (Hinojosa, Moreno, Casado, Munoz, & Pozo, 2005), or when thematic roles can not be assigned (Frisch & Schlesewsky, 2001).

An important issue is how lexical-semantic and syntactic processes interact. Hahne and Friederici (2002) found that the double violation also elicited a biphasic ELAN-P600 pattern, but no N400. This provides strong support for the independence of the early syntactic processes from semantic information. It further demonstrates that early syntactic processes can influence the following semantic processes (suppressing the N400). Friederici, Gunter, Hahne, and Mauth (2004) set out to investigate whether this result was due to the temporal ordering (syntactic information is available prior to semantic information) or whether it is functionally based (syntactic information is used prior to semantic information). The syntactic violation was, thus, either realized in the prefix or in the suffix. The double violation elicited a left anterior negativity (resembling an ELAN, since the word category decision point was later), no N400, and a P600 which was larger for the double violation than for the single syntax violation condition. The results of both studies provided clear evidence for the functional independence of structure-building processes from semantic information: the ELAN is elicited even when the word category information (suffix) becomes available after the semantic information (word stem).

Friederici, von Cramon, and Kotz (2007) demonstrated an interaction of prosodic with syntactic information (a violation of the verb argument structure) in an ERP experiment in patients with lesions in the posterior *corpus callosum* (CC) and normal controls. They underlined the crucial involvement of the posterior third of the CC in the interhemispheric interplay of suprasegmental prosodic information and syntactic information: In the controls an N400-like effect was found for prosodically mismatching verb argument structures (indicating a stable interplay between prosody and syntax). In contrast, patients with lesions in the posterior third of the CC did not show this effect whereas a prosody-independent semantic N400 effect could be elicited.

A LAN (between 300 and 500 ms) was often found in studies investigating processes of thematic role assignment based on morphosyntactic information that signals agreement between different phrases or between elements within a phrase. These studies often used violations of either agreement information (e.g., subject-verb agreement, Hagoort & Brown, 2000) or verb-argument structure information (e.g., Rösler, Friederici, Pütz, & Hahne, 1993). Again, the question arises in how far these processes interact with early syntactic processes. Rossi, Gugler, Hahne, and Friederici (2005) did not observe an interaction between two syntactic anomalies (violation of either word-category or morphosyntax) in the early time range (i.e., for the early negativity *vs*. the LAN), whereas interactive effects are found in a late time range (for the P600).

Phase 3: Syntactic reanalysis and repair

Secondary syntactic processes are assumed to take place in Phase 3. These may be reflected in a P600 which is usually elicited by processes of reanalysis and repair (Friederici & Mecklinger, 1996), or, in a more broad sense, of syntactic integration (Kaan, Harris, Gibson, & Holcomb, 2000). Although the P600 is mainly elicited by syntactic anomalies (Hagoort, Brown, & Groothusen, 1993; Osterhout & Holcomb, 1992), there is some evidence strengthening the interpretation of the P600 as reflecting processes of syntactic reanalysis and repair: The P600 varied as a function of the difficulty of syntactic integration (Kaan et al., 2000), and as a function of the difficulty of semantic integration in syntactically incorrect sentences (Gunter, Friederici, & Schriefers, 2000). Using an artificial grammar task, Bahlmann, Gunter, and Friederici (2006) found an ERP response that was comparable to the P600 in response to violations of the rules of the learned artificial grammar (for both grammar types – a finite-state and a phrase-structure grammar). Further, they demonstrated a posteriorly distributed negativity (around 300 to 400 ms) for the recognition of an unfulfilled expectation in the finite-state grammar.

Friederici et al. (2003) proposed the posterior portion of the STG, in addition to the left *basal ganglia* (BG), to contribute to the late integration processes underlying the P600, since this region was activated in response to both semantic and syntactic violations (Friederici et al., 2003; Newman, Just, Keller, Roth, & Carpenter, 2003). Likewise, evidence from lesion studies demonstrated a lack of a P600 in patients with lesions in the left BG while patients with lesions in the right anterior temporal lobe and the right BG demonstrated a reduced left-lateralized P600 effect (Friederici et al., 1999; Kotz, Frisch et al., 2003; Kotz, von Cramon et al., 2003).

Anatomical correlates of language processing

Two brain regions that are involved in almost all processing phases that are described in the model of Friederici and Kotz (2003) will be discussed in more detail in the next two sections. These brain regions are also main sites of syntactic processing, e.g., the sources of the ELAN were localized in these regions.

Superior temporal gyrus

The *superior temporal gyrus* is involved in all stages of the model by Friederici and Kotz (2003). It is mainly concerned with processing and storing perceptually based information. Several theoretical accounts exist for its functional significance: Scott, Blank, Rosen, and Wise (2000) demonstrated that anterior superior temporal responses are enhanced for intelligible speech whereas the most posterior area were merely associated with analysis of the phonetic cues and features linked to the temporal ordering of acoustic events. Later, Scott and Johnsrude (2003) proposed that the anterior system might be important for mapping acoustic-phonetic cues onto lexical representations, whereas the posterior system might process articulatory-gestural representations. Likewise, Hickok and Poeppel (2000) proposed the *posterior-superior temporal lobe* to be primarily involved in constructing sound-based representations of speech which may interface with different supra-modal systems. Stowe, Withaar, Wijers, Broere, and Paans (2002) proposed, the anterior temporal lobe might be involved in combining activated phonological, semantic and syntactic information or encoding the information for later use. Bornkessel, Zysset, Friederici, von Cramon, and Schlesewsky (2005) found enhanced activation in a network of inferior frontal, posterior superior temporal, premotor and parietal areas when manipulating the complexity of argument hierarchy structure. Within this network, an enhanced sensitivity of the left *posterior superior temporal sulcus* (STS) was related to morphological information and the syntactic realization of the verb-based argument hierarchy, while the activation of the *left inferior frontal gyrus* (*pars opercularis*) corresponded to linearization demands and was independent of morphological information.

Inferior frontal gyrus

The *inferior frontal gyrus* also contributes to almost all processing stages (i.e. Phase 0, 1, and 2) of the model of Friederici and Kotz (2003). This brain region is assumed to have specific importance for the processing of structural aspects of language. It was demonstrated to be relatively heterogeneous and to be the host of a large number of different functions many of which are not related to language processing. These functions include the processing of musical and linguistic syntax which are investigated in the present work. Thus, a comprehensive description of studies that investigated this brain region will be given.

Alexander, Naeser, and Palumbo (1990), and Dronkers (1996), were among the first researchers to provide evidence for functional heterogeneity of the IFG: Different deficits among Broca’s aphasics (including those in articulation, syntax, and naming) indicating that multiple regions of this area are involved in expressive language and that only disruption to all of them produces the catastrophic breakdown of language as revealed in aphasics. Anatomically, Amunts et al. (1997) found cytoarchitectonic differences which may be may be correlated to a functional segregation of the IFG. In a later study, Amunts, Schleicher, Ditterich, and Zilles (2003) reported a co-development of structure and function: While an hemispheric asymmetry is present for BA 45 by the age of 5 years, it is present for BA 44 only by the age of 11 years. Employing another method, subregions of Broca's area (BA 44, BA 45, and the deep *frontal operculum*) were distinguished by their pattern of anatomical connectivity (Anwander, Tittgemeyer, von Cramon, Friederici, & Knösche, 2006).

Dapretto and Bookheimer (1999) demonstrated that a semantic manipulation led to enhanced activity in anterior IFG, whereas a syntactic task activated a more posterior, superior area. Bookheimer (2002), thus, claimed a functional specialization within the IFG with at least three separate regions involved in syntactic, semantic, and phonological processing. Hagoort (2005) proposed the left IFG to play an important role in unification (i.e., to combine perceived or retrieved information into larger units on the basis of structural frames). This unification is assumed to take place in parallel at semantic, syntactic and phonological levels of processing. He further assumed, a separation along a functionally defined anterior-ventral to posterior-dorsal unification gradient (comparable to Bookheimer, 2002): whereas BA 45/47 are involved in semantic processing, BA 44/45 contribute to syntactic processing, and BA 6/44 play a role in phonological processing. Both views are mirrored in a recent review by Vigneau et al. (2006) who also observed a functional separation between several parts of the IFG. They investigating (in a meta-analysis of fMRI studies) which neural systems are dedicated to phonological, semantic, and sentential processing. The network for phonological processing consisted of temporal areas in the middle and posterior STG, extending into the *supramarginal gyrus* (SMG) as well as frontal areas mainly located in the posterior part of the frontal lobe (along the *precentral gyrus*) and one area in the IFG (the dorsal part of the *pars triagularis*). Some temporal clusters were overlapping with semantic clusters, suggesting the existence of crossroad areas linking semantic and phonological processes. A temporo-frontal semantic network is constituted of the *angular gyrus* and the *anterior fusiform gyrus* (two amodal conceptual temporal areas, devoted to meaning) and the temporal pole together with the IFG (*pars orbitalis*). The network for syntactic processing comprises of frontal areas in the IFG (the dorsal part of the *pars opercularis* and the ventral part of the *pars triagularis*) and temporal areas (the temporal pole, the middle portion of the *middle temporal gyrus* (MTG), and the anterior portion of the STG). Again, there is a substantial spatial and functional overlap of semantic and syntactic language functions.

The activation of the IFG (specifically Broca's area, BA 44/45) has been reported in many studies of both syntactic comprehension and production (e.g., Caplan et al., 1998; Dapretto & Bookheimer, 1999; Embick, Marantz, Miyashita, O'Neil, & Sakai, 2000; Friederici, Bahlmann et al., 2006 [for a review]; Friederici, Fiebach, Schlesewsky, Bornkessel, & von Cramon, 2006; Friederici, Meyer et al., 2000; Grewe et al., 2005; Homae, Hashimoto, Nakajima, Miyashita, & Sakai, 2002; Indefrey, Hagoort, Herzog, Seitz, & Brown, 2001; Just et al., 1996; Kaan & Swaab, 2002; Kang, Constable, Gore, & Avrutin, 1999; M. Meyer et al., 2000; Moro et al., 2001; Newman et al., 2003; Ni et al., 2000; Stromswold et al., 1996). From this evidence, it has been concluded that this area has a privileged status with respect to syntax processing. Early studies by Caplan et al. (1998) and Just et al. (1996) already found increased activity in the IFG during additional resource allocation to syntactic complexity.

Friederici, Meyer, and von Cramon (2000) concurrently varied the semanticity (words vs. pseudowords) and the syntacticity (sentences vs. word lists) of their stimuli and found frontal activation in response to semantic as well as to syntactic violations. An increase of activation bilaterally in the *planum polare*, and in the left deep *frontal operculum* was exclusively found for syntactic processing. Meyer, Friederici, and von Cramon (2000) extended these findings, demonstrating a stronger involvement of the right peri-sylvian cortex, in particular, when task demands required an on-line repair of ungrammatical sentences: while left hemisphere activation varied as a function of a sentence's grammaticality, the right IFG (*pars opercularis* and *pars triangularis*), the right *temporal transverse gyrus* (*Heschl's gyrus*) and the anterior portion of the STG bilaterally (*planum polare*) were more strongly affected by a grammatical repair task. Friederici et al., (2003) found distinct areas specialized for semantic and syntactic processes: Processing of semantic violations relied primarily on the mid-portion of the superior temporal region bilaterally and the insular cortex bilaterally, whereas processing of syntactic violations specifically involved the anterior portion of the left STG, the left posterior *frontal operculum* and the *putamen* in the left *basal ganglia*. Grewe (2005) demonstrated an activation of the left IFG (*pars opercularis*) that extended into the deep *frontal operculum* when processing complex (permuted) sentences. They suggest that the *pars opercularis* is selectively sensitive to the language-specific linearization of hierarchical linguistic dependencies while the deep *frontal operculum* is crucial for the detection of ungrammaticality. Likewise, Friederici, Fiebach et al. (2006) demonstrated a dissociation within the left inferior frontal cortex between the deep *frontal operculum* – responding to syntactic violations – and the inferior portion of the left *pars opercularis* (BA 44) – modulated by the complexity of well-formed sentences. The authors claimed, BA 44/45's function is to support the hierarchical reconstruction of the syntactic structure from the sequential input: Because language processing is realized as a sequential process – a word in a non-canonical position has to be identified as a moved element and to be kept active in working memory until its original position in the syntactic structure is reached. BA 44/45 may also serve a non-linguistic function. In these cases, its function may primarily be the internal reconstruction of sequential input (see chapter "Language and music"). Friederici, Bahlmann et al. (2006) related the different sites of activations to the processing of two classes of sequence types (finite-state *vs.* phrase structure grammar): Whereas the processing of local transitions is subserved by the left frontal operculum (which is involved in processing both grammar types), activity in Broca's area was related specifically to the computation of hierarchical dependencies (of the phrase-structure grammar). This assumption can be related to the claim, that recursion (i.e., the ability to process hierarchically structured sequences) is a critical issue to distinguish human and non-human communication systems.

5.3 Conclusions

Language is a unique human capacity with syntax as key component. Syntax may have evolved to overcome mistakes in communication. The sequencing of basic units can make utterances more discriminable and memorable and allows for some understanding even when information is partly missing. During language acquisition children need to master some prerequisite tasks (as word segmentation and the first steps into semantics) before they can acquire syntactic regularities. It is assumed that children are equipped with some constraints to manage these tasks. The acquisition of syntax requires the abstraction of regularities from the language input. To solve this task, statistical learning mechanisms may interact with prosodic cues and semantic knowledge. Neural correlates of syntactic processing may be developed quite early in life. First signs can be observed quite early in development (30 months). Their main anatomical location are regions in the *inferior frontal gyrus* and the *(anterior) superior temporal gyrus*. The *inferior frontal gyrus* is of specific importance for the processing of structural aspects of language. It was demonstrated to be the host of a large number of different functions, many of which are not related to language processing. The *superior temporal gyrus* is also involved in several processes during language perception. These are mainly concerned with processing and storing perceptually based information.

6 Specific Language Impairment

It is very impressive how fast children acquire the regularities of a complex system such as language. Language acquisition is a very demanding task, managed effortlessly by most of the children. It takes place relatively independent of external influences and children learn to perceive language and to produce speech on a roughly equivalent timetable.

However, there is also reasonably amount of children having problems to acquire their native language within the normal time range. Such language impairment may be secondary to other deficiencies as sensory malfunction (e.g., hearing problems, blindness), neurological disorders (e.g., brain lesions), motor malfunction, mental retardation (e.g., Down syndrome, Williams-Beuren syndrome), or pervasive disorders (e.g., autism). Different kinds of impairment are bound to specific problems or losses. This allows a better understanding, which abilities (that might be disturbed in language impaired children) may be essential for proper language acquisition.

In addition to language impairment which is secondary to other factors, 5 to 10 percent of all children (slightly more males) show language deficiencies that cannot be accounted for by such factors (cf. Leonard, 1998).[12] These children are denoted as having specific language impairment. They acquire language not that rapid and effortless compared to children with typical language development (TLD), i.e. they experience difficulties and have an impaired development in their language perception and production.

6.1 Definition

Different terms exist for primary language acquisition disorders: infantile aphasia, developmental aphasia, developmental dysphasia, delayed speech and language learning disability, developmental language disorder, specific language deficit, or language impairment. These reflect differences in theoretical background during the more than 150 years of scientific investigation of language acquisition and its impairments. Nowadays, “specific language impairment” is the most common term (with SLI as abbreviation). It was coined by Leonard (1981) and Fey and Leonard (1983), and is defined as a primary linguistic difficulty in the absence of non-linguistic causes (e.g., problems in intelligence, hearing, oral motor function, neurology, etc.; cf. Leonard, 1998).

Nonetheless, there is some discussion, if the term “specific” is appropriate in the definition of SLI: The assumption that impairment of any individual system remains entirely

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[12] Within Germany the incidence rate for specific language impairment was in a similar range and seems to be largely the same during recent years (Braun, 2006; Schöler, 2004).

independent of other systems is questioned by some evidence portraying the interactive nature of specific systems especially when they develop. Thomas and Karmiloff-Smith (2002) proposed the concept of interactive development, and challenged the assumption of "residual normality" in developmental disorders. Botting (2005) provided evidence for an interaction of non-verbal cognitive abilities that "challenge the implicit assumption that Residual Normality is a feature of SLI, i.e., only linguistic difficulties are problematic whilst other areas of development are 'spared'" (p. 323). It seems unlikely that severe deficits in general cognitive mechanisms would leave other cognitive domains untouched. Thus, it might be appropriate to drop the term "specific" from specific language impairment (Ors, 2002).

Nowadays, there are widely accepted diagnostic criteria for SLI (cf. Leonard, 1998). Most of these criteria are exclusory to allow to differentiate SLI from other types of impairment and typical, but delayed language development: [1] Linguistic abilities, measured with a language development tests (e.g., the SETK 3-5; Grimm, Aktas, & Frevert, 2001), must be at least 1.5 standard deviations (SD) below the mean of the "typical" (unimpaired) population (some authors favour a less, others a more conservative criterion [1.25 SD up to 2.00 SD]). [2] These children must have a nonverbal intelligence with the normal range (within 2 SDs around the population mean, i.e. at least 70 IQ points) and their nonverbal IQ values must be more than 1 SD higher than their scores in any subtest of the language development test. [3] Exclusory criteria are any hearing difficulties or recent episodes of *otitis media* with effusion; anomalies with regard to oral structure and oral motor function; or evidence of neurological dysfunctions (as seizure, cerebral palsy or brain lesions). [4] Finally, the children must not show any symptoms of impaired physical and social interactions (as, e.g., autistic children).

There is some discussion regarding criterion [2] (Bishop, 1997; Fey, Long, & Cleve, 1994; Lahey, 1990; Tomblin, Records et al., 1997). Some authors argue for a more conservative criterion of at least 85 IQ points. It is acknowledged that children with SLI show depressed general cognitive levels compared to children with TLD (Farrell & Phelps, 2000). Further, there is evidence of interactions between language development and non-verbal intelligence (discussed below; also see Botting, 2005). It seems highly unlikely that such severe language deficiencies (as these of children with SLI) will go along with IQ values in the normal range (Dannenbauer, 2004; Fey et al., 1994; Leonard, 1998). Even though a lowered IQ can be assumed as risk-factor, it surely does not provide an exclusive explanation why children develop SLI: Some children with a below-average non-verbal IQ will show typical language development. Moreover, it is assumed that “language impairment cannot be a simple consequence of low intelligence” (Pinker, 2001, p. 465).

There is a considerable amount of variability in the pattern of characteristics among children with SLI and the severity of their deficiencies may reasonably differ. Recently, there is some discussion regarding possible causes and risk factors, and subgroups with specific aetiologies. The different pattern of deficiencies may either reflect different subgroups with own aetiology or may be seen as modifications of SLI (cf. Bishop, 2000; Bishop, Bright, James, Bishop, & van der Lely, 2001; Bishop, Chan, Adams, Hartley, & Weir, 2000; Gopnik, 1997; Leonard, 1998; van der Lely, 2005; van der Lely, Rosen, & McClelland, 1998; van Weerdenburg, Verhoeven, & van Balkom, 2006). For example, Ors (2002) states, that “terminological confusion exists in the field of impaired language development in children” and proposed to use SLI “as an umbrella term, covering a wide range of different profiles that may even change over time” (p. 1025). She demanded a classification, based on empirical analyses of the different pattern of language deficiencies of SLI children that may allow assigning a certain difficulty either to a single subgroup or to regard it as general characteristic of SLI. This may enable describing and testing for different profiles, using comparable diagnostic instruments. In addition, it has to be determined, if such subgroups can be identified within different language backgrounds.

It was possible to identify subgroups by means of a qualitative analysis and a comparison of different linguistic abilities: Grimm (2000) reviews evidence of five subgroups that could be distinguished within a German-speaking population by their different profiles in a standardized language development test (HSET, Grimm & Schöler, 1978). Bishop (2004) reports four subgroups when investigating children in English-speaking countries: the first group showed their difficulties especially within grammar, the second group predominantly problems in understanding language whereas in a third group problems with language production were most obvious and for a fourth group the problems appeared mostly within their pragmatic abilities. Van Weerdenburg et al. (2006) evaluated the linguistic abilities of 6 to 8 year old children with SLI by means of factor and cluster analyses. The factor analysis revealed four factors: [1] lexical-semantic abilities, [2] verbal sequential memory, [3] speech production, and [4] auditory conceptualization. These factors allowed to classify different subgroups in a cluster analysis. This was taken as empirical support for the assumption, different subgroups of SLI children may exist. However, a large heterogeneity remained in the pattern of deficiencies and differences were found between age groups.

6.2 Delayed and impaired language development

Children with language impairment often were “late talkers”. These produce their first words relatively late and have a vocabulary of less than 50 different words at the age of 24 months. In contrast, children with TLD usually acquire these 50 words much earlier (around 18 to 19 months) and have a vocabulary of around 300 words at 24 months. It enables them to produce their first two-words-sentences (cf. Leonard, 1998). 12-20 percent of all children did not reach the 50-words-threshold at 24 months. Around half of these children are “late bloomers”. They return to normal levels of language proficiency by the end of the third year of life. The remaining half of the children shows a delayed language development and is mostly diagnosed as having specific language impairment. Approaching the 50-words-threshold leads to a differentiation of the vocabulary and the acquisition of syntactic regularities (see chapter “Language perception”). Thus, the delay children have in their language development may intensify during further development. Thus, an idea put forward by Leonard (1991) was to conceive SLI not as impairment but the lower end of a normal distribution (also cf. Tomblin & Pandich, 1999). That is, SLI children are assumed to acquire their first words and word combinations later than age-controls but otherwise to mirror the patterns of normally developing children.

Pre-schoolers with SLI usually are characterized by their limited speech production (whereas their language perception is much better developed); by their late acquisition of first words and word combinations; and by their special difficulties with phonological, morphological, and syntactic structure. For most SLI children, there seems to exist a relatively monotonic distance between the level of language perception and speech production (cf. Grimm, 2003). However, semantic and pragmatic abilities were found to be relatively intact (but see the discussion in Tomblin & Pandich, 1999), even though, they may have some word finding difficulties indicated by pauses, non-specific words (“stuff”, “thing”) and phonological and semantic word substitutions.

One of the main characteristics of SLI children are their syntactical and morphological deficiencies. Their problems may be especially severe for grammatical morphology: The use of most grammatical morphemes is lower and mastery is attained later in children with SLI. It remains unclear, if these morphosyntactic deficiencies should be characterized as quantitative (i.e., SLI children show intact grammatical knowledge but are delayed in its acquisition) or as qualitative difference (cf. Grimm, 2003; Leonard, 1998). Children with SLI use specific syntactic structures less frequently than age-controls and perform worse on measures that concern syntactic complexity and syntactic comprehension (e.g., reversible passives). Even though they use most argument structures, there is a lack of consistency in their use (e.g., SLI children frequently omit obligatory arguments).

Leonard (1998, p. 86 f.) concluded: "At a macro level, […] lexical and pragmatic skills tend to be less deficient than morphosyntactic skills, with argument structure and phonology falling somewhere in between. At micro level, we saw, for example, that grammatical morphology is weaker than other areas of morphosyntax, and phonological patterns apply less systematically than the children's phonetic inventories would lead us to expect".

Different pattern of deficiencies in SLI children, observed in different languages, may help to gain additional knowledge: A particular risk factor should lead to a specific pattern of deficiencies in different language backgrounds. This enables creating and testing of hypotheses on the nature of SLI (Clahsen, Bartke, & Gollner, 1997; Leonard, 2000; Leonard & Bortolini, 1998; Leonard, Hansson, Nettelbladt, & Deevy, 2004). Leonard (2000, p.128) states: „Cross-linguistic study has been extremely helpful in narrowing the field of potential factors that might have a detrimental effect […] Through continued cross-linguistic research, we should be able to increase our precision in identifying the crucial factors". Leonard (2000) investigated characteristics of SLI in English, Swedish, Italian, Spanish, and Hebrew, focusing on grammatical morphology and the use of grammatical function words. SLI children in a language background with a high amount of inflectional morphology (e.g., Italian) had fewer deficiencies in morphosyntax compared to children from a language background with relatively sparse inflectional morphology (e.g., English).

SLI children may also have problems with pragmatics, not exclusively caused by their problems with the lexicon and morphosyntax. For example, some SLI children fail to enter into multiparty conversations or use situation-specific phrases in inappropriate contexts. Even though they may interact appropriately in certain situations and may often reach the performance of MLU-matched controls in some respect. When these children grow older, they may lack of meta-linguistic knowledge (especially of phonological awareness), may have difficulties with narrative structure, with text comprehension, and in the acquisition of literary language. Knowledge acquisition is language based and children are required to understand increasingly complex sentences as they grow older. Therefore, children with SLI have a heightened risk for school problems, impaired cognitive abilities, and reduced social interactions (Botting, 2005; Dannenbauer, 2004; Snowling, Bishop, & Stothard, 2000; Suchodeletz, 2004).

6.3 Risk factors

In general, the aetiology of SLI remains elusive, mainly due to a very heterogeneous pattern of deficiencies. Currently, there is no well-accepted explanatory hypothesis the account for the heterogeneous pattern of deficiencies in children with SLI, and several hypotheses on possible causal factors for SLI exist in parallel. None of these hypotheses can account for all characteristics of SLI.

Different disciplines are involved in the scientific research on the nature and the treatment of SLI which may propose different explanations (cf. Ors et al., 2005; Tomblin, Hafeman, & O'Brien, 2003). Moreover, there is a lack of agreement about which symptoms should be regarded as characteristic for SLI (see, e.g., Dannenbauer, 2004). The ambiguity of the definition is not only caused by the complexity of the characteristics of SLI, but further by similar symptoms that may be accounted for by different conditions and etiological factors.

Tomblin et al. (1997) introduced the term “risk factors” instead of causal factors (see also Delgado, Vagi, & Scott, 2005). These may focus on biological, social, or cognitive aspects. Among these risk factors are, e.g., delayed brain development, defects in innate language acquisition mechanisms, deficiencies in auditory perception, difficulties to use language’s rhythmic-prosodic properties to segment the heard auditory information, deficient learning strategies, memory deficits, or an inadequate language environment. Some of these risk factors will be discussed below. They belong to three main categories: [1] General processing limitations, [2] specific deficiencies in auditory and language processing, and [3] biological, genetical, and psychosocial risk factors.

General processing limitations

Children with SLI may be characterized by general processing limitations. Such limitations may cause a wide spectrum of linguistic and non-linguistic deficiencies, including limited working memory capacity (see, e.g., Maillart & Schelstraete, 2002), or insufficient speed at information processing (see, e.g., Johnston & Weismer, 1983; C. A. Miller, Kail, Leonard, & Tomblin, 2001; Weismer, 1985). Compared to age-matched control children, SLI children were observed to be slower by a common factor on a wide range of tasks (Kail, 1994). There is some discussion regarding the relation between a reduced processing speed and the deficiencies of SLI children, specifically those for grammar processing (Dannenbauer, 2004; Maillart & Schelstraete, 2002). However, this risk factor is discussed controversially since the amount of deceleration in information processing was not linearly related to the severity of language impairment (Lahey, Edwards, & Munson, 2001).

Botting (2005) demonstrated interactions between language development and non-verbal intelligence. The pattern of IQ development is (at least to a certain extent) related to the linguistic progress: “IQ differences [between the measurements at 7 and 14 years] remain, even when baseline IQ and language [at 7 years] are controlled for statistically [which] might suggest an underlying cognitive deficit that has in turn affected linguistic ability, especially considering that […] language differences […] disappear when concurrent non-verbal IQ is the covariant” (Botting, 2005, p. 324). These effects might also be accounted for by assuming learning problems that are secondary to the linguistic deficiencies of children with SLI (Dannenbauer, 2004; von Suchodoletz, 2004).

Ullman and Pierpont (2005) proposed SLI as secondary to delayed or impaired development in brain structures essential for procedural memory system. They assume this deficit as causing the linguistic and non-linguistic deficiencies of SLI children. These may have problems in acquiring new or elaborating established motor or cognitive skills. This may especially affect the acquisition of grammar. SLI is seen by them as the linguistic expression of a more general deficit. This allows to account for the heterogeneous pattern of deficiencies and to incorporate non-linguistic deficiencies that may also be found in SLI children. It is, furthermore, argued that children with SLI might compensate at least for some deficiencies by exploiting the declarative memory system (e.g., by explicitly learning grammatical rules).

Specific deficiencies in auditory and language processing

Children with SLI may have difficulties on several stages of language processing. At ***early auditory processing stages***, problems due to poor processing of rapid or brief auditory stimuli may occur which in turn may contribute to SLI children’s language deficiencies. The seminal work of Tallal and Piercy (1973) revealed problems in the auditory processing for children from families that were at risk to develop language impairment. These children had problems to separate two tones that were intermitted by a short break of some milliseconds (see also Tallal, 1999; Zhang & Tomblin, 1998). These difficulties become more obvious with increased speed of presentation, when differences between the stimuli are decreased, when the memory load was increased (by adding redundant information), or when the information content of the auditory signal is decreased (Hayiou-Thomas, Bishop, & Plunkett, 2004; Kraus et al., 1996; Stark & Heinz, 1996; Tallal & Newcombe, 1978; Tallal & Rice, 1997). *Vice versa*, language comprehension of children with SLI improved to the level of children with TLD when sentences were presented at a slower rate (25% time expanded compared to a normal speaking rate; cf. Montgomery, 2004). Their difficulties in auditory processing were demonstrated to be a predictor for the linguistic abilities of these children at a later time

(Benasich & Tallal, 2002). Children with SLI seem delayed in their auditory development, since they performed like 4 years younger children with TLD in an auditory masking task (cf. Bishop & McArthur, 2004).

Bishop et al. (2005) compared children with SLI and TLD in an auditory discrimination task with a speech (discriminating minimal word pairs with background silence or noise) and a non-speech part (detecting the direction of frequency glides). While control and SLI groups did not differ on the glide tasks, a small but significant group difference was observed in the speech-in-noise task whose scores were weakly related to literacy level. McArthur and Bishop (2004; Bishop & McArthur, 2004) proposed a delayed development of the auditory cortex may be responsible for the difficulties of SLI children. They demonstrate age-inappropriate auditory ERP components in SLI children that, moreover, reached an adult-like appearance much later in development. Gilley, Sharma, Dorman, and Martin (2006) found different morphological categories of ERP responses in children with language-based learning problems: While one third had normal ERP responses, the remaining two thirds formed three atypical categories: [1] delayed P1 latencies and absent N1/P2 components; [2] typical P1 but delayed N1 and P2 responses; [3] generally low-amplitude responses. However, differences in auditory perception will not provide an exclusive causal explanation, because children with sensorineural hearing loss have difficulties in discriminating speech sounds, but may have relative normal linguistic abilities (Briscoe, Bishop, & Norbury, 2001). Further, the perceptual deficits in children with SLI can lose their impact whereas the linguistic deficiencies persist over time (Bernstein & Stark, 1985).

Joanisse and Seidenberg (1998; see also Joannisse & Seidenberg, 2004) assumed that deficits in basic (auditory) processing will also lead to deficiencies in learning and memory. The deficits in the linguistic (e.g., the phonological) abilities of SLI children are considered as secondary to such basic deficits. Perceptual deficits may result in a lack of some acoustic information consisted in the speech signal. In line with this argumentation, Weinert (1991, 2000) showed difficulties of SLI children to utilize prosodic-rhythmic properties when segmenting spoken language. For example, quite a lot of phonological cues are transient (e.g., formant transitions, voice onset time, aspiration, etc.) and require unimpaired perceptual processing.

At a second processing stage, the extracted information has to be stored and integrated. A crucial component at this stage is the ***phonological working memory***. There may be deficiencies in its function such that only a smaller amount of items can be hold in it (compared to children with TLD). These may be due to less capacity of the store, a more quickly decay of the representations, or not well-formed representations due to poor segmental analysis (Baddeley, 2003; Baddeley, Gathercole, & Papagno, 1998; Gathercole, Willis, Baddeley, & Emslie, 1994).

The neurophysiological investigation of phonological working memory often employs MMN paradigms, investigating the ability to detect (non-attentively) occasionally occurring 'deviant' stimuli within a sequence of identical 'standard' sounds. These deviants elicit a particular event-related potential (ERP) component, the mismatch negativity (MMN), reflecting an automatic comparison process within auditory sensory memory. Weber, Hahne, Friedrich, and Friederici (2005) compared the MMN responses to stimuli of bisyllabics that either had a very frequent word stress pattern (i.e. the trochee) or a less frequent one (i.e. the iambus). 5-month old infants that later had a very low word production (at 12 and 24 months), displayed a normal response when the more frequent (trochaic) pseudoword but a reduced response amplitude when the less frequent (iambic) pseudoword was the deviant item. That is, an impaired processing of word stress may be utilized as an early marker of risk for SLI. Uwer, Albrecht, and von Suchodoletz (2002) presented 5 to 10 year old children with tones, that differed in frequency (1000 vs. 1200 Hz) or duration (175 vs. 100 ms), and syllables (/ba/, /da/, and /ga/). Children with SLI had attenuated MMN amplitudes to speech stimuli, whereas the MMN response to tone stimuli did not differ between the children with SLI and TLD.

Working memory problems may also contribute to difficulties in language processing (especially at high processing speed). A possible interpretation for SLI children's deficiencies with complex syntax relies on the burden imposed on working memory by grammatical processing (Maillart & Schelstraete, 2002). Sentence understanding involves processing of grammatical cues. These have to be maintained in working memory. If children with SLI are restricted in their processing capacity they will base their sentence understanding on less demanding information. For the acquisition of grammar in children with TLD, working memory load was also a critical factor (Valian, Hoeffner, & Aubry, 1996).

SLI children's weaknesses in grammar were assumed to represent a lack of knowledge of a rule, principle or constraint, that is, insufficient mechanisms for processing grammar (see, e.g., Clahsen et al., 1997; Gopnik, 1997; van der Lely, 2005; van der Lely & Harris, 1990). Especially nativists (see the chapter "Language perception") postulate such an impairment of innate ***grammatical mechanisms***. These deficits may lead to an inefficient analysis of the language, causing the deficiencies of morphosyntax observed in children with SLI. Children with SLI may also misanalyse function words or other grammatical elements (such as bound morphemes) as lexical items. It might lead to difficulties in acquiring flexion rules to mark tense, number and person since (Gopnik, 1999) which can manifest in problems with generalizing morphologyical rules and applying them on nonsense-words. Most presumably, these deficiencies are not secondary to perceptual dysfunction: Even easy-to-be-perceived phonemes are often omitted or inappropriately utilized, or the same phoneme can be used more ore less appropriately in different contexts, e.g., the same suffix “-s” is more often correctly applied as possession marker in nouns than as a plural marker in nouns or as a third person singular marker in verbs (cf. Leonard, Sabbadini, Leonard, & Volterra, 1987). Moreover, several studies demonstrated that children with deficits in phonological short-term memory do not necessarily exhibit morphosyntactic deficits (Gathercole, Tiffany, Briscoe, & Thorn, 2005; Ramus, 2003).

Some of the theories proposing deficient grammar mechanisms will be outlined briefly: [1] The congruency deficit theory (Clahsen et al., 1997) assumes deficiencies to mark grammatical properties, equally within all word categories (e.g., to transfer person and number from noun to verb). [2] The extended optional infinitive theory (Rice & Wexler, 1996) proposed a delayed acquisition of grammatical tense and an extended period of its incomplete specification. [3] The deficit in Computational Grammatical Complexity (CGC) hypothesis assumed, children with SLI may be impaired in computing hierarchical, structurally-complex forms for one or more component of grammar (cf. van der Lely, 2005).

Children with SLI often lack using of complex syntax in conversation (i.e., sentences with embedded clauses; Marinellie, 2004). They were shown to have the ability to produce complex sentences (with examples of most syntactic structures), but they differed from children with TLD in the degree to which they use these linguistic structures. When the event memory of children with SLI was tested (using pictorial narratives), their abilities to use complex syntax and causal concepts was a better predictor than non-verbal IQ (Bishop & Donlan, 2005). Moreover, measures of narrative retelling and expressive syntactical skills were strong predictors of good language outcome, i.e. a return to typical language development (Botting, Faragher, Simkin, Knox, & Conti-Ramsden, 2001).

All these specific processing deficits may impair the abstraction of regularities (cf. Höhle, Weissenborn, Schmitz, & Ischebeck, 2001; Kuhl, 2004; Saffran, 2001b, 2002; Werker & Yeung, 2005). *Vice versa*, lack of these grammatical analysis mechanisms may interact with the acquisition of lexical material and contribute to deficiencies in word acquisition: Friedrich and Friederici (2006) demonstrated a lack of the N400 (an ERP component reflecting semantic processing) in 19 month old children at risk for SLI, i.e. children, that underperformed in a test of linguistic abilities (SETK-2; Grimm, Aktas, & Frevert, 2000) at 30 months of age.

Biological, genetic and psychosocial risk factors

Biological and genetic influences on SLI are mainly discussed, since more boys than girls suffer from language impairment and some evidence that SLI is highly heritable and tends to run in families (Stromswold, 1998, 2001).

Genetic influences on language development and the occurrence of SLI are an issue of intensive discussion (see, e.g., Bishop, Adams, & Norbury, 2006; S. E. Fisher, Vargha-Khadem, Watkins, Monaco, & Pembrey, 1998; Gopnik, 1997; Kovas et al., 2005; Meaburn, Dale, Craig, & Plomin, 2002; Palmour, 1997; SLI Consortium, 2004; Viding et al., 2004). It was shown, that SLI tends to run in families (Stromswold, 1998) and has a much higher concordance in monozygotic compared to dizygotic twins (Tomblin & Buckwalter, 1998).

The search for genetic factors is hampered by the heterogeneity of the deficiencies, i.e. the absence of a phenotype of this impairment: This is reflected by the lack of replication (see, e.g., Meaburn et al., 2002; SLI Consortium, 2004) for the finding of the gene FOXP2 on chromosome 7 responsible for SLI (Lai, Fisher, Hurst, Vargha-Khadem, & Monaco, 2001) – in this region a point mutation was observed in the affected members of the KE family and one unrelated person (the pattern of disorders in the KE family has been extensively studied, as half of them are affected by SLI). In contrast, the SLI consortium (2002, 2004) localized possible risk factors for SLI on regions on chromosome 16 (*SLI1,* correlated especially with the non-word-repetition-performance), on chromosome 19 (*SLI2,* correlated with performance in expressive language). Other studies found such regions on chromosome 13 (SLI3, see Bartlett et al., 2002), and on chromosome 3 (SSD, related to speech sound disorder, see also Stein et al., 2004). Newbury et al. (2005) differentiated, relying on this evidence, genetic risk factors for phonological working memory, and for deficiencies in the development of morphosyntax. They further describe risk factors in the child's environment. However, none of these factors is regarded as an exclusive explanation for SLI (see also Bishop et al., 2006).

Biological risk factors might be the lack of specialization of the two brain hemispheres, delays in the brain development, and differences in brain anatomy. SLI seems to have some relation to hemispheric dominance and there is an above-average proportion of non-right-handed children that suffer from SLI, whose handedness is less pronounced (Bishop, 2005; Grimm, 2003; Leonard, 1998; Neils & Aram, 1986). Ors et al. (2005) proposed differences in brain development and lateralization as a risk factor for SLI. They found a symmetrical instead of the (usual) asymmetrical pattern of cerebral blood flow. Locke (1997) assumed delayed brain development (resulting from genetic predisposition) which may cause language impairment – especially, if critical periods are missed due to the delay. Szagun (2001) provided evidence against this hypothesis, demonstrating more extended and flexible critical periods in language acquisition as assumed before: Cochlea-implanted children were able to acquire language, but their success was correlated with their pre-operative hearing skills. Moreover, their abilities in prosodic analyses were essential for their success in language acquisition.

Furthermore, there is some evidence for differences in brain anatomy between children with SLI and TLD (for a review, see von Suchodoletz & Allmayer, 2001). Anatomic differences were found, firstly, for the *planum temporale* (essential for phonological processing), e.g., a lack the usual leftward asymmetry (Gauger, Lombardino, & Leonard, 1997), or a bilaterally shrunk size (Preis, Jancke, Schittler, Huang, & Steinmetz, 1998); and secondly, for the inferior frontal lobe, e.g., a shrunk *pars triangularis* (Gauger et al., 1997), or a different configuration of *sulci* (Clark & Plante, 1998). In addition, a reduced cerebral blood flow was found for areas involved in language processing (cf. von Suchodoletz & Allmayer, 2001). However, it remained elusive, in how far these differences are crucial for the manifestation of SLI. Moreover, these neurobiological correlates may differ with respect to the specific pattern of deficiencies which is very heterogeneous among the children with SLI.

Social and psychological environment are essential for providing the growing up child with a stimulating atmosphere. There is heterogeneous evidence and controversial discussion if the socioeconomic status of the family should be regarded as risk factor. Several studies observed it – measured, e.g., as the level of parent's education, the number of siblings, and the position among siblings – as a risk factor for language impairment (for reviews, see Hoff & Tian, 2005; Noterdaeme, 2001). Other studies did not find such a relation (e.g., Delgado et al., 2005; Tomblin, Smith et al., 1997).

Children from lower socioeconomic strata acquired language more slowly (Dollaghan et al., 1999; J. Huttenlocher, Vasilyeva, Cymerman, & Levine, 2002; Rescorla & Alley, 2001), and had poor communication skills (Tomblin, Hardy, & Hein, 1991). This was, most presumably, related to the nature of their mothers' talk to them (Hoff, Laursen, & Tardif, 2002). Parental speech properties (specifically these of maternal speech) are important for language development (Bornstein, Haynes, & Painter, 2000; Hart & Risley, 1995; Hoff & Naigles, 2002; Weizman & Snow, 2001). An insufficient language environment is hypothesized as a strong risk factor on the emergence of specific language impairment, e.g., parents of SLI children were found to show non-appropriate reactions on their language impairment (for reviews, see Grimm, 2003; Leonard, 1998).

The findings on biological and genetic influences on SLI remain contradictory. SLI is clinically heterogeneous, and likely influenced by several genes that interact, both with each other and with the environment, to produce an overall susceptibility to the development of this disorder. It is, therefore, unlikely that they provide an exclusive explanation and not yet clear, how the genetic factors fit with other causal explanations of SLI. Even though psychosocial influences can be regarded as risk factors, moderating the severity of SLI, most presumably they also will not provide an exclusive causal explanation.

6.4 Specific language impairment and music perception

There is very few evidence concerning music perception in children with language disorders (Alcock, Passingham, Watkins, & Vargha-Khadem, 2000; Overy, Nicolson, Fawcett, & Clarke, 2003) and only few studies investigated music perception in children with SLI (e.g., Sallat, 2007; Weinert, 2000). For example, the ability to discriminate sounds of different frequency (pitch) may be impaired in SLI (for review, see McArthur & Bishop, 2001). Otherwise, there is a lack to find consistently a relation of nonverbal auditory deficits and problems with speech perception (see, e.g., Rosen, 2003). Therefore it might be interesting to determine in how far music perception is influenced in children with SLI.

Music therapy is common practise in the treatment of language impairment (Albert, Sparks, & Helm, 1973; Jungblut & Aldridge, 2004; Sparks & Holland, 1976). Music may also be utilized as soothing background music in special education populations (as children with SLI). Such therapeutic techniques included the structured use of music to reduce arousal which, in turn, increased attention and improved concentration (Savan, 1999). Unfortunately, there is comparably sparse scientific research regarding the principles on the basis of which both kinds of therapies work.

A strong relationship exists between music and language with music influencing, e.g., prosodic and semantic processing. Furthermore, it was demonstrated that there are common underlying neural resources of music and language processing. Specifically, a strong overlap was found for the neural substrates of music- and linguistic-syntactic processing. Moreover, prosody, i.e. the musical aspects of language, was demonstrated to contribute importantly to language learning. It may especially pave the way to the acquisition of syntax.

6.5 Conclusion

The different theoretical accounts to account for SLI and the heterogeneous pattern of deficiencies found in these children make it difficult to draw a firm conclusion. Instead, there is lack of causal explanation and one is left with a lot of puzzle pieces that not easily fit together. There are lots of possible risk factors which may result in SLI when they co-occur: “although previously proposed explanatory hypotheses can individually capture specific aspects of the empirical data, none of them can easily account for either the range or the variation of the particular impaired linguistic and non-linguistic functions found across SLI, and even within SLI subgroups.” (Ullman & Pierpont, 2005, p. 400). In a more strict way, Tomblin et al. (2003) summarized this in the statement: “Aetiology of SLI is unknown.” (p. 235).

In their acquisition of grammar, children with SLI might miss to notice the regularities in the language input. Many prerequisites of language acquisition may be important for music perception as well. For example, capacity limitations of the information processing – hypothesized for children with SLI – may hamper them to assess regularities in language and music. During language acquisition, these children may rely for a longer period on lexically specific item-based information and may require a larger verb vocabulary to extract pattern or schemata. Further, it might be harder for these children to build a critical mass of verb tokens and construction types which is crucial for this process.

7 Electroencephalography and Event-Related Potentials

Interactions between neurons evoking current flow across cell membranes are the essence of brain activity. The direction and magnitude of current flow in a neuron depends on the neurons it communicates with. This activity may be recorded by an electrode that will detect rapid change in voltage (or potential) caused by rapid changes in current flow due to action potentials. Current flow can also observed in the vicinity of synapses. The summed activity of many synapses on many neighbouring neurons (called field potential) can be recorded by a pair of electrodes – one placed directly in neural tissue and one some distance away.

Electroencephalography: Neuronal activity can also be recorded non-invasively from electrodes placed on the scalp. Such record of fluctuating potential across time is considered as an objective marker of neural activity that underlies cognitive processes, called EEG. Its amplitude is much smaller than invasively recorded field potentials because the skull and the scalp are strong electrical insulators.

The EEG is mainly caused by synchronously occurring post-synaptic potentials and thought to consist of sources from numerous cerebral areas with opposite electrical poles that constantly fluctuate. Its amplitude and polarity depends on the number and the amplitude of the contributing synaptic potentials, on whether current is flowing into or out of cells (i.e., movement of positive or negative ions, excitatory or inhibitory synaptic potentials), and on the geometric relationship between the synapses and electrode (i.e., current flow toward versus away from the electrode, or both toward and away, which will lead to cancellation of the opposing signals; Nunez, 1981). Cortical pyramidal cells (particularly in layer IV and V of the cortex) dominate the EEG signal, because they are the largest and most numerous cell type, and their dendritic processes are spatially parallel to their neighbours (Elul, 1971). Such an organization leads to summation of the small electrical fields generated by each active synapse. Given the low electrical conductivity of the skull, electrical potentials recorded from the scalp must reflect the activity of large numbers of neurons, estimated 1000 to 10,000 for the smallest signals recorded.

Usually, the electrodes used to measure EEG are placed at standardized positions at the scalp. Historically, the system of locating electrodes is referred to as International 10-20 system (Jasper, 1958): In this system, the electrodes are placed at sites that are placed in 10% and 20% distances from four anatomical landmarks (nasion, inion, and the perauricular points in front of the ears; see Figure 7-1). The American Electroencephalographic Society (1994) added electrode placement nomenclature guidelines that designate specific locations and identification of 75 electrode positions (see Figure 7-1, right part).

Any record of electrical potential consists of the difference between two locations, so that the polarity and spatial distribution of the EEG across the head depends on what pairs of electrodes is chosen. Typically, a single location or pair of locations that are somewhat more insulated from brain activity are used for reference. The difference of the electric potential between these electrodes and the remaining scalp electrodes is recorded.

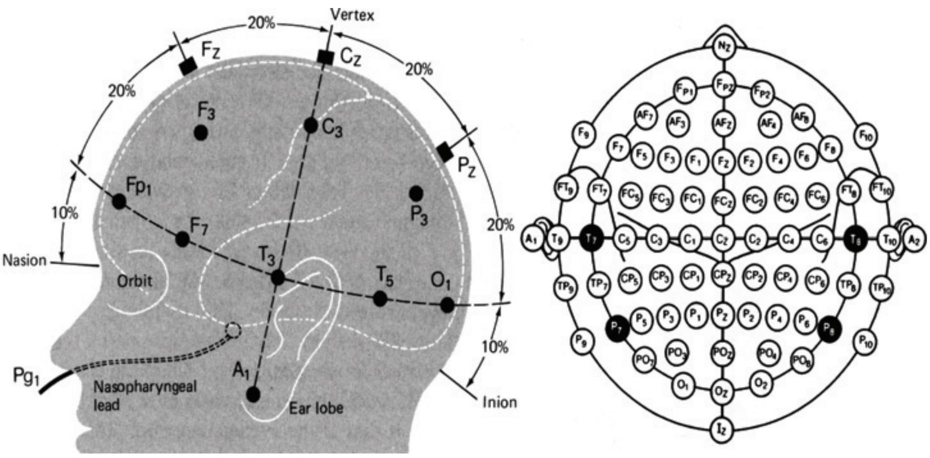

Figure 7-1 Electrode positions of the Internationational 10-20 system (left) and the extended International 10-20 system (right). Single plane projection with the location of the rolandic and the sylvian fissure. In the projections from top of the head (right) the outer circle represents the level of nasion and inion, the inner circle the temporal line of electrodes.

Event-related potentials: The electrical brain activity – reflected in the EEG – may be synchronized to some external event. At the scalp an event-related potential (ERP) is substantially smaller in amplitude (5-10 µV) than the background EEG (50-100 µV) and must, therefore, be extracted by averaging. This involves recording EEG within a particular time window following the (repeated) presentations of conceptually, if not physically, similar stimuli. According to the most widely accepted model, ERPs are generated by neuronal populations that become active time-locked to the stimulus. Another view is that ERPs result from reorganizing ongoing EEG activity, that is from a process incorporating phase control (e.g., from stimulus-induced phase resetting of ongoing EEG; Makeig et al., 2002). The basic assumption of averaging these time-locked epochs is that voltage fluctuations generated by neurons, unrelated to the processing of the stimuli of interest will be random and thus cancel each other, leaving a record of event-related activity. The number of stimuli needed for a reliable average is, thus, a function of the amplitude of the ERP component and the question under study: the smaller the component, the more trials that are needed to extract it from the spontaneous EEG.

The ERP waveform of voltage plotted against post-stimulus time consists of a series of positive and negative peaks; these are typically compared to a pre-stimulus baseline. Voltages are thus only negative or positive with respect to the baseline. The ERP peaks are typically labelled according to their polarity (negative [N] or positive [P]) and their latency in milliseconds relative to stimulus onset (e.g., N100, P230, P300). Occasionally, peaks are designated by their polarity and ordinal position in the waveform (e.g., N1, P1, and N2). Sometimes, the labels denote a functional description (e.g., mismatch negativity), refer to its presumed neural generator (e.g., auditory brainstem response) or its most reliable scalp location (e.g., left anterior negativity). Particular ERP "components" denote that, in response to an external stimulus, different parts of the nervous system with different function are involved at different time points. Thus, different temporal intervals of the waveform likely reflect different anatomical locations and different functional processes. Moreover, any particular interval may reflect more than one underlying process.

Usually, the amplitudes, latencies, and scalp distributions of the earlier ERP components (with latencies up to 100 ms) are highly reproducible across sessions within an individual (Halliday, 1993). Systematic variations in the physical parameters of the evoking stimulus (e.g., intensity, frequency, duration) lead to predictable changes in these early components reflecting the altered activation of sensory pathways. Hence, the earlier evoked components are considered to be "exogenous" or stimulus bound. For research on cognitive processes, the more informative brain waves are the "endogenous" components. The relative insensitivity of endogenous components to variations in the physical stimulus parameters contrasts with their exquisite responsiveness to task demands, instructions, and subjects' intentions, decisions, expectancies, strategies, etc. Thus, the same physical stimulus may (or may not) be followed by particular endogenous components depending on how the subject chooses to process it. Endogenous ERP components are not "evoked" by a stimulus but elicited by the perceptual and cognitive operations that are engendered by that stimulus.

EEG pre-processing: ERPs are so small that an artefact in a single trial may influence the appearance of the average. Time-linked artefacts may be emphasized by averaging. Thus, it is necessary to remove these artefacts before averaging. There are at least three different strategies to remove artefacts in EEG data: [1] filtering, [2] removing particular ICA components that represent artefacts, and [3] rejecting artefact-loaden trials.

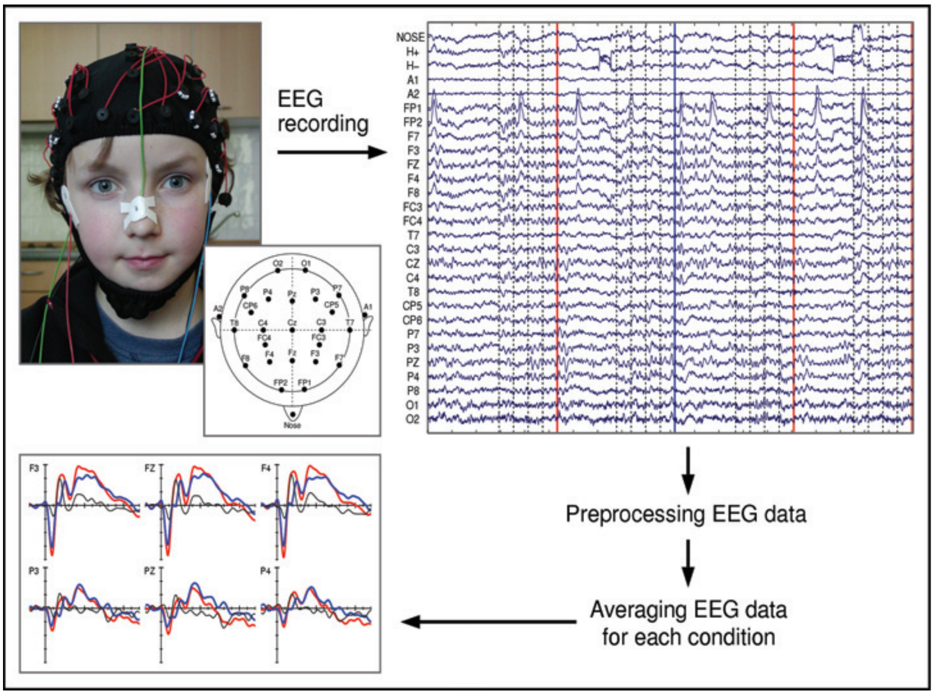

Figure 7-2 Schematic overview of recording and processing an EEG. Data (right-top) are recorded from several positions at the scalp (left-middle). Data are pre-processed (e.g., filtered, rejected). Finally, trials of the experimental conditions were averaged, resulting in event-related potentials (left-bottom). Different conditions are indicated by different colors of the ERPs and their respective trigger marks in the EEG.

Filtering: The basic idea of filtering EEG data is to remove frequency components that are regarded to represent noise. Filter may be either high-pass (removing low frequency components; e.g., electrode drifts), low-pass (removing high frequency components; e.g., muscle tension), or a combination of high- and low-pass filters (i.e., band-pass or band-stop filter). Filter design involves finding a good compromise between reduction of extraneous and the preservation of as much as possible from the fidelity of the brain waves that should be observed.

Removing ICA components: Basically, an ICA separates EEG activity into a number of distinct temporally maximally independent components (that may reflect either particular brain processes or artefacts; Bell & Sejnowski, 1996; Makeig, Jung, Bell, Ghahremani, & Sejnowski, 1997). Particular components that are regarded to reflect noise are rejected. This decision may be based on the scalp distribution of the component, on its frequency spectrum, or on the time course of the components activity (e.g., its coincidence with an eye-blink artefact in the EEG data).

Rejecting artefact-loaden trials: Rejecting denotes the exclusion of trials on the basis of particular, mostly statistical, criteria (e.g., if the amplitudes within that trial exceed a certain voltage threshold, the standard-deviation in a particular time window exceeds a threshold, etc.). These trials are excluded from the average.

When the EEG data are pre-processed, typically a defined epoch after the onset of a particular stimulus (representing a certain experimental condition) is averaged, resulting in an ERP (see above). A schematic overview of the different steps of recording and processing an EEG is given in Figure 7-2.

8 Experiments I – IV: Introduction

The present work investigated the processing of musical and linguistic syntax with four experiments in children of different age groups (2½, 5, 9, and 11 years old). Further, the influences of language impairment and musical training on these processes were examined.

Experiment I evaluated the processing of musical syntax in **2½-year old children**. It was set out to determine whether neural correlates of music syntactic processing can be already observed in children of this age.

Experiment II compared the processing of musical syntax in **5-year old children** which either had typical language development or specific language impairment (SLI). As children with SLI have clear deficiencies in their processing of linguistic syntax it should be investigated if comparable deficiencies could be observed in their processing of musical syntax.

Experiment III investigated the processing of musical and linguistic syntax in **9-year old children**. These children were either musically trained or not. An earlier study investigating the processing of musical syntax in adult musicians (Koelsch, Schmidt et al., 2002) found an enlarged brain response to a violation of musical syntax. The first objective of this experiment was to determine if a comparable enlargement could be observed in children with musical training. Moreover, there is mounting evidence for a considerable overlap in the neural resources that are involved in the processing of musical and linguistic syntax (see chapter “Music and Language”). Thus, another objective of Experiment III was to investigate if this overlap in the neural resources can lead to transfer effects from music- to linguistic syntactic processing, i.e. to an enlarged brain response when processing linguistic syntax in musically trained children.

Experiment IV investigated similar issues as Experiment III in an older group of **11-year old children** which were either musically trained or non-musically trained. The same experimental paradigm was employed to investigate how a higher amount of musical training influences the neural correlates of processing musical and linguistic syntax. It was expected that an enlarged brain response to both a violation of musical and linguistic syntax will be found in children with musical training.

9 Experiment I: Neural correlates of processing musical syntax in 2½-year old children

9.1 Introduction and Hypotheses

Experiment I investigated the neural correlates of music-syntactic processing in 2½-year old children. Specifically, it was set up to determine if these processes are already established in this age group. Currently, it is not known, at which age knowledge of music-syntactic regularities is acquired. Many researchers assume that this acquisition takes place until late childhood (i.e., 6 to 7 years; for a review, see Trehub, 2003d). In contrast, recent studies demonstrated that 5-year old children process musical syntax comparably to adults (Jentschke et al., 2005; Koelsch et al., 2003), but it is not clear if signs of these processes can be observed in younger children.

In the language domain, a recent study by Oberecker, Friedrich, and Friederici (2005) demonstrated that an adult-like ERP response to a violation of linguistic syntax is established in 2½-year old children. A considerable overlap in the neural resources that underlie syntactic processing for music and language was demonstrated in a number of studies (see chapter "Music and Language"). Moreover, some constraints that are involved in language acquisition may also contribute to the acquisition of music-syntactic regularities (see chapter "Music and Language"). Specifically, they may be utilized in the abstraction of structural regularities in accordance to which musical phrases are built. These findings indicate that both, the neural resources of syntactic processing and the cognitive mechanisms to acquire syntactic regularities are established in children of that age.

Therefore, it was hypothesized that neurophysiological correlates of music-syntactic processing are already established in children of this age group. This led to the expectation that an ERP response reflecting music-syntactic processing can be observed in 2½-year old children.

9.2 Methods

Participants

2½-year old children were examined in an ERP experiment investigating the processing of musical syntax. Data were collected from 96 children from native German-speaking parents.[13] All children were healthy, and had no hearing problems (i.e., they passed a screening for oto-acoustic emissions). Their parents signed a written informed consent that allowed the children to participate in the experiment. They received a compensation for expenses (20.00 €).

Children were excluded, [1] if they did not finish the experiment (12 children excluded), or [2] if the EEG measurement could not be evaluated (due to many artefacts, i.e., drifts, chewing, or excessive movement; 15 children excluded). All in all, the data of 69 children were evaluated (43 boys, 26 girls; 29 to 31 months old, *M* = 30 months).

The children were divided in two groups in which a slightly different experimental paradigm was used. The set of stimuli used in these paradigms differed with respect to the irregular chords: in one group (*N* = 37; 22 boys, 15 girls), the irregular chord at the end of a sequence was a supertonic; in another group (*N* = 32; 21 boys, 11 girls), it was a Neapolitan sixth chord.

Stimuli and paradigm

Experimental paradigm

In the ERP experiments, a well-established paradigm to investigate the processing of musical syntax in adults (e.g., Koelsch et al., 2000) and in children (Koelsch et al., 2003) was used. In this paradigm, EEG data were recorded while children listened to chord sequences that ended either on a regular or on a slightly irregular chord.

Figure 9-1 Examples of the musical stimuli that were used in the experiment. A: Chord sequence ending with a regular tonic. B: Chord sequence ending with an irregular supertonic. C: Chord sequence ending with an irregular Neapolitan sixth chord.

These sequences had a duration of 4800 ms and consisted of five chords (see Figure 9-1) and a pause. Two groups of participants were presented with a slightly different paradigm. These paradigms differed in the type of chord sequences that was used. In both groups, the first four chords (each 600 ms) were always the same – tonic, subdominant, supertonic and dominant. They were arranged according to the classical rules of harmony (Hindemith, 1940) and established a musical context toward the end of the sequence. With regard to the rules of harmony, the fourth chord (the dominant) induced a strong expectancy for a tonic chord at the fifth position of a sequence, since the domi-

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[13] The children took part in the German Language Development (GLaD) study. This study was supported by the Deutsche Forschungsgemeinschaft (FR-519/18-1). I am grateful to Angela Friederici for providing the opportunity to investigate the processing of musical syntax in these children.

nant-tonic progression at the end of a chord sequence is a prominent marker for the end of a harmonic sequence and is considered as basic syntactic structure of Western tonal music (Riemann, 1877). The last chord (1200 ms) was either a regular tonic (Figure 9-1A), or an irregular chord. It was different for the two subgroups: In the one group, it was a supertonic (Figure 9-1B) (previously used in two studies with adults: Koelsch, Jentschke, & Sammler; Koelsch et al., 2007). In the other group, it was a Neapolitan sixth chord (Figure 9-1C) (comparable to earlier studies with adults and children: e.g., Koelsch et al., 2003; Koelsch et al., 2000). In both cases, the irregular chord (supertonic and Neapolitan sixth chord) violated the expectancy of a regular musical structure. The fifth chord was followed by a pause of 1200 ms.

The objective of using different chord sequences was to investigate a more or less salient difference between regular and irregular chords: The regular tonics and the irregular supertonics used in the first group are very similar with regard to their acoustic properties (i.e., with regards to pitch repetition, roughness, and pitch commonality with the directly preceding chord; Koelsch et al.; Koelsch et al., 2007). In contrast, the irregular Neapolitan sixth chord used in the second group introduced both, an acoustic deviance (introducing two out-of-key notes) and a violation of harmonic regularities compared to the regular tonics.

The chord sequences were transposed to all twelve keys and repeated eight times, leading to 96 sequences per condition. They were presented in direct succession in pseudo-randomised order via loudspeakers. During the experiment (duration approx. 17 min) children sat in front of a monitor and watched a silent movie without semantic content.[14]

Behavioural measures

The participants of the GLaD study were evaluated on a wide range of different measures. One of these measures, a language development test (SETK 3-5, Grimm et al., 2001), was acquired in a further session (when the children were around 44 months old). The test contains four subtests evaluating different aspects of language processing:[15] [1] "Sentence comprehension" is assumed to reflect the complex interplay of phonologic, lexical-semantic, and morphologic-syntactic processing steps. [2] "Generation of plurals" is related to syntactic processing, especially knowledge of morphological rules, which are induced from spoken language by extracting rule-based patterns. [3] "Non-word repetition" is a measure of the ability to process and to store unknown phoneme

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[14] In the same session a language experiment was run which was part of the dissertation of Oberecker (2007).

[15] For a further, fifth subtest (Memory for Words) no population norms are provided. Therefore, we did not include this test in the evaluation.

patterns in short-term memory. [4] "Repetition of sentences" is taken to reflect grammatical knowledge and working memory functions, i.e. to employ knowledge of grammatical structures to process sentences and to store them in memory in a compact form. As outlined in the chapter "Specific Language impairment" one core diagnostic criterion for this disorder are below-average results (-1.25 SD) in any subtest of a language development test. This criterion was used to classify the children in two groups (at-risk vs. not at-risk for language impairment; $N = 13$ *vs.* $N = 43$) which were compared in a further analysis.

EEG recording and processing

EEG data were recorded with Ag-AgCl electrodes from 21 scalp locations (F7, F3, FZ, F4, F8, FC3, FC4, T7, C3, CZ, C4, T8, CP5, CP6, P7, P3, PZ, P4, P8, O1, O2) and 6 further locations on the head (V+, V-, H+, H−, M1, M2). Data were sampled at 250 Hz, with a reference at the left mastoid and without online filtering (using a PORTI-32/MREFA amplifier, TMS International B.V., Enschede, NL). Impedances of the scalp electrodes were (mostly) kept below 3 kΩ, for the remaining electrodes below 10 kΩ. Data were processed offline using EEGLab 4.515 (Delorme & Makeig, 2004). The data were re-referenced to linked mastoids (mean of M1 and M2), and filtered with a 0.25 Hz high-pass filter (finite impulse response (FIR), 1311 points; to remove drifts) and a 49 to 51 Hz band-stop filter (FIR, 437 points; to remove line noise). An independent component analysis (ICA) was conducted and artefact components (eye blinks or eye movements, muscle artefacts) were removed. Then the data were filtered with a 25 Hz low-pass filter (FIR, 277 points).[16] Data were rejected [1] for threshold (if amplitude exceeded ±120 μV), [2] for linear trends (if linear trend exceeded ±160 μV in a 400 ms gliding time window), [3] for improbable data (if the trial was lying outside a ±6 SD range (for a single channel) or ±3 SD range (for all channels) of the mean probability distribution)[17], [4] for abnormally distributed data (if the data were lying outside a ±6 SD range (for a single channel) or a ±3 SD range (for all channels) of the mean distribution of kurtosis values)[18], and [5] for improbable spectra (spectrum should not deviate from baseline by ±30 dB in the 0 to 2 Hz frequency window [to reject eye movements] and +15/−30 dB in the 8 to 12 Hz frequency window [to reject alpha activity]). Finally, non-rejected epochs were averaged (29 to 91 trials, $M = 70$) in a period of 0 to 1200 ms

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[16] This was done in a second step, firstly, since the ICA might not work properly on filtered data and, secondly, to allow for later frequency analysis with the same dataset. For the evaluation of the ERPs, frequencies above 25 Hz can be regarded as noise and should be removed.

[17] It is assumed that trials containing artefacts are improbable events.

[18] It is assumed that data epochs with artefacts sometimes have very "peaky" activity value distributions resulting in a high kurtosis whereas abnormal flat epochs have a small kurtosis.

after stimulus onset (length of the final chord) with a baseline from -200 to 0 ms. Epoch length and baseline values were chosen in accordance with earlier experiments using the same paradigm (e.g., Koelsch et al., 2003; Koelsch et al., 2000).

Statistical evaluation

It was assured that variables used in the analyses did not deviate from a standard normal distribution (with Kolmogorov-Smirnov tests; $0.11 \leq p \leq 1.00$; median = 0.70). For the analysis of the ERPs, four regions of interest (ROIs) were computed: left-anterior (F3, F7, FC3), right-anterior (F4, F8, FC4), left-posterior (P3, T7, CP5), and right-posterior (P4, T8, CP6), and three time windows were evaluated: [1] 240 to 320 ms (ERAN), [2] 650 to 850 ms (N5), and [3] 120 to 200 ms after stimulus onset. In a first analysis, ERPs were evaluated statistically by mixed-model ANOVAs for repeated measures containing the within-subject factors chord function (regular [tonic] *vs.* irregular chords [supertonic, Neapolitan sixth chord]), anterior-posterior distribution, and hemisphere (left *vs.* right) and the between-subjects factor subgroup (supertonics vs. the Neapolitan sixth chords as irregular chords). In a second analysis, the same ANOVA with an additional between-subjects factor subgroup was employed to compare the ERP responses in the children that were either at-risk or not at-risk for language impairment.

9.3 Results

Figure 9-2 and 9-3 present the ERP responses to the regular and the irregular chords. They show that an ERAN was elicited in response to the irregular supertonics compared to the regular tonics (Figure 9-2) and in response to the irregular Neapolitan sixth chords compared to the regular tonics (Figure 9-3). The N5, that usually follows the ERAN, had a very small amplitude size and could be observed only at few electrodes. In addition, another unexpected ERP component was observed around 100 ms. Its short latency indicates that it presumably reflects acoustic processing. Thus, this component is termed early acoustic difference (EAD).

ERAN: For the first analysis, the data from both subgroups were pooled. An ERAN was observed, peaking around 300 ms (see Figure 9-2 and 9-3). It was relatively broadly distributed over the scalp. It was larger in the right compared to the left hemisphere and in the anterior compared to the posterior ROIs (left-anterior: M = -0.61 µV, SEM = 0.39 µV; right-anterior: M = -0.94 µV, SEM = 0.42 µV; left-posterior: M = -0.47 µV, SEM = 0.32 µV; right-posterior: M = -0.87 µV, SEM = 0.32 µV). However, the lateralization of the ERAN was slightly different in the two subgroups: In the paradigm with the Neapolitan sixth chords, the ERAN was rather right-lateralized (right-anterior: M =

-1.02 µV, *SEM* =0.62 µV; left-anterior: *M* = -0.09 µV, *SEM* = 0.57 µV; see Figure 9-3). In the paradigm with the supertonics, it was rather bilaterally distributed (left-anterior: *M* = -1.12 µV, *SEM* = 0.54 µV; right-anterior: *M* = -0.86 µV, *SEM* = 0.56 µV; see Figure 9-2). Moreover, the ERAN was most prominent at central electrodes (see Figure 9-2 and 9-3). In contrast, in older children and adults the difference is strongest at frontal leads (see, e.g., Experiment III and IV and Koelsch et al., 2000; Koelsch et al., 2007).

An ANOVA with the within-subject factors chord function (irregular *vs*. regular chord), anterior-posterior distribution, and hemisphere and the between subjects factor subgroup (supertonics *vs*. Neapolitan sixth chords as irregular chords) was employed to statistically evaluate these effects. It revealed an main effect of chord function ($F_{(1,67)} = 6.67$, $p = 0.012$), reflecting the difference in the responses to the irregular vs. the regular chords. Moreover, an interaction of chord function × hemisphere × subgroup was slightly above the significance threshold ($F_{(1,67)} = 3.86$, $p = 0.054$) which likely reflects the slightly different lateralization of the ERAN in the two experimental paradigms.

Each of the two subgroups was further examined in another ANOVA (with the same within-subject factors as above). In the group in which the Neapolitan sixth chords were compared to the tonics, a main effect of chord function ($F_{(1,31)} = 3.69$, $p = 0.064$), and an interaction of chord function × hemisphere ($F_{(1,31)} = 3.80$, $p = 0.060$) were slightly above the significance threshold. In the group in which the supertonics were compared to the tonics, the ANOVA revealed an main effect of chord function that was approaching significance ($F_{(1,36)} = 3.11$, $p = 0.086$). Presumably, the relative small amplitude size of the ERAN led to the increase in error probability when the two subgroups were evaluated separately.

When children that were at-risk for language impairment were compared with children that were not at-risk, descriptively a difference of the ERAN amplitude was found between these groups: In the left hemisphere the ERAN amplitude was different for the two groups (not at-risk: *M* = -0.51 µV, *SEM* = 0.53 µV; at-risk: *M* = 0.29 µV, *SEM* = 0.79 µV) whereas no difference was found for the right hemisphere (not at-risk: *M* = -0.71 µV, *SEM* = 0.53 µV; at-risk: *M* = -0.84 µV, *SEM* = 1.00 µV). This might indicate deficient neural correlates of syntactic processing in the left hemisphere in the children that were at-risk for language impairment. However, given the small group size, and the small amplitude size together with a relatively large standard error of mean these descriptive results should not be overrated. In accordance, in an ANOVA with the same within-subject factors as above and risk status as between-subjects factor neither significant interactions of chord function with risk status nor any other significant main effect or interactions with chord function were revealed. An interaction of chord func-

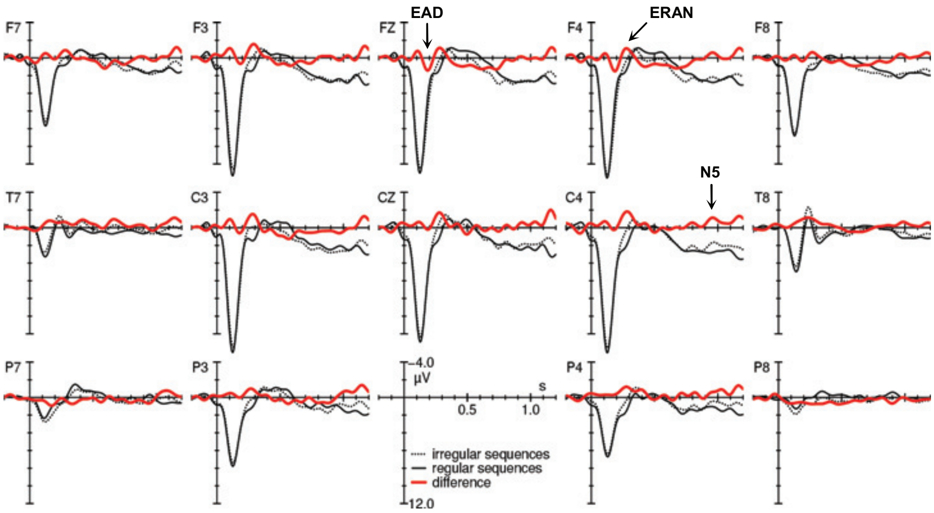

Figure 9-2 Grand-average ERP waveforms in the subgroup in which the supertonics were used as irregular chords. ERPs elicited by the final chords. Black solid lines indicate potentials elicited by regular (tonic) chords, black dotted lines responses to irregular chords (supertonics). Red solid lines represent the difference wave (regular subtracted from irregular chords). The evaluated ERP components are indicated by the arrows: ERAN, N5, and early acoustic difference (EAD).

tion × hemisphere ($F_{(1,54)} = 3.55$, $p = 0.065$) was approaching significance. It presumably reflects the stronger ERAN amplitude in the right hemisphere.

A further analysis evaluated, whether the ERAN remained significant when the children that were at-risk for language impairment were excluded. 43 children were classified to be not at-risk for language impairment; these were included in the analysis. An ANOVA with the same within-subject and between-subjects factors as the first analysis revealed an interaction of chord function × hemisphere × subgroup ($F_{(1,41)} = 7.48$, $p = 0.009$). It reflects the variable lateralization of the ERAN in the two experimental paradigms (see above; the difference in the response to the Neapolitan sixth chords compared to the tonics was more strongly right lateralized than the difference between the supertonics and the tonics).

N5: The ERAN is (in adults and older children) usually followed by an N5 taken to reflect processes of harmonic integration (cf. Koelsch, 2005). Descriptively, almost no difference was found in the ERP response to the irregular compared to the regular chords in this time window (left-anterior: $M = 0.32$ μV, $SEM = 0.36$ μV; right-anterior: $M = 0.23$ μV, $SEM = 0.32$ μV; the differences at posterior sites were smaller). In accordance, an ANOVA did not reveal any effects or interactions with chord function.

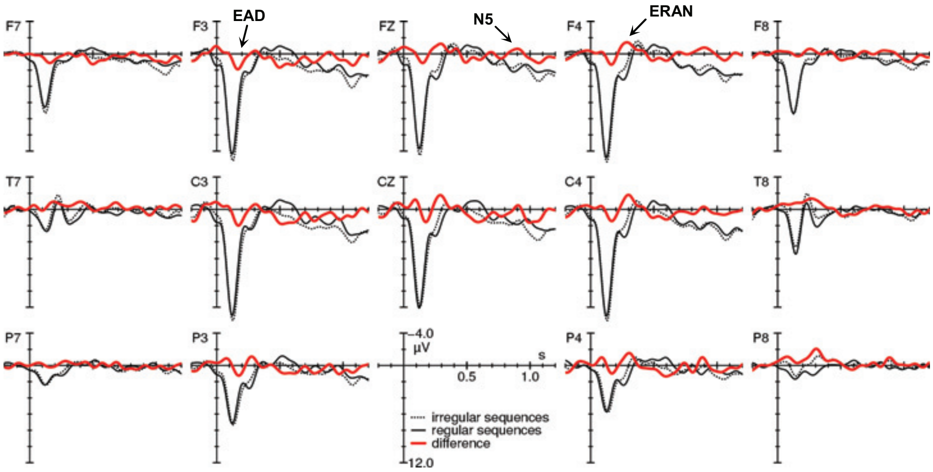

Figure 9-3 Grand-average ERP waveforms in the subgroup in which the Neapolitan sixth chords were used as irregular chords. ERPs elicited by the final chords. The black solid lines indicate potentials elicited by regular (tonic) chords, the black dotted lines responses to irregular chords (double dominants). The red solid lines represent the difference wave (regular subtracted from irregular chords). The evaluated ERP components are indicated by arrows: ERAN, N5, and early acoustic difference (EAD).

Furthermore, an early difference (EAD in Figure 9-2 and 9-3, preceding the ERAN) was observed. Descriptively, it appeared as a difference in the ERP response to the irregular and the regular chord functions with a maximum amplitude around 160 ms. It had a positive polarity and its amplitude was larger in the anterior (left-anterior: *M* = 0.64 µV, *SEM* = 0.31 µV; right-anterior: *M* = 0.55 µV, *SEM* = 0.27 µV) compared to the posterior ROIs (left-posterior: *M* = 0.38 µV, *SEM* = 0.31 µV; right-posterior: *M* = 0.02 µV, *SEM* = 0.31 µV). Such difference was also observed in other experiments using the same paradigm in children (other experiments of this work) and adults (Koelsch et al.; even though it was not evaluated in these experiments; Koelsch et al., 2007). Its functional significance remains to be specified in more detail. An ANOVA with the within-subject factors chord function, anterior-posterior distribution, and hemisphere and the between-subjects factor subgroup (Neapolitan sixth chords vs. supertonics as irregular chords) did not reveal any significant main effects or interactions with chord function. The main effect of chord function was approaching significance ($F_{(1,67)} = 3.72$, p = 0.058).

9.4 Discussion

The present experiment revealed that 2½-year old children process musical syntax comparable to older children and adults. The present data are the first evidence that an ERAN – reflecting the processing of musical syntax – is already established in 2½-year old children. However, the amplitude size of the ERAN was relatively small and, thus, the effect was significant only if the participants from both experimental paradigms were pooled. It might be present in some children, but absent in others. Thus, when the two experiments were evaluated separately, the ERAN is only approaching significance (for either subgroup). Moreover, whereas in adults and older children, violations of the musical syntax usually elicit an ERAN-N5 pattern in the ERP response, only an ERAN was observed in the 2½-year old children. Moreover, as in earlier studies (Koelsch et al., 2003), the latency of the ERAN was somewhat delayed compared to adults and older children (see, e.g., Jentschke et al., 2005).

The ERAN was – as in adults and older children – most prominent at right-anterior scalp sites. There was a slightly different lateralization of the ERAN in the two subgroups: The ERAN in response to the Neapolitan chords (compared to the tonics) was more right-lateralized, while the ERAN elicited by the supertonics was more bilaterally distributed. To account for this different pattern, one may consider that Neapolitan sixth chords are both, acoustic deviants (these chords contain two out-of-key notes) and music-syntactically irregular. In contrast, supertonics are no acoustic deviants (i.e. these chords are more strongly related to the sensory memory trace established by the previously heard chords than the tonics) but music-syntactically irregular (Koelsch et al., 2007). One may, thus, speculate that a stronger rightward lateralization of the ERAN can be observed when the eliciting chord is a salient acoustical deviant. A more bilateral distribution may be found when this chord represents a small acoustical deviance. This speculation is in accordance with earlier evidence: A stronger rightward lateralization was found, when Neapolitan sixth chords were used as irregular chords (see, e.g., Koelsch et al., 2000, Figure 3a). In contrast, a rather bilateral distribution was observed in experiments using supertonics as irregular chords (see, e.g., Koelsch et al., 2007, Figure 5B).

Descriptively, a difference between children that were at-risk or not at-risk for language impairment was found. Whereas in the left hemisphere an ERAN was present only in the children that are not at-risk for language impairment, the amplitude size in both groups for the right-hemisphere was similar. Some speculative reasoning might help to account for this finding. Children with specific language impairment are proposed to have a deficient processing of linguistic syntax (see chapter "Specific Language Impairment"). The ELAN, reflecting processing linguistic syntax, crucially involves neural generators in the left *inferior frontal gyrus* and the (*anterior*) *superior temporal gyrus* (see chapter "Language Perception"). A deficient function of these brain regions and the neural generators of this ERP response might lead to the lack of an effect in the left hemisphere in the children at-risk for language impairment. However, given the small amplitude size of the ERAN and the lack of significance, this difference should not be overrated.

In older children and adults, the ERAN is usually followed by an N5 taken to reflect processes of integration of the actual chord into the previous harmonic context (built up by the preceding chords). In 2½-year old children no N5 was found. It is possible that the positivity around 400 to 700 ms – that appears in the same time range as the N5 – reduced the amplitude size of this ERP component. Further studies should help to determine, when the processes of harmonic integration that are reflected in the N5 become established. Currently, there is evidence for their presence in 5-year old children (Experiment II and Koelsch et al., 2003). It remains to be specified, whether it can be observed in children that are between 2½-year and 5 years old.

An early difference around 120 to 200 ms (with a positive polarity) was approaching significance. It could also be observed in other experiments of this dissertation and previous experiments in adults using the same paradigm (Koelsch et al., 2007). As its amplitude was of almost the same size as the ERAN amplitude and has a similar scalp distribution (most prominent at anterior scalp sites) but a different polarity, there might have been an interaction of the ERAN with this component, leading to a reduction of the ERAN amplitude. The functional significance remains to be specified in further experiments. Some discussion about this issue can be found in the next chapter ("Experiment II").

Finally, it should be emphasized that the present experiment provides the first empirical results that neural correlates of music-syntactic processing are established in 2½-year old children, i.e. much earlier in development than previously assumed. They are, thus, in contradiction with assumptions that the acquisition of the musical regularities of Western tonal music has a relatively long duration, extending into late childhood (i.e., 6 to 7 years; cf. Sloboda, 1985; Trainor & Trehub, 1994; Trehub, 2003b). However, most of the measures used in these studies require the direct evaluation of musical stimuli and may, thus, underestimate children's musical knowledge. In contrast, ERPs reflect implicit knowledge and may thus be more sensitive than these explicit measures. A further advantage of this method is its applicability in preverbal children.

9.5 Conclusion

The present data provide evidence that first indicators of music-syntactic processing can be observed in 2½-year old children. The ERAN had a relatively small amplitude size and a higher latency (than in older children and adults). Commonly, an ERAN-N5 pattern is observed in response to a violation of musical syntax. However, an N5 was not observed in children of that age, demonstrating that processes of harmonic integration that are reflected by an N5 are not established yet. The small ERAN amplitude, its heightened latency, and the lack of an N5 indicated that the neural correlates of music-syntactic processing are still in development in 2½-year old children.

10 Experiment II: Neural correlates of processing musical syntax in 5-year old children with either Specific Language Impairment or typical language development

10.1 Introduction and Hypotheses

The present experiment compared music-syntactic processing in children with typical language development (TLD) and with specific language impairment (SLI). The strong relation of music and language (see the chapter “Music and Language”), specifically the strong overlap in the neural resources for music- and linguistic-syntactic processing is a central topic for all experiments in this work. Both the processing of musical and linguistic syntax involve the *inferior frontal gyrus* and the *(anterior) superior temporal gyrus* (see the chapters “Music and Language”, “Music Perception”, and “Language Perception”). In addition, the importance of the musical aspects of language (i.e., its prosody) in language acquisition is widely acknowledged (see the chapter “Music and Language”), and there is evidence for comparable mechanisms and constraints in the acquisition of both, music and language (see chapter “Music and Language”; also cf. Kuhl, 2004; McMullen & Saffran, 2004). Further, deficiencies in processing linguistic syntax are one of the main characteristics of children with SLI (see chapter “Specific Language Impairment”). Considering these aspects, one may hypothesize that the commonalities of music and language, the overlap in the neural resources and the difficulties of these children with linguistic-syntactic processing may lead to comparable deficiencies for the processing of musical syntax children with SLI.

The present study was designed to specify, [1] how the neural correlates reflecting processing of musical syntax develop during childhood, and [2] in how far these neural correlates interact with the occurrence of SLI. It was expected that 5-year old children with SLI would not show ERP responses that reflect the processing of musical syntax. In contrast, it was expected that the neural correlates of music-syntactic processing will be established in the children with TLD.

10.2 Method

Participants

Two groups of 5-year old children with either TLD or SLI were compared.[19] All children were right-handed (according to the Edinburgh Handedness Inventory; Oldfield, 1971) native speakers of German. Their parents signed a written informed consent to allow them to participate in the experiment. Children received a gift (e.g., a book, a game, a CD, etc.; value approx. 10.00 €) and a cuddly toy for their participation. The parents received a compensation for their expenses (7.50 €).

The children with SLI (N = 21) were recruited in a kindergarten for special education where they were treated in order to improve their language skills. Before entering the kindergarten, the children were screened for intelligence, language abilities, normal hearing and neurological deficits by a public health officer and the speech therapists at the kindergarten. Only children for which parents and teachers reported normal hearing and no history of hearing disease were included. Children were excluded, if [1] the EEG measurement could not be evaluated (due to many artefacts; 1 girl excluded), [2] the amplitudes of their ERP responses were outliers compared to the distribution in both groups (1 boy excluded; see “Statistical evaluation”), [3] they had less than 70 IQ points in the non-verbal part of the Kaufman Assessment Battery for Children (K-ABC; Kaufman, Kaufman, & Melchers, 1994; 1 girl excluded), or [4] they were not at least 1.5 SD below the mean of the population in any subtest of a language development test (SETK 3-5; Grimm et al., 2001; 2 boys excluded). Some researchers argue in favour of a further criterion: values in any subtest of the language screening should be more than 1.0 SD below the nonverbal IQ. Therefore, a separate analysis was conducted in which children who did fulfil this criterion (1 girl and 1 boy) were temporarily excluded. Since the pattern of results was similar, these children were re-included to improve the statistical power in further analyses. All in all, the data of 15 children with SLI were evaluated (4;8 to 5;11 years old, mean = 5;2 years; 8 boys, 7 girls).

The children of the TLD group (N = 24) were recruited from public nursery schools in Leipzig. The same criteria for inclusion and exclusion were applied: 3 children were excluded due to criterion [1] and 1 girl was excluded due to criterion [2]. In this group, the data of 20 children were evaluated (4;3 to 5;11 years old, mean = 5;3 years; 9 boys, 11 girls).

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[19] Children were between 4 and 5 year old, and had a mean age of around 5 years. For the sake of brevity, they are termed 5-year old children. The same applies for the older age groups (9- and 11-year old children).

Stimuli and paradigm

The experimental paradigm was essentially the same as in Experiment I, except that there was no second group (in which Neapolitan sixth chords were compared with tonics). In this experiment, irregular supertonics – that did not introduce a very salient violation – were compared to regular tonics (for a discussion, see Koelsch et al., 2007). Figure 9-1 provides an overview of the chord sequences. It could be demonstrated that the supertonics were acoustically more similar compared to the pitch representation of the preceding chords than the tonics: Figure Figure 9-1D presents the results from modelling the function of echoic memory using the IPEM-Toolbox (Leman et al., 2005).[20] This modelling determines the congruency of the actual chord with the pitch representation established by the previous chords in the chord sequence. It revealed that supertonics are more expected than tonics from an acoustical point of view. At the same time, these chords are harmonically irregular and violated the expectancy of a regular musical structure. *Vice versa*, the tonics do conform to the harmonic expectancies but are less expected from an acoustical point of view.

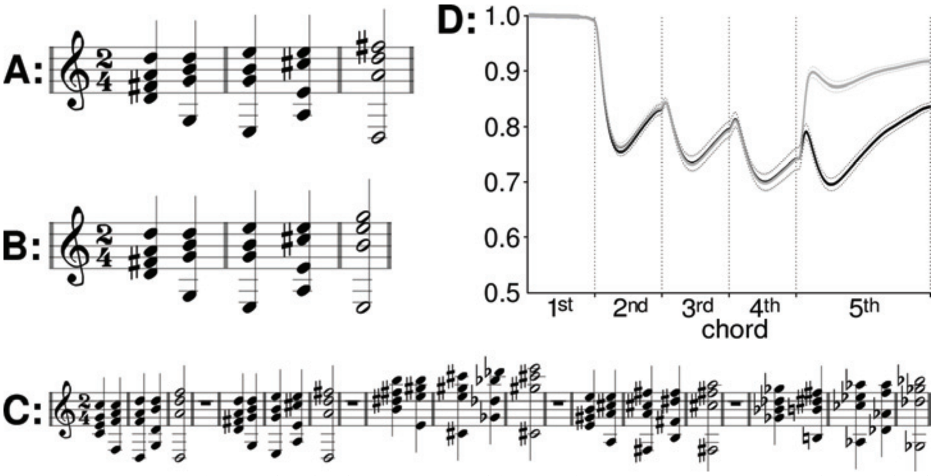

Figure 10-1 Overview of the chord sequences used in Experiment II – IV. **A-C**: Examples for chord sequences ending either on a regular tonic (A) or on an irregular supertonic (B). These sequences were played in direct succession (C). **D**: Correlation of the local context (pitch representation of the current chord) with the global context (pitch representation of the previous chords stored in echoic memory). The music-syntactically irregular supertonics (grey line) were more congruent with this context than the regular tonics (black line). Each line represents the mean of all twelve major keys (small dotted lines represent the standard error of mean). The modelling was performed using the IPEM Toolbox (Leman, Lesaffre, & Tanghe, 2005).

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[20] The results of this modelling were recently published in Koelsch et al. (2007).

Behavioural measures

It was necessary to acquire the current status of the linguistic development and the non-verbal intelligence of the children that participated in the study. These behavioural measures, i.e., the tests of language and music perception as well as the nonverbal part of an intelligence test, were acquired in further sessions (each approx. ½ to 1 hour). To evaluate the ***linguistic skills*** of the children, a language development test was employed (SETK 3-5; Grimm et al., 2001). It consisted of four subtests in order to measure different aspects of language processing. These were described in the previous chapter ("Experiment I"). Children with SLI are known to be especially hampered with respect to the induction of grammatical regularities. This is usually reflected in their below-average results, specifically for subtest "Generation of plurals" and "Sentence repetition". Difficulties in the subtest "Non-word repetition" are acknowledged to be a classical marker of SLI. These might be related to a lower capacity of the phonological store, a quicker decay of the representations or not well-formed representations due to poor segmental analysis in children with SLI.

The ***musical skills*** of the children were evaluated with several self-authored tests (cf. Sallat, 2007).[21] From these tasks, factors accounting for different classes of musical abilities (e.g., memory for musical phrases, reproduction of rhythms, etc.) were extracted (using principal component analysis). Only one of these factors ("memory for musical phrases") was significantly correlated with the amplitude of the ERP components. The tasks contained in this factor require melodic and rhythmic-melodic processing as well as the ability to store musical phrases in memory. Stimuli were either well-known or unknown phrases (beginning of German children songs or short melodies, 3 to 4 beats long), and their melodically or rhythmically modified versions. The factor was extracted from reaction times measures and represents how fast the children were able to identify if the original or a modified versions of a certain musical phrase was heard.

Non-verbal intelligence was measured with the Kaufman Assessment Battery for Children (K-ABC; Kaufman et al., 1994). The task sets differed slightly between the 4-year-olds and the 5-year-olds and contained the subtests "Hand movements" (repeating a sequence of hand movements), "Triangles" (constructing a given figure with rubber triangles), "Face Recognition" (recognizing a particular face within a picture; only for 4-year-olds), "Gestalt closure" (determining which complex figure in a set differs from the other figures; only for 5-year-olds), and "Spatial memory" (remembering the posi-

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[21] Only 25 of all children participated in these tests of musical abilities (all subjects of the SLI group and 10 subjects of the TLD group).

tion of objects; only for 5-year-olds). “Gestalt closure” did not conform to a normal distribution and for “Face recognition” only few measurements were acquired. These variables were therefore not included in the evaluation.

EEG recording and processing

The configuration of the channels used for EEG recording did slightly differ from that in Experiment I:[22] EEG data were recorded from 23 scalp locations (FP1, FP2, F7, F3, FZ, F4, F8, FC3, FC4, T7, C3, CZ, C4, T8, CP5, CP6, P7, P3, PZ, P4, P8, O1, O2) and 5 further locations on the head (NOSE, H+, H−, M1, M2). Other parameters were exactly the same as in Experiment I.

Statistical evaluation

For the statistical evaluation of the ERPs, four regions of interest (ROIs) were computed: left-anterior (F3, F7, FC3), right-anterior (F4, F8, FC4), left-posterior (P3, T7, CP5), and right-posterior (P4, T8, CP6). To guarantee that both groups did not differ in their primary auditory processing, the onset of the first chord of the sequence was evaluated. Two time windows were used in this analysis: [1] 0 to 100 ms, and [2] 100 to 200 ms. Statistical evaluation was performed with mixed-model ANOVAs for repeated measurements containing the within-subject factors time window (0 to 100 ms *vs.* 100 to 200 ms), anterior-posterior distribution, and hemisphere (left *vs.* right) and the between-subjects factor subgroup (TLD *vs.* SLI).

For the comparison of the irregular supertonics and the regular tonics four time windows were used (relative to stimulus onset): [1] 230 to 350 ms (ERAN), [2] 500 to 700 ms (N5), [3] 100 to 180 ms (early difference in the SLI group around 100 to 200 ms; due to an overlap with the beginning of the ERAN the time window was set to 100 to 180 ms), and [4] 800 to 1000 ms (late difference in the SLI group). All time windows were centred on the peak of the components. Two time windows were set to the peak of ERP components, consistently elicited by violations of musical syntax (see, e.g., Koelsch et al., 2003; Koelsch et al., 2000): the ERAN [1] and the N5 [2]. Two other time windows ([3], [4]) were suggested by visual inspection of the ERPs.

Outliers in the data were detected and removed (by means of the SPSS procedure EXAMINE) in order to guarantee for normality of the data. Thereafter, a Kolmogorov-Smirnov test revealed that the variables in the analyses did not deviate from a standard normal distribution ($0.383 \leq p \leq 0.990$; Median = 0.853).

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[22] The children in Experiment I participated in the German Language Devleopment (GLaD) study. Their EEG measurements were, thus, performed in Berlin. The measurement of the older age groups (Experiment II to IV) took place at the Max Planck Institute for Human Cognitive and Brain Sciences in Leipzig.

The statistical analysis was performed in two steps: In a first step, the ERPs of both subgroups were statistically evaluated by mixed-model ANOVAs for repeated measures containing the within-subject factors chord function (tonic *vs.* supertonic), anterior-posterior distribution, and hemisphere (left *vs.* right), as well as the between-subjects factor subgroup (TLD *vs.* SLI). The results of these ANOVAs are summarized in Table 10-1. As "chord function" was the factor that was experimentally manipulated only main effects and interactions with this factor will be mentioned in the "Results" section. Whenever the interaction of chord function × subgroup was significant, in a second step, two further ANOVAs were computed for each group of children separately. The ANOVAs had the same within-subject factors as above and tested which effects are significant in each group. Within all ANOVAs, user-defined contrasts were computed. They were used to specify the ROIs at which the difference between the two chord functions was significant.

Correlation analyses were used to investigate the relation between the ERP indicators of music-syntactic processing and the behavioural measures of linguistic abilities, musical skills, and non-verbal intelligence. Due to the bimodal distribution of the most variables (i.e., to the relatively distinct values in the two groups) non-parametric (Spearman) correlations were used. Finally, by means of a linear discriminant analysis, it was tested whether the children in the two groups (TLD or SLI) could be classified according to the amplitudes of their ERP responses.

10.3 Results

To ensure that difficulties of children with SLI in their processing of musical syntax are not due to deficiencies in primary auditory processing, the ERP response to the onset of the first chord of the chord sequence was evaluated (see Figure 10-2).

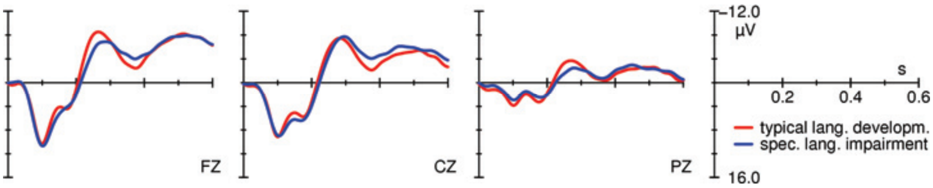

Figure 10-2 ERP responses to the onset of the first chord in the sequence: Children with typical language development (red solid lines) were compared to children with specific language impairment (blue solid lines)

No differences in the ERP responses reflecting early stages of auditory processing were observed between the children of both groups (TLD *vs.* SLI). In both groups, the amplitude of the ERP response was larger at anterior scalp sites and had essentially the same amplitude in the earlier (*0 to 100 ms, anterior ROIs*, TLD: *M* = 2.93 µV, *SEM* = 0.34 µV *vs*. SLI: *M* = 2.96 µV, *SEM* = 0.39 µV) and the later time window (*100 to 200 ms*, TLD: *M* = 3.92 µV, *SEM* = 0.87 µV *vs*. SLI: *M* = 4.54 µV, *SEM* = 1.00 µV). An ANOVA revealed neither a significant main effect nor any interaction with subgroup.

Thus, ERP response that reflect music-syntactic processing could be evaluated because differences that are found for these processes were most presumably not due to deficiencies in earlier processing stages. ERPs elicited by irregular (supertonic) compared to regular (tonic) chord sequence endings are shown in Figure 10-3, the scalp distributions of the amplitude differences in Figure 10-4.

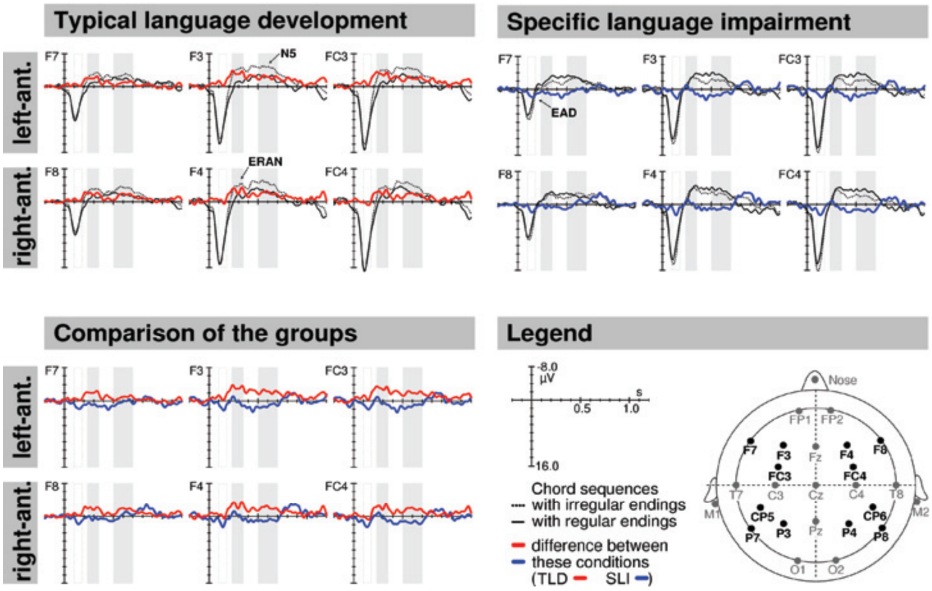

Figure 10-3 ERP responses to the irregular (black dotted lines) compared to the regular chords (black solid lines) and the difference between these conditions (red and blue solid lines). In the upper panel the ERP responses were shown for both subgroups: children with TLD (left), and children with SLI (right). In the left bottom panel the difference waves for both groups can be directly compared between children with TLD (red solid lines) and children with SLI (blue solid lines). Head positions of the electrodes from which data were acquired are shown in the right bottom panel (electrodes with labels written in black were contained in the ROIs used for statistical evaluation). Grey shaded and grey dotted rectangles in the diagrams represent the investigated time windows.

ERAN**:** The ERP data showed that an ERAN was elicited in the TLD group in response to the irregular supertonics compared to the regular tonics (*M* = -2.17 µV, *SEM* = 0.33 µV; anterior ROIs). The ERAN peaked around 240 ms and was most prominent over frontal leads (see Figure 10-3). In contrast, in the SLI group the response in the ERAN time window had an inverted polarity and its amplitude was very small (*M* = 0.82 µV, *SEM* = 0.77 µV). These differences between groups were also reflected in the scalp topographies: in the TLD group, a prominent negativity was clearly visible at anterior sites whereas none was evident in the SLI group (see Figure 10-4).

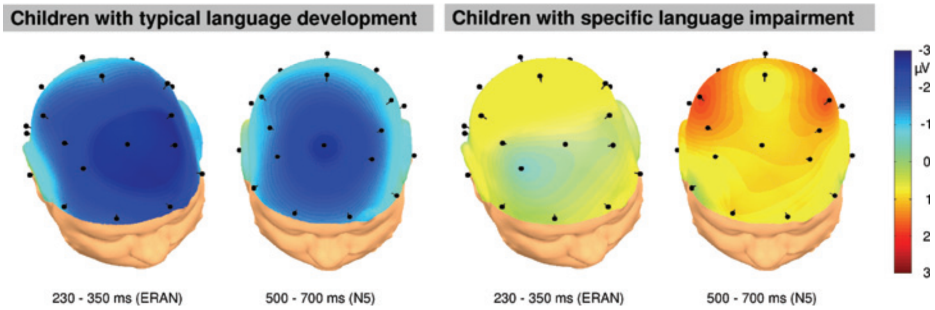

Figure 10-4 Scalp topography of the investigated ERP components (ERAN and N5): Mean of the difference amplitude of the two conditions (supertonics minus tonics) for the evaluated time windows. In the left panel the topographies in the group of children with typical language development are shown, the right panel contains the topographies in the group of children with SLI.

An ANOVA with the within-subject factors chord function (regular vs. irregular chords), anterior-posterior distribution, and hemisphere and the between-subjects factor subgroup (children with SLI vs. TLD) was employed to evaluate the ERP responses. For an overview of the results, see the second column of Table 10-1. The ANOVA revealed an interaction of chord function × subgroup and an interaction of chord function × anterior-posterior distribution × subgroup, indicating the elicitation of an ERAN in response to the harmonically less related chords compared to the harmonically related chords. The ERAN was present only in the children with TLD, and was most prominent over anterior sites. The main effect of subgroup was not significant, suggesting that the two groups differed in their responses to the experimental conditions but were comparable in their overall amplitude values.

To examine the interaction of chord function × subgroup in more detail, two further ANOVAs were computed for each group separately (with the same within-subject factors as above). In the TLD group, the ANOVA revealed a strong main effect of chord function ($F_{(1,\ 19)} = 24.10$, $p < 0.001$) and an interaction of chord function × anterior-posterior distribution ($F_{(1,\ 19)} = 9.18$, $p = 0.007$). In contrast, for the SLI group, neither a main effect nor any interaction with chord function was found. When the site of effect was tested (employing user-defined contrasts), a significant amplitude difference between to the two chord functions (supertonics vs. tonics) was found at both anterior ROIs in the TLD group (left: $F_{(1,19)} = 22.51$, $p < 0.001$; right: $F_{(1,19)} = 23.17$, $p < 0.001$)

as compared to no significant difference at any ROI in the SLI group. This reflects the elicitation of an ERAN over anterior sites in the children with TLD which could not be observed in the children with SLI.

Table 10-1 Overview of the results from the ANOVAs used to statistically evaluate the ERP responses. Three time windows were investigated: the early difference in acoustic processing (100 - 180 ms), the ERAN (230 - 350 ms) and the N5 (500 - 700 ms).

	100 -180 ms		230 – 350 ms		500 – 700 ms	
	$F_{(1,33)}$	p	$F_{(1,33)}$	p	$F_{(1,33)}$	p
chord func.	7.88	0.008	2.31	0.138	0.20	0.658
chord func. × subgroup	7.63	0.009	15.27	<0.001	8.33	0.007
chord func. × ant.-post. × subgr.	1.69	0.203	4.23	0.048	1.89	0.179
ant.-post. distribution	123.15	<0.001	20.54	<0.001	47.78	<0.001
ant.-post. × hemisphere	6.07	0.019	6.19	0.018	0.78	0.382
subgroup	1.49	0.230	0.01	0.936	0.25	0.619

NOTE: For the sake of brevity, only effects significant at least within one time window are reported in the table. Main effects and interactions with chord function are printed in the uppermost part of the table. Significant effects are written in black.

N5**:** The ERAN is usually followed by an N5 that was apparent in the TLD group as a negative difference in response to the irregular supertonics compared to the regular tonics (M = -1.47 µV, SEM = 0.52 µV). In contrast, the SLI group showed a response of a comparable size but with a reversed polarity (M = 1.14 µV, SEM = 0.87 µV). This was also reflected in the different scalp distribution in the two groups (see Figure 10-4): In the children with TLD, a marked negativity at frontal sites was visible whereas a positive difference was found at lateral parietal sites in the N5 time range for the children with SLI.

An ANOVA with the within-subject factors chord function, anterior-posterior distribution, and hemisphere and the between-subjects factor subgroup was employed to statistically evaluate the N5. The results are summarized in the third column of Table 10-1. It revealed a significant interaction of chord function × subgroup. As for the ERAN, there was a lack of main effect of subgroup, indicating that the overall amplitude values did not differ significantly between the groups. Again, two further ANOVAs (with the same within-subject factors as above) were employed to investigate the ERP response separately for each group. In the TLD group, the ANOVA revealed a main effect of chord function ($F_{(1, 19)} = 5.45, p = 0.031$) as well as an interaction of chord function × anterior-posterior distribution ($F_{(1, 19)} = 6.15, p = 0.023$). This indicated different responses to the irregular as compared to regular chords which was more pronounced in the anterior ROIs. In contrast, in the group of children with SLI, there was no significant difference in the ERP response to the two chord functions. User-defined contrasts helped to determine the scalp site at which the difference between the two chord functions was significant: In the TLD group significant differences were found for both anterior ROIs (left: $F_{(1,19)} = 4.49$, $p = 0.048$; right: $F_{(1,19)} = 8.90$, $p = 0.008$) whereas in the SLI group the differences were not significant at any ROI. Taken together, the pattern of results for the N5 resembled the pattern for the ERAN.

In addition to the results for the ERAN and the N5 (in the children with TLD), which are in accordance with our hypotheses, there was also an unexpected finding in the children with SLI: In contrast to the children with TLD, ERP responses to tonics and supertonics differed in the children with SLI around 100 ms after stimulus onset (see Figure 10-3). In children with SLI, tonic chords elicited a less positive potential around 100 ms ($M = 4.89$ µV, $SEM = 0.66$ µV; mean amplitude of all ROIs) compared to children with TLD ($M = 6.65$ µV, $SEM = 0.57$ µV). The ERP responses to the supertonics were similar in both groups (SLI: $M = 6.42$ µV, $SEM = 0.65$ µV; NLD: $M = 6.67$ µV, $SEM = 0.57$ µV).

An ANOVA with the within-subject factors chord function, anterior-posterior distribution, and hemisphere revealed a main effect of chord function and an interaction of chord function × subgroup (see first column of Table 10-1). However, no main effect of subgroup was found. That is, the amplitude values *per se* did not differ in the two groups. To investigate the chord function × subgroup interaction in more detail, two further ANOVAs were computed for each group separately. In the group of children with SLI, a main effect of chord function ($F_{(1,14)} = 10.72$, $p = 0.006$) was revealed whereas neither a main effect nor interactions with chord function were found in the TLD group.

For the difference in the ERP waveforms around 800 to 1000 ms, neither significant main effects nor interactions were found.

Correlation analyses and classification of the groups**:** In the hypotheses comparable difficulties with syntax processing in children with SLI were assumed for both language and music. This was tested by means of correlation analyses. Variables were, on the one hand, the ERP amplitudes in the ERAN and the N5 time window (at anterior ROIs; rows of Table 10-2) and, on the other hand, the behavioural measures (all subtests of a language development test, tests of musical abilities, and subtests of a non-verbal intelligence; columns of Table 10-2). For the amplitude of the early difference (around 100 to 180 ms) no significant correlations were found. All correlations are negative since superior results in the tests (mostly for children with TLD) are related to large (more negative) amplitudes for ERAN and N5 whereas inferior results in the tests (mostly for children with SLI) are linked to small (less negative) amplitudes for ERAN and N5.

Table 10-2 Correlations for the amplitudes of the ERAN, and the N5 (mean of the anterior ROIs) with measures of linguistic abilities, non-verbal intelligence, and musical abilities

		sentence compreh.	plural generat.	non-word repetition	sentence repetition	musical memory	hand movem.	tri-angles	spatial mem.
	N	*= 35*	*35*	*35*	*35*	*25*	*35*	*35*	*29*
ERAN	r	-0.390	-0.377	-0.456	-0.419	0.428	-0.397	-0.239	-0.452
	p	*0.021*	*0.026*	*0.006*	*0.012*	*0.037*	*0.020*	*0.174*	*0.014*
N5	r	-0.093	-0.295	-0.293	-0.262	0.296	-0.338	-0.352	-0.462
	p	*0.597*	*0.085*	*0.087*	*0.129*	*0.161*	*0.051*	*0.041*	*0.012*

NOTE: “r” denotes the correlation coefficient, “*p*” their statistical significance, and “N” the number of participants in that test. Significant correlations are written in black.

For all four subtests of the language development test a correlation with the ERAN amplitude was found. These subtests are taken to reflect the complex interplay of phonological, lexical-semantic, and linguistic-syntactic processing. For the sentence comprehension task, the plural generation and sentence repetition task, it is essential to employ grammar processing and knowledge of grammatical structures. The non-word repetition task is assumed to particularly tap the use of the phonological store. Some of the tasks, furthermore, require intact attention and working memory functions which are supposed to play an important role for establishing such structural relations between different parts of linguistic and musical material respectively during on-line processing.

Additionally, several tests of musical abilities were conducted. Within these, only the factors representing “memory for musical phrases” (column “musical memory” in Table 10-2) had a significant relationship with the ERAN amplitude. This factor reflects the ability for melodic and rhythmic-melodic processing and to store musical phrases in memory. It was extracted from reaction times measures and represents how fast the children were able to identify, if the original or a modified versions of a certain musical phrase was heard. The task is, on the one hand, based on melodic and rhythmic-melodic processing, that are central aspects of music-structural processing. Thus, it can be assumed that the difficulties of the SLI children might be related to their basic processing deficits with respect to structure in music and language. On the other hand, the correlation underlines the importance of short-term memory functions in music-syntactic processing (crucial for the ability to represent musical phrases in memory). The deficient memory functions might also contribute to the difficulties of children with SLI in this aspect of music processing.

Some theoretical accounts to SLI assume general processing limitations. Such limitations may lead to difference in general intelligence. Thus, we computed correlations of the amplitudes of ERAN and N5 with the subtests of a non-verbal intelligence test. The subtests “hand movements” and “spatial memory” correlated significantly with the amplitude of the ERAN. For the N5 amplitude, correlations were found with the subtests “triangles” and “spatial memory”. Again, this might be taken as evidence for the importance of working memory functions and (at least for “hand movements”) the ability to process and store ordered sequences, which can be relevant for these tests as well as for the processing of structure in music and language.

In this experiment, a characteristic pattern of results was observed: whereas an ERAN and an N5 were found in the group of children with TLD, these ERP responses were not found in the group of children with SLI. To investigate whether this pattern could be used to assign the children to their group based on their amplitude values, a linear discriminant analysis was used with the ERAN and the N5 amplitudes as variables (for the mean of the anterior ROIs). Since the N5 amplitude did not increase the amount of correct classifications, only the amplitude of the ERAN was used as predictor variable. With a significant canonical discriminant function (Wilks $\Lambda = 0.682$; $\chi^2_{(1)} = 12.45$, $p < 0.001$), 18 of the 20 participants in the TLD group and 9 of the 15 participants in the SLI group were correctly classified (77.1% of all participants).

10.4 Discussion

The present experiment evaluated the processing of musical syntax in children with TLD and children with SLI. An ERAN and an N5 in response to an irregular compared to a regular chord were found in 5-year old children with TLD. A comparable pattern of ERP components is observed as neural correlates of processing musical structure in adults (e.g., Koelsch et al., 2000). This indicates that 5-year old children utilize comparable neural mechanisms for these processes as adults. However, compared to adults, the latency of the ERAN was delayed, which replicates finding from earlier studies (Koelsch et al., 2003).

Notably, the elicitation of ERAN and N5 is due to the processing of a music-syntactic (not of a physical) irregularity. Tonics and supertonics are very similar in their acoustic properties (i.e., with regards to pitch repetition, roughness, and pitch commonality with the directly preceding chord; see Koelsch et al., 2007). Supertonics were acoustically even more similar to pitch representation of the preceding chords in the echoic memory (Figure Figure 9-1D): The supertonic is the more expected chord from an acoustical point of view whereas, at the same time, it is harmonically irregular and violated the expectancy of a regular musical structure. This indicates that even 5-year old children already possess cognitive representations of the syntactic regularities of Western tonal music, and they are able to process musical events fast and accurately according to these representations.

In contrast, for children with SLI, neither an ERAN nor an N5 were observed. Our hypotheses supposed that these children would have difficulties with music-syntactic processing and expected that they would show different ERP responses compared to the children in the TLD group. A very characteristic difference in the ERP pattern was found for the two groups. Thus, it was possible to correctly classify 77.1% of the children to either of the two groups (TLD, SLI) on the basis of their ERAN amplitude values in a linear discriminant analysis. These findings underline that difficulties in the language domain might lead to comparable difficulties in music perception.

To ensure that deficiencies in the processing of musical syntax in these children are not due to differences in their early auditory processing the ERP responses to the onset of the first chord in the sequence were analysed. No differences in the ERP responses to the onset of the first chord were observed between children with SLI and with TLD.

Correlations of the ERAN and N5 amplitudes with behavioural measures from several other cognitive and motor domains were found: Firstly, a clear correlation was found between the subtests of the language development test and the ERAN amplitude. This clearly indicates the strong relationship of music-syntactic and linguistic-syntactic processing, the latter of which is essential for the most tasks of the language development test. Secondly, the correlation of the ERAN with measures of musical short-term memory reflects an overlap of electrophysiological and behavioural indicators of the processing of musical phrases. Thirdly, the correlation of the spatial memory and hand movement subtests with the ERAN amplitude emphasizes the necessity of encoding and storing information in short-term memory and the ability to process and store ordered sequences. Results, in accordance with this finding, were obtained by Bauer, Hertsgaard, Dropik, and Daly (1998): The accurate reproduction of ordered (event) sequences was predictive for later language development. Furthermore, the correlations indicate comparable processing advantages or disadvantages, respectively, for children with TLD or with SLI. They further strengthen the assumption of a strong relation of syntactic processing in music and language.

An unexpected finding was a significant difference between the two chord functions around 100 to 180 ms in the children with SLI. It was not hypothesized and has not yet been described in earlier studies. However, it was observed in all experiments of this work and in earlier studies with adults using the same paradigm (Koelsch et al.; Koelsch et al., 2007; even though it was not evaluated there). Somewhat puzzling is that the difference should be apparent in both groups if it is elicited by processing acoustical information. A likely explanation is an interaction of the amplitude of this early difference with that of the ERAN. Both ERP components have a comparable scalp distribution but different polarity. Thus, it is possible that in children that show an ERAN (i.e., the children with TLD) this early difference is reduced because it overlaps with the onset of the ERAN. In contrast, in children with SLI (that do not show an ERAN) this effect can be more clearly observed since the onset of the ERAN does not overlap with it and reduces its amplitude size.

To account for this finding one may assume two processes that contribute to the processing of the two chords (tonic and supertonic): a merely acoustical and a merely cognitive process. These processes are thought to interact and to complement each other. In the model of Koelsch and Siebel (2005) the acoustic process may be related to “Gestalt formation” whereas the cognitive process may be related to “Structure building” (see chapter “Music Perception” for an introduction to this model). It might be further assumed that the acquisition of the music-syntactic regularities may influence the processing of acoustical information.

The acoustical process may be based on the overlap of the frequency spectrum of the actual chord (used to extract the pitch) and an echoic memory representation that contains the integral of the frequency spectrum of the preceding chords. In contrast, the cognitive process is assumed to rely on (mainly implicit) knowledge about Western tonal music (e.g., regular progressions of chords): The succession of chords activate a given key representation and give rise to expectations for further events, notably for events that are harmonically related to the context. Children with SLI, who lack this knowledge, may merely rely on acoustical information and therefore show this difference in the time range around 100 ms.

When the acoustical process, which is based on the function of echoic memory is modelled (see Figure 9-1D), the supertonic (grey line) is the more expected compared to the tonic (black line) at the onset of the fifth chord. With regard to the cognitive process, the dominant-tonic progression is one of the most basic syntactic structures of Western tonal music, and a prominent marker for the end of a harmonic sequence. Thus, the expectations of the chord to follow will depend on which kind of processing is the predominant one: when relying on the acoustic process, the supertonic is the most expected chord at the end of the sequence; when relying on the cognitive process, the most expected chord is the tonic. Children with TLD did acquire knowledge of harmonic relationships and key membership. Thus, they may rely primarily on the cognitive process, easily integrate an incoming acoustic stimulus into the tonal context, and rely less on physical judgements. In contrast, children with SLI may primarily rely on the acoustical process and have deficiencies in the cognitive process (which is indicated by their lack of an ERAN and an N5). The ability to detect invariant aspects of the structural relations within the elements of the sequences (e.g., chords or tones) might be deficient in SLI children. This ability is essential for the acquisition of implicit knowledge of musical syntax. This knowledge provides the basis for the cognitive operations involved in syntax processing. Moreover, these processes appear in direct succession and their onset is overlapping in time: the acoustic process around 100 to 200 ms, the cognitive process (reflected by the ERAN) around 230 to 350 ms. As the observed ERP components have a different polarity, the onset of the ERAN may reduce the amplitude size of the early acoustic difference.

Somewhat contrasting with the assumption that children with SLI may merely rely on the acoustical process is the lack of a difference between children with SLI and children with TLD in their ERP responses to the first chord of the sequence: For the initial 200 ms of the first chord no difference between the two groups was found (neither a main effect nor any of the interactions with subgroup were significant). It should be emphasized that the lack of finding a different ERP response to the onset of the chord sequence and the above made assumptions differ with regard to the processes that underlie them: At the onset of the chord sequence there is no memory representation of preceding chords in echoic memory (because the preceding sequence was finished and followed by a silent interval) whereas the acoustic process mentioned above builds upon these echoic memory representations.

However, even though the above made reasoning is consistent, it remains speculative. Thus, this early effect should be replicated and confirmed, and its functional significance remains to be specified in further studies. Unfortunately, no correlations of the amplitude of the early acoustic difference with other behavioural measures were found. Such correlation would have allowed getting an idea of what cognitive processes are related to this early acoustic difference.

The results of this experiment can be summarized focussing on underlying memory processes and the commonalities of language and music. These accounts do not exclude each other. Firstly, the memory deficiencies contributing to the differences between children with TLD and with SLI might be related to a deficit of the procedural memory system in children with SLI (Ullman & Pierpont, 2005). Further, some of the correlations with the ERAN amplitude emphasize the importance of working memory functions for music-syntactic processing: A prerequisite to comprehend a musical or a sentential phrase is to hold the elements of this phrase in memory and to build relations between these elements in order to detect the underlying structure, to group these elements together, and to build a coherent percept. It is conceivable that children with SLI are impaired with regard to these processes, which may lead to their deficiencies in both, processing of musical and linguistic syntax.

Secondly, the present results may reflect that children with SLI may demonstrate comparable difficulties when processing musical and linguistic syntax because comparable neuronal networks underlie these processes. On a more abstract level, the results of the present study (especially the correlations of the ERAN amplitude with behavioural measures from different domains) might be accounted for by assuming a common underlying factor related to processing and storing ordered sequences which rely on structures and regularities. As pointed out (see chapter "Music and Language"), the *inferior frontal gyrus* (IFG) can be assumed to be a neural basis for these processes. Specifically, the correlations of the ERAN amplitude with all subtests of the language development test are taken to reflect the strong neural overlap when dealing with linguistic and musical syntax. These abilities, essential for both domains, might be disturbed in children with SLI leading to the difficulties of these children for language as well as music. The perception of music might implicitly train certain parts of the language network and could therefore be an important contribution for the treatment of SLI. A more detailed discussion of these issues will be provided in the "General Discussion".

Thirdly, these correlations of the ERAN amplitude with the language development test may also be an indicator for the importance of musical elements in early language acquisition in children. It has been hypothesized that music and speech are intimately connected in early life (Trehub, 2003c), and that musical elements pave the way to linguistic capacities (Fernald, 1989; Papoušek, 1996).

10.5 Conclusion

The main finding of this experiment is the absence of ERP indicators of music-syntactic processing (ERAN and N5) in children with SLI whereas these indicators are present in children with TLD. This indicates that the deficiencies with syntactic processing in language, commonly found in children with SLI, were also observed for the processing of musical syntax. The most likely explanation for these finding are the shared neural resources that underlie these processes.

11 Experiment III: Neural correlates of musical and linguistic syntax processing in 9-year old children with or without musical training

11.1 Introduction and Hypotheses

This experiment investigated the processing of musical and linguistic syntax in 9-year old children. Up to now, the evidence on how these processes develop is relatively sparse and only few studies investigated these issues with neurophysiological methods (e.g., Hahne et al., 2004; Koelsch et al., 2003; for a more detailed overview, see the chapter "Music Perception" and "Language Perception"). Thus, one aim of the present experiment was to increase our knowledge about the development of the neural correlates of the processing of syntax in music and language.

Another aim was to compare these neural correlates of syntax processing in children that either were or were not musically trained. This aim builds upon evidence from a number of previous studies. Firstly, there is mounting evidence that musical training may lead to changes in the neural correlates of music perception. This neural plasticity may take place on several levels of music perception (for a discussion, see the chapter "Musical Training"). A study by Koelsch et al. (2002) that demonstrated an influence of musical training on the brain correlates of music-syntactic processing. Secondly, a strong relation of music and language is proposed by a number of researchers (e.g., S. Brown et al., 2006; Koelsch & Siebel, 2005). Particularly, the musical aspects of language are proposed to be important for its acquisition (e.g., Papoušek et al., 1992; for a more detailed discussion, see the chapter "Music and Language"). Of specific importance for this study is a strong overlap in the neural correlates of processing musical and linguistic syntax (see the chapter "Music Perception", "Language Perception", and "Music and Language"). Based on this evidence, it was hypothesized that musical training may lead to changes in the processing of both musical and of linguistic syntax.

Therefore, this experiment evaluated two groups of children that either received musical training or not. A within-subject comparison – involving two sessions in which the neural responses to either a violation of musical or of linguistic syntax were measured – was performed. It was expected that the neural correlates of syntactic processing should be present in both groups. Since children with musical training have an increased knowledge of music-syntactic regularities, it was further hypothesized that the neural correlates to music-syntactic processing would have an enlarged amplitude in the musically-trained children. Furthermore, since there is an overlap in the neural resources underlying syntax processing in music and language, these children were also expected to have an enlarged amplitude of their neurophysiological correlates of linguistic-syntactic processing.

11.2 Methods

Participants

9-year old children (N = 42) were assigned to groups depending on whether they had or had not received extracurricular musical training. All were right-handed (according to the Edinburg Handedness Inventory; Oldfield, 1971), native speakers of German. They did not have any known hearing or neurological deficits, nor attention deficit disorders, nor reading or learning disabilities (e.g. dyslexia). All parents gave a written informed consent to allow their children to participate in the experiment. Children and parents were compensated as in Experiment II.

The children with musical training (MT; *N* = 23) were recruited from the public music school in Leipzig. Children were excluded, if any of the following three conditions was met: [1] The EEG measurement could not be evaluated (due to many artefacts; 1 girl and 1 boy excluded), [2] there were any problems or delays in their language development (1 boy excluded), or [3] the group classification was not clear (e.g., if the children stopped to learn an instrument; 1 boy excluded). Finally, 19 children were evaluated (12 girls, 7 boys; 8;5 to 9;11 years old, *M* = 9;4 years). They had played an instrument for 17 to 69 months (*M* = 40 months).

The children without musical training (NM; N = 19) never learned an instrument or received no singing lessons and did not have any special musical education besides normal school education. They were recruited from public schools in Leipzig. Children were excluded, if [1] the experiment could not be finished (e.g., due to lack of compliance or problems with the measurement; 1 girl and 1 boy excluded), [2] they had language impairment or learning difficulty (1 girl and 2 boys excluded), or [3] the group classification was not clear (e.g., if the child started to learn an instrument for less than 1 year; 1 girl excluded). Finally, 13 children were evaluated (8;1 to 9;11 years old, M = 9;1 years; 4 girls, 9 boys).

There was no group difference in the results of the verbal part of the Wechsler Intelligence Scale for Children (HAWIK-III; Tewes, Rossmann, & Schallberger, 2000). These analyses are described in the “Results” section. Further, there was no difference in duration of their mother’s education, or the socio-economic status values of their mother’s occupation (ISEI; Ganzeboom & Treiman, 1996). The values of their father’s duration of education and socio-economic status were larger in the MT group. However, in Experiment IV – where the subgroups were better matched with regard to these variables – a group difference between musically trained and non-musically trained children was found for the processing of musical and linguistic syntax. It suggests that this group difference is relatively independent of such variables as intelligence and parental education.

Stimuli and paradigm

Experimental paradigm

EEG data were recorded in two experimental sessions investigating either a violation of musical syntax or a violation of linguistic syntax. The order of the music and the language sessions was counter-balanced across participants within each group.

The stimuli for the **music experiment** were the same as in Experiment II. The paradigm was slightly changed. Firstly, to increase the signal-to-noise ratio of the EEG measurements a further part was added to the experiment. In this first part, children sat in front of a monitor and looked at a fixation cross (attentive part). The second part was the same as in Experiment I and II, i.e. the children saw a silent movie (non-attentive part). Both parts had a duration of around 17 min. Between the two parts of each session subtests of an intelligence test (Tewes et al., 2000) were performed. Secondly, additional 18 sequences consisting of one chord played by a deviant instrument were presented. In both parts of the experiment, the children had to react with a key press whenever they heard a deviant instrument (to control for their attention).[23]

The **language experiment** employed a well-established paradigm to investigate the processing of linguistic syntax in adults (Friederici et al., 1993) or in children (Hahne et al., 2004). In this paradigm, sentences were presented that were syntactically either correct or incorrect. These sentences consisted of at least four words that had the same grammatical function, i.e. an article, a noun, an auxiliary and a past participle (see Figure 11-1). The correct sentences consisted only of these four words. A syntactic violation was introduced by sentences in which a preposition appeared after the auxiliary and was directly followed by a past participle, thereby leading to a phrase structure violation. Because the preposition indicates the beginning of a prepositional phrase – necessarily consisting of a preposition and a noun phrase (e.g., noun or adjective plus noun) – this sequence of words creates a clear word category violation. Filler sentences that consisted of the whole prepositional phrase (i.e. preposition followed by a noun phrase)

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[23] Such task would have not been feasible in 30 months old children and would have been to attention-demanding for the five year old children (specifically those with SLI). Thus, this task was not used in Experiment I and II. Further, since the primary focus of this study was to investigate the processing of musical syntax and there were relatively few trials with deviant instruments or the deviant voice timbre, the MMN response was not evaluated.

were introduced but not evaluated. This was done to disguise that sentences of interest induced a syntactic violation and to ensure that participants were not able to anticipate the violation when encountering the preposition. The syntactic violation condition contained a further aspect: the phrase structure violation represented a prosodic incongruence. On the prosodic level, a preposition signals that additional constituents should follow. That is, the word immediately following the preposition is not expected to convey the sentence or phrase final prosody. Because the noun phrase was removed by the splicing procedure, the constituent following the preposition contains sentence final prosody and therefore resulted in an incongruent continuation of the sentence melody (see Sabisch, Hahne, Glass, von Suchodoletz, & Friederici, 2006; Methods and Figure 1).

correct:	Die Tante	wurde			geärgert.	(The aunt was angered.)
incorrect:	Die Mutter	wurde	im		geärgert.	(The mother was angered in.)
filler:	Der Onkel	wurde	im	Bett	geärgert.	(The uncle was angered in the bed.)
	noun phrase	auxiliary	prep.	noun	participle	

Figure 11-1 Examples of the sentence types used in the language experiment. The noun phrase, the auxiliary and the participle are contained in all sentences. The syntactic violation was introduced by a preposition that was not followed by a noun. In the filler sentences the complete prepositional phrase (preposition and noun) was presented.

The experiment was divided in two parts: During each part (of approx. 21 min duration) children sat in front of a monitor. In one part they looked at a fixation cross (attentive part), in the other part they watched a silent movie (non-attentive part). In each part of the experiment 96 correct, 96 incorrect and 48 filler sentences were used (for a complete list of these sentences, see Appendix). The sentence stimuli were usually spoken by a female speaker, but in 32 sentences one word was replaced by the same word spoken by a male voice. In both parts of the experiment, the task was to detect the change in the voice timbre. As in the music experiment, subtests of an intelligence test were administered between the two parts of each session.

Behavioural measures

As described above, the task for the participants was to press a button whenever the instrumental timbre was changed (in the music experiment) or when the voice timbre was changed (in the language experiments). The reaction times and the number of correct responses were statistically evaluated.

The nonverbal part of the German version of the Wechsler Intelligence Scale for children (Tewes et al., 2000) was used to control for possible group differences in the educational background of the children. To control for the socio-economic background of the children's families, the occupation of the parents was first classified in terms of the International Standard Classification of Occupation 1988 (ISCO88; International Labour Organization, 1990). Then, the International Socio-Economic Index of Occupational Status (ISEI; Ganzeboom & Treiman, 1996) was acquired as a transformation of the ISCO88 codes. These values provide a measure of the status for a certain occupation (e.g., the highest ISEI value in the sample was 90 [judge], the lowest was 16 [cleaner]). Parents filled out a questionnaire (see Appendix) providing additional information on the health status of the children, their educational background, their language acquisition, their musical background, and other familial variables (e.g., number of siblings). This information allowed to decide which children had to be excluded. Initially, it was planned to use some of these variables (e.g. how long an instrument was learned) as further predictors. However, for none variable, a reliable correlation with the electrophysiological measures was found.

EEG recording and processing

EEG recording was identical to Experiment II. There were minor changes with regard to the rejection criteria: the amplitude threshold (criterion [1] in Experiment I and II) was lowered to ±100 µV; and the threshold for the linear trend (criterion [2]) was lowered to ±120 µV.[24] Non-rejected epochs were averaged (*music*: $M = 69$ trials [attentive part], $M = 81$ trials [non-attentive part]; *language*: $M = 62$ trials [attentive part], $M = 76$ trials [non-attentive part]). For the language experiment – that was not part of Experiment I and II – a period of 0 to 1500 ms after stimulus onset was averaged with a baseline from 0 to 100 ms. These values were chosen in accordance with earlier experiments using the same paradigms (e.g., Friederici et al., 1993; Hahne et al., 2004).

Statistical evaluation

It was not necessary to remove outliers in the data since all used variables did conform to a standard normal distribution (with Kolmogorov-Smirnov tests; the probability of deviating from a standard normal distribution was not significant: $0.25 \leq p \leq 1.00$; Median = 0.84). The values of the duration of education and the socio-economic status of the parents as well as the verbal IQ values were compared by means of t-tests for independent samples for each of the variables separately. The behavioural data (number of correct responses and reaction times for the button-presses in response to a timbre

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[24] The different amplitude thresholds were chosen because the amplitudes of the EEG measurement differed between the age groups (i.e., younger children usually show larger amplitudes in the EEG, presumably due to a lower thickness of their skull).

change) were evaluated by mixed-model ANOVAs for repeated measurements with the within-subject factors session (music vs. language) and attentiveness (look at a fixation cross *vs*. watching a silent movie) and the between-subjects factor subgroup (MT vs. NM).

For the statistical evaluation of the ERP data, the same four regions of interest (ROIs) as in the previous experiments were used. Based on a visual inspection of the ERPs and in accordance with earlier studies (e.g., Koelsch et al., 2003), three time windows were evaluated in the music experiment: [1] 160 to 280 ms (ERAN), [2] 400 to 800 ms (N5), [3] 90 to 150 ms after stimulus onset. The time windows were centred on the peak of the ERP components. In the language experiment one time window was evaluated: 500 to 1100 ms (later sustained negativity in response to a syntactic violation; LSN). Even though a difference of the experimental conditions could be observed in an earlier time window, it was not evaluated since both groups differed with regard to the latency of this difference (see "Results" for further explanation). Mixed-model ANOVAs for repeated measurements were computed to determine the statistical significance. In the music experiment this ANOVA contained the within-subject factors syntactic regularity (irregular supertonics *vs.* regular tonics), anterior-posterior distribution, hemisphere, and attentiveness, as well as the between-subjects factor subgroup (MT *vs.* NM). In the language experiment the factor syntactic regularity compared the ERP response to the syntactically incorrect and the correct sentences. The results of these ANOVAs are summarized in Table 11-2. Since "syntactic regularity" was the experimentally manipulated factor, only main effects and interactions with this factor will be mentioned in the "Results" section (but the remaining effects and interactions are listed in Table 11-2). If interactions of syntactic regularity × subgroup were found, two further ANOVAs were computed for each group of children separately (i.e. with the same within-subject factors as above). This was to test which of the effects are significant in either group. Within all ANOVAs, user-defined contrasts were employed to specify at which ROI the difference between the two chord functions was significant.

11.3 Results

Cohort description and behavioural measures

IQ values, parents' duration of education and parents' socioeconomic status (ISEI): The two groups of children were compared with regard to their parents' education and their parents' socioeconomic status (ISEI; Ganzeboom & Treiman, 1996). This was done to guarantee that differences in the processing of linguistic and musical syntax are due to a different amount of musical training, excluding other possible influences. The group means of these measures are summarized in Table 11-1.

There were group differences in the duration of the parents' education (in years). This group difference that was larger for the father's values. Hence, it did not reach significance for the mothers ($t_{(26)} = 0.66, p = 0.516$) but for the fathers ($t_{(27)} = 3.91, p = 0.001$). For the socioeconomic status, the difference for the mothers was not significant ($t_{(25)} = 1.65$, $p = 0.111$), whereas the difference for the fathers was ($t_{(26)} = 4.26$, $p < 0.001$). Considerable group differences were also found for the verbal IQ values of the children (7.96 IQ points). However, these did not reach significance ($t_{(30)} = 1.85$, $p = 0.074$). Because some variables differed significantly between the groups, correlation analyses were performed to determine whether these variables influenced the amplitudes of the investigated ERP components.

Table 11-1 Mean values and standard error of mean (in parentheses) for the values denoting the socioeconomic status and the education of the parents as well as the verbal IQ of the children

	Parents' education		Socioeconomic status		Verbal IQ
	Mother	Father	Mother	Father	
Children with musical training	16.84 (0.60)	18.53 (0.59)	63.12 (3.22)	67.16 (2.87)	126.11 (2.89)
Children without musical training	16.11 (0.99)	14.50 (0.87)	53.40 (5.41)	43.44 (5.42)	118.15 (3.02)

Behavioural data: During the experiment, the children had to press a button whenever one chord was played by another instrument than piano (in the music experiment) or when the voice timbre changed from the standard female voice to a male voice (in the language experiment). The task was quite manageable for the children: the proportion of correct responses was quite high ($M = 92.6\%$). An ANOVA for the correct responses with the factors session (music session *vs*. language session) and attentiveness (fixation-cross *vs*. silent movie) revealed a main effect of experimental session ($F_{(1,25)} = 8.90$, $p = 0.006$) and of attention ($F_{(1,25)} = 28.22$, $p < 0.001$). This effect was due to the higher percentage of correct responses in the music session ($M = 95.7\%$) compared to the language session ($M = 89.4\%$) and in the session parts in which the children looked at a fixation cross ($M = 98.7\%$) compared to the parts when they watched a movie ($M = 86.4\%$). The ANOVA for the reaction times revealed a main effect of attention ($F_{(1,24)} = 22.13$, $p < 0.001$). The reaction times were shorter for the part when children looked at the fixation cross ($M = 768.7$ ms) than in the part when they watched the silent movie

(*M* = 893.4 ms). None of the two ANOVAs revealed any interactions with subgroup indicating that the children of both groups performed similarly in the behavioural task.

ERP results

Figure 11-2 presents the ERPs for the two subgroups – MT (left) and NM (right) – in the two sessions, the music experiment (upper panel) and the language experiment (lower panel).[25] In Figure 11-3 the scalp topographies of the three investigated ERP components are shown: In the upper panel the topography for the ERPs in the MT group can be found, the lower panel presents the topography of the ERPs in the NM group. Within each panel the scalp topography of the ERAN is shown on the left side, the N5 in the middle, and the later sustained negativity (LSN) on the right side.

Music experiment

ERAN: An ERAN was elicited in response to the irregular compared to regular chords at the end of a chord sequence (see Figure 11-2). The ERAN was most prominent at the electrodes of anterior ROIs and had a slightly higher amplitude in the right (*M* = -2.53 µV, *SEM* = 0.35 µV) compared to the left hemisphere (*M* = -2.26 µV, *SEM* = 0.36 µV). The amplitudes in the posterior ROIs were much smaller (left: *M* = -1.00 µV, *SEM* = 0.30 µV; right: *M* = -0.92 µV, *SEM* = 0.27 µV). The amplitudes in the MT children were considerably larger than those in the NM children: In the anterior ROIs the amplitudes in the MT group were enlarged by 65 percent (left: *M* = -2.69 µV, *SEM* = 0.47 µV; right: *M* = -3.28 µV, *SEM* = 0.48 µV) compared to the NM group (left: *M* = -1.83 µV, *SEM* = 0.54 µV; right: *M* = -1.79 µV, *SEM* = 0.49 µV). In both groups, the scalp topography of the ERAN was most prominent at anterior scalp sites (see Figure 11-3). In the MT group the ERAN had a much larger amplitude than in the NM group, mainly at the right-anterior scalp electrodes.

An ANOVA with the within-subject factors syntactic regularity, anterior-posterior distribution, hemisphere, and attention and the between-subjects factor subgroup was used to clarify these differences. The results are summarized in Table 11-2 (column 1). They revealed a main effect of syntactic regularity, an interaction of syntactic regularity × anterior-posterior distribution, and an interaction of syntactic regularity × anterior-posterior distribution × subgroup. This indicates that an ERAN was found in both groups, but more pronounced in the MT group. It was most prominent over anterior

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[25] For the sake of brevity and simplicity, only the ERPs at the anterior ROIs will be shown since these ROIs are the main site of effect. Furthermore, for the same reason the ERPs of the two parts of each session (attentive and non-attentive) will be averaged. ERPs from both parts were largely the same, as indicated by the few interactions of syntactic regularity × attention (see Table Table 11-2).

scalp sites. Planned comparisons with user-defined contrasts were employed. Firstly, with these contrasts it was investigated at which ROI the ERAN was significant when both groups were considered. The ERAN was significant in all four ROIs (left-anterior: $F_{(1,30)} = 39.35$, $p < 0.001$; right-anterior: $F_{(1,30)} = 52.01$, $p < 0.001$; left-posterior: $F_{(1,30)} = 11.16$, $p = 0.002$; right-posterior: $F_{(1,30)} = 11.65$, $p = 0.002$) which reflects its relatively broad distribution. Secondly, it should be determined at which ROI the ERAN was significantly larger in the MT group compared to the NM group. Such group difference was observed in the right-anterior ROI ($F_{(1,30)} = 4.53$, $p = 0.042$).

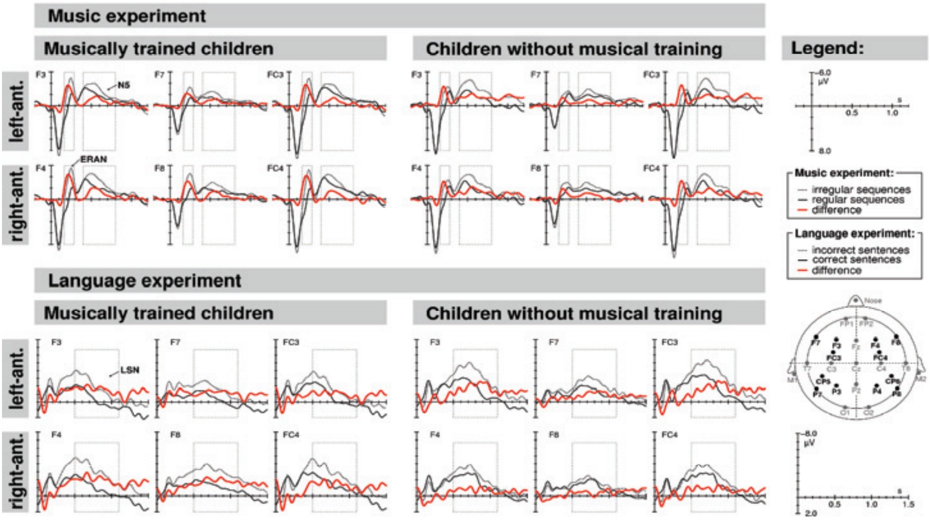
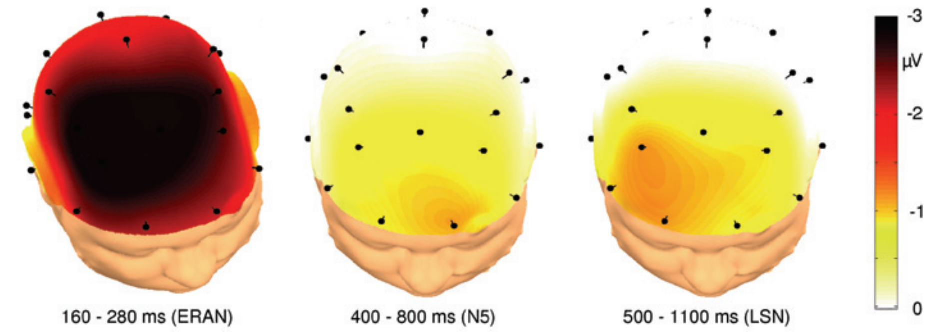


Figure 11-2 ERPs from the music (upper panel) and the language experiment (bottom panel): The group means are given in separate panels, either left for the musically trained children (MT) or right for the children without musical training (NM). Within each panel the upper rows contain the electrodes from the left-anterior ROI, and the bottom rows the electrodes of the right-anterior ROI. Black dotted lines represent the ERP response to the irregular chords (in the music experiment) or to the syntactically incorrect sentences (in the language experiment), black solid lines these to the regular chords or to the syntactically correct sentences. The red solid lines shows the difference of these conditions (i.e., between irregular and regular chords or between syntactically incorrect and correct sentences). In the figure presenting the head position of the electrodes, electrodes that are contained in the ROIs, used for statistical evaluation, are printed in black.

To investigate whether an ERAN was present in either group, an ANOVA with the same within-subject factors as above was computed, separately for each group. As expected, a main effect of syntactic regularity was found in both groups (MT: $F_{(1,18)} = 27.08$, $p < 0.001$; NM: $F_{(1,12)} = 24.99$, $p < 0.001$). In addition, an interaction of syntactic regularity × anterior-posterior distribution was found in the MT group ($F_{(1,18)} = 26.64$, $p < 0.001$). This reflects that an ERAN was elicited in both groups, which had a higher amplitude at anterior sites in the MT group.

N5: In the present experiment, an N5 was observed as a difference between irregular and regular chords around 400 to 800 ms (see Figure 11-2). It had a negative polarity and was most prominent in the anterior ROIs (left: *M* = -1.02 µV, *SEM* = 0.36 µV; right: *M* = -0.93 µV, *SEM* = 0.34 µV) whereas there were only small differences in the posterior ROIs (left: *M* = -0.41 µV, *SEM* = 0.26 µV; right: *M* = -0.15 µV, *SEM* = 0.22 µV). The amplitude in the MT group (left-anterior: *M* = -0.88 µV, *SEM* = 0.40 µV; right-anterior: *M* = -0.90 µV, *SEM* = 0.39 µV) and in the NM group (left-anterior: *M* = -1.15 µV, *SEM* = 0.64 µV; right-anterior: *M* = -0.96 µV, *SEM* = 0.59 µV) was of a similar size. The scalp distribution of the N5 (see Figure 11-3) was most prominent at anterior electrodes: in the MT group it was more anterior than in the NM group.

Children with musical training



Children without musical training

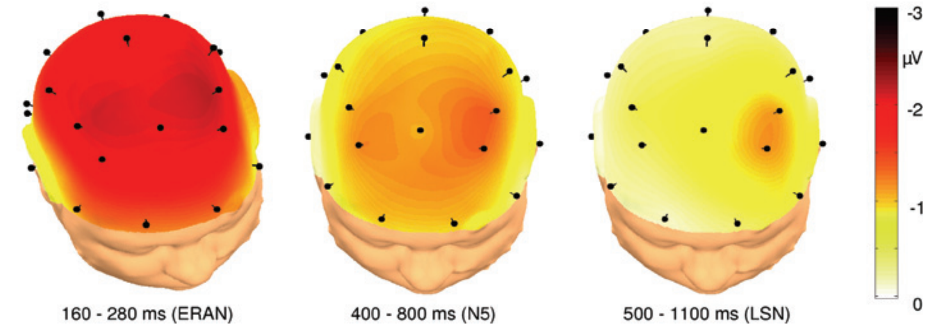


Figure 11-3 Scalp topographies of the investigated ERP components (ERAN, N5, and LSN). The head plots represent spherical spline interpolations of the amplitude difference between either irregular and regular chords (ERAN and N5) or syntactically incorrect and correct sentences (LSN). The time windows were the same as these used for statistical evaluation. The upper panel shows the head plots from the children with musical training (MT), the bottom row these of the children without musical training (NM).

An overview of the results of the ANOVA (with the same within-subject and between-subjects factors as above) is shown in Table 11-2. The ANOVA revealed a main effect of syntactic regularity, an interaction of syntactic regularity × anterior-posterior distribution, and an interaction of syntactic regularity × hemisphere × attention. This indicates a significant difference of the two experimental conditions with a prominently anterior distribution. Furthermore, the hemispheric weighting of the N5 was different for the attentive and the non-attentive part of the experiment. The same result was revealed by the user-defined contrasts: for both groups, the N5 was significant in the two anterior ROIs (left: $F_{(1,30)} = 8.08$, $p = 0.008$; right: $F_{(1,30)} = 7.57$, $p = 0.010$). The two subgroups did not differ in their ERP response to the regular *vs*. irregular chords in the N5 time range (reflected by the lack of interactions of syntactic regularity × subgroup). This result is in accordance with earlier evidence from adults (Koelsch, Schmidt et al., 2002).

Table 11-2 Overview of the results of the ANOVAs used to statistically evaluate the ERP components (ERAN, N5, and LSN). These had the factors syntactic regularity (regularity), anterior-posterior distribution (region), hemisphere, attention (fixation cross *vs*. silent movie), and subgroup (musically trained *vs*. non-musically trained children).

	ERAN		N5		LSN	
	$F_{(1,30)}$	p	$F_{(1,30)}$	p	$F_{(1,30)}$	p
regularity	43.63	<0.001	5.83	0.022	10.76	0.003
regularity × region	19.43	<0.001	7.79	0.009	16.26	<0.001
regularity × region × subgroup	4.23	0.048	0.42	0.523	0.97	0.334
regularity × region × attention	1.10	0.303	1.62	0.213	15.19	0.001
regularity × hemisph. × attention	0.27	0.609	4.69	0.038	0.60	0.445
regularity × region × hemisphere	1.65	0.209	0.92	0.345	4.16	0.050
region	3.91	0.057	42.54	<0.001	24.78	<0.001
region × hemisphere	0.70	0.409	5.23	0.029	5.86	0.022
region × hemisphere × subgroup	1.00	0.326	0.06	0.808	12.00	0.002
region × attention	7.68	0.009	16.23	<0.001	20.57	<0.001
region × attention × subgroup	10.05	0.004	12.59	0.001	0.54	0.466

NOTE: Only main effects and interactions that were significant in any of the ANOVAs were reported. The main effect and the interactions with syntactic regularity can be found in the upper part of the table.

Whereas the ERAN and the N5 were in accordance with a number of earlier studies there was an additional early difference (around 70 to 130 ms) that was not expected. However, it was found in almost all experiments of this work and in earlier studies with adults with the same paradigm (Koelsch et al.; Koelsch et al., 2007; even though it was not statistically evaluated in these studies). It appears as a positive difference because the amplitude of the response to the supertonics is more positive in that time window compared to the response to the tonics. The difference is most prominent at anterior scalp sites (left: $M = 0.44$ µV, $SEM = 0.37$ µV; right: $M = 0.78$ µV, $SEM = 0.33$ µV) than at posterior sites (left: $M = 0.10$ µV, $SEM = 0.27$ µV; right: $M = 0.41$ µV, $SEM =$

0.23 µV) and larger in the right than the left hemisphere. An ANOVA revealed no other main effects or interactions with regularity, except for an interaction of regularity × anterior-posterior distribution × subgroup × attention ($F_{(1,30)} = 5.01$, $p = 0.033$). It is difficult to account for a four-way interaction like this. However, the interaction might reflect a more strong right-lateralization in the NM group (left-anterior: $M = 0.29$ µV, $SEM = 0.67$ µV; right-anterior: $M = 0.94$ µV, $SEM = 0.55$ µV) compared to the more bilateral distribution in the MT group (left-anterior: $M = 0.60$ µV, $SEM = 0.40$ µV; right-anterior: $M = 0.63$ µV, $SEM = 0.39$ µV) which might be further modulated by the attentiveness of the children.

Language experiment

In adults, a phrase structure violation usually elicits an ELAN. It is a negative amplitude difference (around 150 to 200 ms after onset of the critical word) in response to the syntactically incorrect compared to correct sentences. Such an early difference was observed in both groups. However, it appeared in different time windows in the two groups: in the MT children around 100 to 200 ms, in the NM children around 200 to 300 ms. Furthermore, its amplitude was relatively small. For this reasons, this difference was not investigated.

Later, sustained negativity: A later sustained negativity (LSN) in response to a violation of linguistic syntax may be found, during the time period in which the ELAN develops. It is regarded as a predecessor of the ELAN (cf. Hahne et al., 2004) and appears as a negative amplitude difference between the responses to the syntactically incorrect vs. the correct sentences (see Figure 11-2). Compared to the ELAN, it has a later onset and a more sustained time course. This difference was most prominent at the electrodes of the left-anterior ROI ($M = -1.58$ µV, $SEM = 0.46$ µV), slightly smaller in the right-anterior ROI ($M = -1.36$ µV, $SEM = 0.28$ µV), i.e. it was distributed relatively bilaterally in the anterior ROIs. In the posterior ROIs, almost no difference was found (left: $M = 0.18$ µV, $SEM = 0.25$ µV; right: $M = -0.18$ µV, $SEM = 0.30$ µV). The amplitude size of this component was similar in both groups whereas the lateralization differed: In the MT group a slightly right lateralization was observed, with a larger amplitude in the right-anterior ($M = -1.67$ µV, $SEM = 0.38$ µV) compared to the left-anterior ROI ($M = -1.25$ µV, $SEM = 0.54$ µV). In contrast, in the NM group the response was larger at the left ($M = -1.90$ µV, $SEM = 0.78$ µV) compared to the right hemisphere ($M = -1.06$ µV, $SEM = 0.40$ µV). This different hemispheric weighting can also be observed in the scalp topographies for the LSN (see Figure 11-3): The LSN is more focused to the left-anterior scalp sites in the NM group, and more broadly distributed in the MT group (with a maximum over right-frontal ROIs that extends to the left hemisphere).

Even though descriptively a difference in lateralization between the two groups was observed, the interaction of syntactic regularity × hemisphere × subgroup was only approaching significance ($F_{(1,30)} = 3.05$, $p = 0.091$) when evaluated in an ANOVA (with the same within-subject and between-subjects factors as above). This ANOVA (see column 3 of Table 11-2) revealed further a main effect of regularity, an interaction of syntactic regularity × anterior-posterior distribution, an interaction of syntactic regularity × anterior-posterior distribution × hemisphere, and an interaction of syntactic regularity × anterior-posterior distribution × attention. These interactions indicate that an LSN was mainly found in the anterior ROIs, with a stronger leftward lateralization, that might be further modulated by the attentiveness of the participants.

To ensure that the amplitudes of the ERP components were not influenced by the educational background, correlation analyses were employed. Because only for the ERAN a reliable interaction with subgroup was found (syntactic regularity × anterior-posterior distribution × subgroup) the amplitude of the ERAN in both anterior ROIs was correlated with the variables that describe the educational background of the participants (parent's duration of education, parent's socio-economic status, and non-verbal IQ of the children). All correlations were around zero ($-0.095 \leq r \leq 0.105$) and not statistically significant ($0.601 \leq p \leq 0.993$). Thus, it may be concluded that the ERP variables that differed between the groups were not influenced by variables reflecting the educational background of the children.

11.4 Discussion

The present experiment investigated the processing of musical and linguistic syntax in children that either received musical training or did not have any extracurricular music lessons. An ERAN could be observed in both groups. It was bilaterally distributed (but had a slightly higher amplitude in the right hemisphere) which is in accordance with earlier experiments using the same class of stimuli (Koelsch et al., 2007). The ERAN peaked later than in adults (see, e.g., Koelsch et al., 2007), and older children (Jentschke et al., 2005). The main finding of this experiment was the observation of an enlarged ERAN amplitude size in MT children compared to NM children. This finding was expected, because an earlier study (Koelsch, Schmidt et al., 2002) investigating the processing of musical syntax in adult musicians and non-musicians found an enlarged ERAN amplitude in adult musicians. More generally, the present results are in accordance with evidence for differences in auditory processing at many stages of music perception (see the chapter on "Musical Training"). This represents an intriguing finding, given that these children learned an instrument not longer than around 39 months.

An N5 often succeeds the ERAN and is thought to reflect processes of harmonic integration (cf. Koelsch et al., 2000). For this ERP component, no difference is found between the two groups. However, such difference was not expected, firstly, because no such difference was found in earlier studies. Secondly, previous studies indicated that musical training influences particularly early non-attentive stages of music perception (see chapter on "Musical Training"; for a review, see Bigand & Poulin-Charronnat, 2006).

In the language experiment, one ERP component – the LSN - was investigated. It was observed in both groups. Both – the LSN and the ELAN – reflect the processing of linguistic syntax, and the LSN is regarded as a precursor of the ELAN, which develops until around 13 years of age for the sentences with passive mode construction (Hahne et al., 2004). Thus, as expected, no ELAN was found in either group in this experiment. Whereas the ELAN is taken to reflect early and automatic processes of initial syntactic structure building, the LSN does not reflect such early, automatic processes, but such with a higher latency and a more sustained time course.

Because of the overlap in the neural correlates of processing musical and linguistic syntax it was assumed that musical training may lead to an enlarged amplitude size of the LSN (comparable to the enlarged ERAN amplitude in the MT group). However, no difference in the amplitude size of the LSN was found between the two groups. The lateralization of this ERP response was slightly different in the MT and the NM children: whereas a clear leftward lateralization was found in NM children the response was more bilaterally distributed in the children with MT. This argues for a stronger involvement of right-hemispheric brain areas – also involved in the processing of musical syntax – in the processing of linguistic syntax.

Usually the ELAN is followed by a P600 (e.g., Hahne et al., 2004; Hahne & Friederici, 1999). This ERP component is thought to reflect fairly controlled later processes of reanalysis and repair (cf. Hahne & Friederici, 1999). It was not observed in this experiment. The lack of observing this ERP component is likely caused by the nature of the task of the children during the experiment: In most of the previous studies using this paradigm, participants had to judge the grammaticality of the sentence. In contrast, in the present experiment the children attended to a change in the timbre of the speaker's voice. This task was chosen to provide a similar task as in the music experiment (where the children attended to a change in the instrumental timbre). The judgement of grammaticality forced to reanalyse and to repair the sentence which was not necessary in the present study which might be the reason for the lack of the P600.

In this experiment, it was not possible to match the socio-economic status and the education of the parents, and the non-verbal IQ of the children in a comparably good fashion than in the 11-year old children from Experiment IV. This was due to several reasons: Firstly, the children in this experiment attended elementary schools where the pupils within a class are more heterogeneous than in the grammar schools from which the 11-year old children were recruited. Secondly, the 9-year old children of the MT group came from the public music school and most of their parents were academics. Thus, it was more difficult to find comparable controls. Since a good matching of the two groups was not possible, it was statistically controlled for that the socio-economic status and the education of the parents and the children's non-verbal IQ did not modulate the amplitude of the ERP responses. For the ERAN amplitude – the only variable for which an interaction with group subgroup (MT *vs*. NM) was found – no significant correlations with these variables were observed, arguing against an impact of these socio-economic variables on the processing of syntax.

11.5 Conclusion

The main finding of this experiment was an enlarged ERAN amplitude size in MT children compared to NM children. This indicates that the heightened implicit and explicit knowledge of music-syntactic regularities in MT children resulted in an improved function of the neural correlates that underlie music-syntactic processing. Notably, the relatively short period in which these children learned an instrument (around 3 years) is sufficient to impose a change in the neural correlates of music-syntactic processing. The N5 (indicating processing of harmonic integration) was found equally in both groups. The amplitude size of the LSN (reflecting processing of violations of linguistic syntax) did not differ between the groups. This indicates that the period in which these children received musical training was not long enough to evoke transfer effects. An ELAN was not yet developed and was not observed in any group.

12 Experiment IV: Neural correlates of processing syntax in music and language in 11-year old children with or without musical training

12.1 Introduction and Hypotheses

Experiment IV investigated the same issues as Experiment III in a different age group of 11-year old children. The main purpose was to investigate the influence of a higher amount of musical training (than in the 9-year old children in Experiment III) on the processing of musical and linguistic syntax. Another aim of this experiment was to extend the knowledge how the neural correlates of processing musical and linguistic syntax develop. In order to address these issues, a within-subject comparison of the ERP correlates of processing of musical and linguistic syntax in 11-year old children was conducted. Two main topics were examined: [1] how violations of musical and linguistic syntax are processed in 11-year old children; and [2] whether there is a difference in the amplitude of the ERP responses to a violation of musical and linguistic syntax between children with and without musical training; specifically, if a transfer effect to the processing of linguistic syntax can be observed in children with musical training.

It was hypothesized that an enlarged ERP response to a violation of musical syntax (ERAN) can be observed in the children with musical training. Moreover, these children were also expected to demonstrate facilitation in their processing of linguistic syntax, which might be reflected in an enlarged amplitude of the later sustained negativity (LSN; a precursor of the ELAN, reflecting the detection of a violation of linguistic syntax) and in an earlier presence of the ELAN.

12.2 Methods

Participants

Two groups of 11-year old children were compared that were either musically trained or not. They were right-handed (according to the Edinburg Handedness Inventory; Oldfield, 1971), native speakers of German. None of them suffered from any known hearing or neurological deficits, or had attention deficit disorders, reading or learning disabilities (e.g. dyslexia). Their parents signed a written informed consent. The children were rewarded and parents were compensated as in the former experiments.

The children with musical training (MT; $N = 24$) were recruited from the St.-Thomas-Boys-Choir and from the public music school in Leipzig. Children were excluded, if [1] their EEG measurements could not be evaluated (e.g., due to many artefacts; 1 girl excluded), [2] they learned at least one foreign language before 6 years of age (1 boy excluded), or [3] they had any problems or delays in language acquisition (1 boy excluded). Finally 21 children were evaluated (12 boys, 9 girls; 10;1 to 11;7 years old, *M* = 10;8 years). They did play an instrument for 33 to 79 months (*M* = 57 months).

The children without musical training (NM; *N* = 31) did not learn an instrument, did not sing in a choir, and received no extracurricular music lessons.[26] They were recruited from public schools in Leipzig. Children were excluded, if any of the following conditions was met: [1] They did not finish the experiment (e.g., due to lack of compliance or problems with the measurement; 1 girl and 3 boys excluded); [2] they had language impairments or a delayed language acquisition (2 girls and 1 boy excluded); [3] they started to learn an instrument but gave up (1 girl excluded), [4] they had learning problems (e.g., attention deficits or less than 70 IQ points; 2 girls excluded); or [5] they visited another school type than the musically trained children (1 girl excluded). Finally 20 children were evaluated (10;3 to 11;10 years old, *M* = 11;1 years; 9 boys, 11 girls).

Notably, there was no group difference, neither in the results of the verbal part of the Wechsler Intelligence Scale for Children (HAWIK-III; Tewes et al., 2000), nor in duration of their parents education, nor with regard to the socio-economic status values of their parents occupation (ISEI; Ganzeboom & Treiman, 1996). The statistical evaluation is described in the section "Results".

Stimuli and paradigm as well as the EEG recording and processing were identical to Experiment III. For the ERPs, all non-rejected epochs were averaged (music: *M* = 77 trials [attentive part], *M* = 78 trials [non-attentive part]; language: *M* = 67 trials [attentive part], *M* = 71 trials [non-attentive part]).

Statistical evaluation

The variables used in the analyses did not deviate from a standard normal distribution (evaluated with Kolmogorov-Smirnov tests; $0.23 \leq p \leq 1.00$; Median = 0.85). Thus, there was no need to detect and remove outliers in the data. The duration of education and the socio-economic status of the parents as well as the verbal IQ values were compared with t-tests for independent samples separately for each variable. Like in this experiment, none of the additional variables from the parent's questionnaire (e.g., the duration of musical training in months) was significantly correlated with the ERP variables. The behavioural results – the number of correct responses and the reaction times – were evaluated in mixed-model ANOVAs for repeated measurements with the within-

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[26] It was very difficult to find participants that not even tried to learn an instrument (specifically in girls). Thus, two children were included even though they started to learn an instrument for approx. 3 months.

subject factors session (music vs. language) and attention (attended vs. non-attended part of the session) and the between-subjects factor subgroup (MT vs. NM).

For the statistical evaluation of the ERP data, the same four regions of interest (ROIs) as in the previous experiments were used. Two time windows were evaluated for each session, in the music session: [1] 130 to 250 ms (ERAN), and [2] 400 to 800 ms (N5); and in the language session: [1] 100 to 220 ms (ELAN), and [2] 400 to 1400 ms (later sustained negativity in response to a syntactic violation, LSN). Mixed-model ANOVAs for repeated measurements were used to evaluate the ERP responses.[27] In the music experiment, the model contained the within-subject factors syntactic regularity (regular *vs*. irregular chords), anterior-posterior distribution, hemisphere (left *vs.* right), and attentiveness (looking at a fixation cross *vs*. watching a silent movie), as well as the between-subjects factor subgroup (MT *vs.* NM).

In the language experiment the same model was used, but the factor syntactic regularity in this model contained the ERP responses to the syntactically correct vs. incorrect sentences. For the ELAN – which previously had been demonstrated to develop until 12 to 13 years (Hahne et al., 2004) – a further ANOVA with the same factors as above but with age (in months) as a covariate was employed. Whenever the interaction of syntactic regularity × subgroup was significant, two further ANOVAs were computed for each group of children separately (with the same within-subject factors as above) to examine the statistical significance of the effects in either group. Within all ANOVAs user-defined contrasts were employed to specify – separately for each ROI – if the difference between the two chord functions was significant. Since all investigated ERP components have a more anterior scalp distribution (see, e.g., Hahne et al., 2004; Hahne & Friederici, 1999; Koelsch et al., 2003; Koelsch et al., 2000), it was expected to find significant differences between the two experimental conditions (i.e. between supertonics *vs*. tonics and syntactically incorrect *vs*. correct sentences) mainly in the anterior ROIs.[28]

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[27] For the sake of clarity, the results of all ANOVAs are summarized in Table 12-2 with their F- and p-values and these values will not be reported again in the text. Secondly, since only the factor "syntactic regularity" was experimentally manipulated, main effects and interactions that not involve this factor will not be mentioned in the "Results" section. However, these effects and interactions are listed in Table 12-2.

[28] Only ERPs in the anterior ROIs will be shown (these ROIs are the main site of effect) for the sake of brevity. Furthermore, the ERPs of the two parts of each session (attentive and non-attentive) will be averaged (because attentiveness did not interact with syntactic regularity (i.e., an interaction was found only for the LSN).

12.3 Results

Cohort description and behavioural measures

IQ values, parents' duration of education and parents' socioeconomic status (ISEI): The two groups of children were matched with regard to their parents' education and their parents' socioeconomic status (ISEI; Ganzeboom & Treiman, 1996). This was done to guarantee that observed differences in the processing of linguistic and musical syntax were due to a different amount of musical training but not influenced by such factors. The group means of these measures are summarized in Table 12-1. There were small differences in the duration of parents' education. These were larger for the mothers than for the fathers. The differences did not reach significance (mother: $t_{(34)} = 1.83$, $p = 0.075$; father: $t_{(33)} = 0.58$, $p = 0.565$). Small group differences were also found for the socioeconomic status of the parents. These were larger for the fathers' values compared to the mothers' values. Again, these differences did not reach significance (mother: $t_{(34)} = 0.56$, $p = 0.578$; father: $t_{(35)} = 0.83$, $p = 0.414$). The group difference in verbal IQ values was small and did not reach significance ($t_{(39)} = 0.70$, $p = 0.487$).

Table 12-1 Mean values and standard error of mean (in parentheses) for the values denoting the socioeconomic status and the education of the parents as well as the verbal IQ of the children

	Parents' education		Socioeconomic status		Verbal IQ
	Mother	Father	Mother	Father	
children with musical training	17.05 (0.71)	16.32 (0.56)	61.80 (4.00)	62.29 (3.13)	122.19 (2.29)
children without musical training	15.18 (0.74)	15.75 (0.82)	58.56 (4.03)	57.94 (4.41)	119.95 (2.22)

Behavioural data: During the experiment, the children had to press a button whenever one chord was played by another instrument than piano (in the music experiment) or when the voice timbre changed was changed from the female standard voice to a male voice (in the language experiment). The task was easily manageable for the children and the proportion of correct responses was quite high (M = 97.5%). A higher amount of correct responses was observed in the part in which the children were looking at a fixation cross ($M = 99.2\%$) compared to the part when they were watching a film ($M = 95.8\%$). The proportion of correct responses virtually did not differ for the different sessions (i.e. the music and the language experiment). In accordance, an ANOVA revealed only a main effect of attention ($F_{(1,39)} = 6.69$, $p = 0.014$).

The reaction times were shorter for the music ($M = 541$ ms) compared to the language session ($M = 603$ ms) and for the attentive ($M = 540$ ms) compared to the non-attentive part of the session ($M = 603$ ms). The difference in the reaction times between the parts was larger in the music session ($M = 31$ ms) than in the language session ($M = 94$ ms). The ANOVA for the reaction times revealed main effects of session ($F_{(1,39)} = 25.39$, $p < 0.001$) and attention ($F_{(1,39)} = 35.81$, $p < 0.001$), as well as an interaction of session × attention ($F_{(1,39)} = 6.40$, $p = 0.016$), but it did not reveal any interactions with subgroup. This indicates that the children of both groups did not differ in their results in this task.

ERP results

Figure 12-1 presents the ERPs for the music experiment (upper panel) and the language experiment (lower panel) in the two subgroups: children with musical training (left) and children without musical training (right). In Figure 12-2, the scalp distributions of the four investigated ERP components are shown: In the upper panel the topographies of the ERP components from the music experiment (ERAN and N5), and in the lower panel these from the language experiment (ELAN and LSN) can be found. Within each panel, the left part contains the topographies from the MT children the right part these of the NM children.

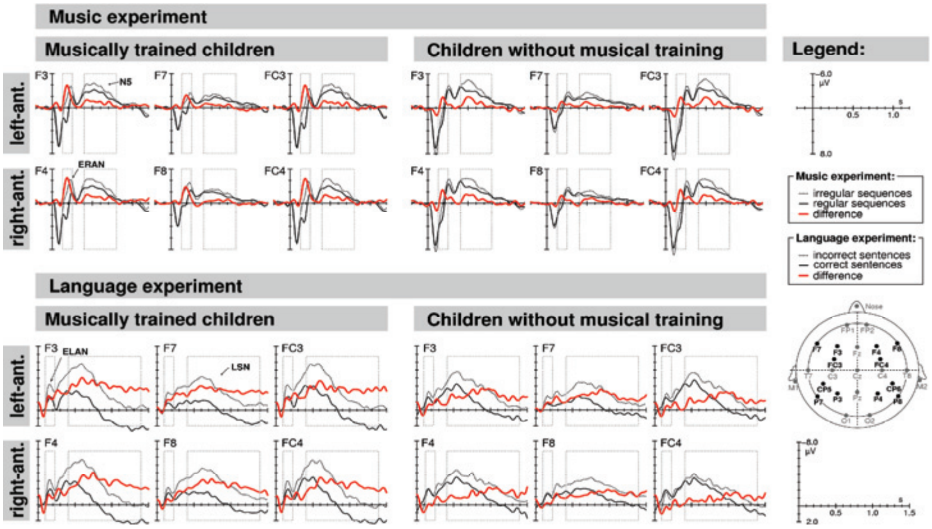

Figure 12-1 ERPs from the music (upper panel) and the language experiment (bottom panel): The group means are given in separate panels – from the group of musically trained children (MT) at the left side and from the group of children without musical training (NM) at the right side. In the upper rows of each panel the electrodes from the left-anterior ROI are shown, the bottom rows contain the electrodes of the right-anterior ROI. Black dotted lines represent the ERP response to the irregular chords (in the music experiment) or to the syntactically incorrect sentences (in the language experiment), black solid lines these to the regular chords or to the syntactically correct sentences. The red solid lines indicate the difference of these conditions. Electrodes that are contained in the ROIs used for statistical evaluation are written in black in the figure of their head position.

Figure 12-3 summarizes the findings for all four investigated ERP components. The chart in the upper panel shows (for all four ROIs) the amplitude of the ERPs from the music experiment (ERAN and N5), the lower panel contains the corresponding data for the language experiment (ELAN and LSN). In the table below each chart, an overview of the results of the planned comparisons with user-defined contrasts is given. It is shown in which ROI the investigated ERP component was significant. Four different comparisons were reported at the table's rows: It is indicated whether a significant difference was found, in the first line for the mean of both groups, in the third line for the MT group, and in the fourth line for the NM group. In the second line, it was determined if the amplitude in the MT group was larger than in the NM group.

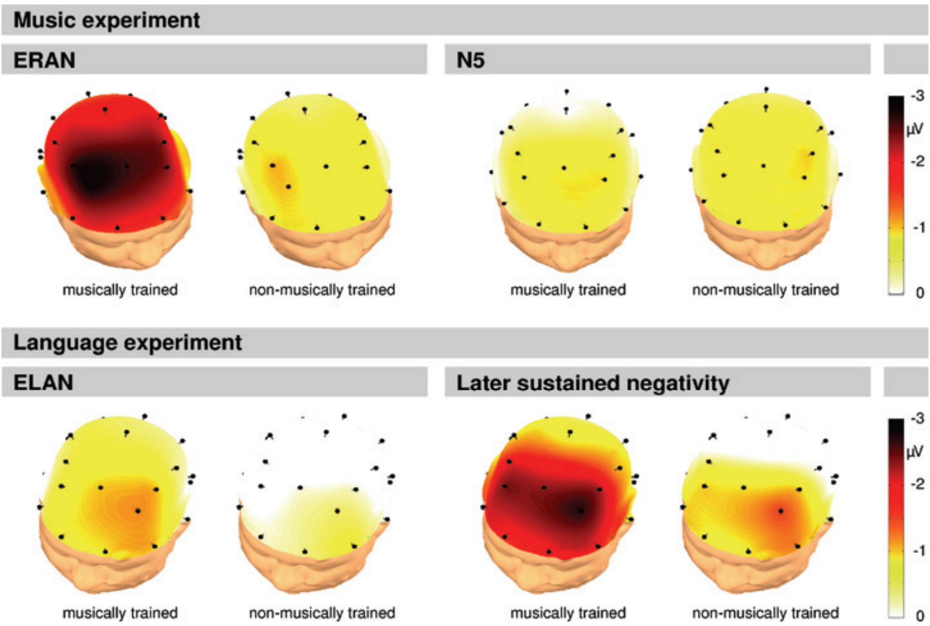

Figure 12-2 Scalp topographies of the investigated ERP components (ERAN, N5, ELAN, and LSN). The topographies are a spherical spline interpolation of the amplitude difference between either irregular and regular chords (ERAN and N5) or syntactically incorrect and correct sentences (ELAN and LSN). The time windows were the same as these used for statistical evaluation. In the upper panel the ERPs from the music experiment, in the bottom panel these from the language experiment are shown. For each ERP component the head plots from the children with musical training (MT) are on the left side, the these of the children without musical training (NM) on the right side.

Music experiment

ERAN: An ERAN was elicited in response to the irregular compared to regular chords at the end of a chord sequence (see Figure 12-1). It was most prominent at the electrodes of the anterior ROIs and had a slightly higher amplitudes over the right (*M* =

-1.93 µV, *SEM* = 0.29 µV; mean of all participants) compared to the left hemisphere (*M* = -1.60 µV, *SEM* = 0.27 µV). The amplitudes in the posterior ROIs are much smaller (left: *M* = -0.56 µV, *SEM* = 0.18 µV; right: *M* = -0.75 µV, *SEM* = 0.18 µV). The amplitudes in the musically trained children were considerably larger than those in the children without musical training: In the anterior ROIs, the amplitudes in the MT group were more than twice as large (left: *M* = -2.31 µV, *SEM* = 0.39 µV; right: *M* = -2.75 µV, *SEM* = 0.45 µV) than in the NM group (left: *M* = -0.88 µV, *SEM* = 0.36 µV; right: *M* = -1.11 µV, *SEM* = 0.36 µV). This can also be seen in Figure 12-3 (left upper panel). The ERAN had a scalp distribution with a maximum peak at right-anterior scalp sites (see Figure 12-2). It can be clearly observed that the amplitude in the group of MT children was much larger than the amplitude in the group of NM children.

These differences were tested for their statistical significance in an ANOVA with the within-subject factors syntactic regularity, anterior-posterior distribution, hemisphere, and attention and the between-subjects factor subgroup. The results are summarized in Table 12-2 (column 1). It revealed a main effect of syntactic regularity, an interaction of syntactic regularity × subgroup, an interaction of syntactic regularity × anterior-posterior distribution, and an interaction of syntactic regularity × hemisphere. This indicates that an ERAN was found in both groups, but more pronounced in the MT group. It was most prominent over anterior scalp sites and the right hemisphere. Planned comparisons with user-defined contrasts were employed to further investigate, firstly, in which ROI the ERAN was significant for both groups, and, secondly, in which ROI the ERAN was significantly larger in the MT group compared to the NM group. The ERAN had a relatively broad distribution and was, when both groups are considered, significant in all four ROIs (left-anterior: $F_{(1,39)} = 35.55$, $p < 0.001$; right-anterior: $F_{(1,39)} = 44.70$, $p < 0.001$; left-posterior: $F_{(1,39)} = 9.72$, $p = 0.003$; right-posterior: $F_{(1,39)} = 17.81$, $p < 0.001$). In the left-anterior ($F_{(1,39)} = 7.06$, $p = 0.011$), the right-anterior ($F_{(1,39)} = 8.03$, $p = 0.007$), and the right-posterior ROI ($F_{(1,39)} = 6.04$, $p = 0.019$) its amplitude was significantly larger in the MT group compared to the NM group.

An ANOVA with the same within-subject factors as above was computed for each subgroup separately to investigate if an ERAN was present in either group. As expected, in both groups a main effect of syntactic regularity (MT: $F_{(1,20)} = 37.71$, $p < 0.001$; NM: $F_{(1,19)} = 8.11$, $p = 0.010$), and an interaction of syntactic regularity × region were found (MT: $F_{(1,20)} = 18.32$, $p < 0.001$; NM: $F_{(1,19)} = 5.13$, $p = 0.035$). This reflects a significant amplitude difference between supertonics and tonics that was stronger at anterior sites in both groups. Planned comparisons revealed a significant ERAN amplitude in all four ROIs in the MT group (left-anterior: $F_{(1,20)} = 34.42$, $p < 0.001$; right-anterior: $F_{(1,20)} = 37.45$, $p < 0.001$; left-posterior: $F_{(1,20)} = 8.33$, $p = 0.009$; right- posterior: $F_{(1,20)} = 18.04$,

$p < 0.001$). In the NM group, differences were found only in the anterior ROIs (left: $F_{(1,19)} = 6.00$, $p = 0.024$; right: $F_{(1,19)} = 9.69$, $p = 0.006$). That is, the ERAN in the MT group had a larger amplitude and thus reached significance in all four ROIs.

N5: The N5 (see Figure 12-1), observed in this experiment, peaked around 500 ms. It was most prominent in the anterior ROIs (left: $M = -0.93$ µV, $SEM = 0.20$ µV; right: $M = -0.79$ µV, $SEM = 0.22$ µV) compared to the posterior ROIs (left: $M = -0.16$ µV, $SEM = 0.21$ µV; right: $M = -0.18$ µV, $SEM = 0.19$ µV). Its amplitudes in the MT group (left-anterior: $M = -0.88$ µV, $SEM = 0.26$ µV; right-anterior: $M = -0.79$ µV, $SEM = 0.23$ µV) were of a similar size as in the NM group (left-anterior: $M = -0.98$ µV, $SEM = 0.32$ µV; right-anterior: $M = -0.79$ µV, $SEM = 0.38$ µV). The scalp topography also shows that the N5 was maximal over the anterior electrodes (see Figure 12-2). As in the group of 9-year old children, a slightly broader scalp distribution was found in the NM children whereas the scalp distribution in the MT children was more focused to the anterior electrodes.

Table 12-2 Overview of the results of the ANOVAs used to statistically evaluate the four ERP components (ERAN, N5, ELAN, and LSN). These had the factors syntactic regularity (regularity), anterior-posterior distribution (region), hemisphere, attention (fixation cross *vs.* silent movie), and subgroup (musically trained vs. non-musically trained children).

	ERAN		N5		ELAN		LSN	
	$F_{(1,39)}$	p	$F_{(1,39)}$	p	$F_{(1,39)}$	p	$F_{(1,39)}$	p
regularity	42.69	<0.001	8.76	0.005	3.60	0.065	34.58	<0.001
regularity × subgroup	8.98	0.005	0.15	0.700	4.01	0.052	5.82	0.021
regul. × subgr. × hem. × att.	1.68	0.203	0.14	0.714	0.26	0.615	4.20	0.047
regularity × region	22.15	<0.001	19.20	<0.001	9.12	0.004	75.79	<0.001
regularity × region × hem.	0.65	0.424	0.68	0.416	16.21	<0.001	7.66	0.009
regularity × region × att.	0.76	0.390	1.10	0.300	0.13	0.719	6.07	0.018
regularity × hemisphere	3.94	0.054	0.26	0.616	4.44	0.042	0.18	0.675
subgroup	4.64	0.038	0.29	0.596	4.74	0.036	0.18	0.677
subgroup × attention	0.37	0.548	7.37	0.010	12.11	0.001	4.63	0.038
region	0.16	0.688	97.30	<0.001	59.19	<0.001	64.46	<0.001
region × hemisphere	1.33	0.255	9.71	0.003	0.00	0.951	0.61	0.441
region × attention	10.40	0.003	4.65	0.037	5.78	0.021	12.55	0.001
hemisphere	6.00	0.019	19.98	<0.001	0.02	0.885	0.42	0.521
hemisphere × attention	2.39	0.130	3.02	0.090	1.28	0.265	12.90	0.001

NOTE: The main effect and the interactions with syntactic regularity can be found in the upper part of the table. Effects are only reported if they were significant in at least one ANOVA.

An overview of the results of the ANOVA with the same within-subject and between-subjects factors as above is shown in Table 12-2 (column 2). It revealed a main effect of syntactic regularity, an interaction of syntactic regularity × anterior-posterior distribution, and an interaction of syntactic regularity × hemisphere. This indicates that a significant N5 was found with a anterior, slightly left-lateralized distribution. The same result were revealed by the user-defined contrasts: for both groups, the N5 was significant in the two anterior ROIs (left: $F_{(1,39)} = 21.15$, $p < 0.001$; right: $F_{(1,39)} = 13.00$, $p = 0.001$). A significant group difference was not revealed for any ROI. As expected, the two subgroups did not differ in their ERP responses (reflected in the lack of syntactic regularity × subgroup interaction). This is in accordance with earlier evidence from adults (Koelsch, Schmidt et al., 2002).

In addition to the ERAN and the N5 that were observed in many earlier experiments (e.g., Koelsch et al., 2003; Koelsch et al., 2000) an early acoustic difference was found. It appeared as a more positive ERP response to the supertonics compared to the tonics around 70 to 130 ms. This difference was more pronounced in the left hemisphere (anterior: $M = 0.45$ µV, $SEM = 0.21$ µV; posterior: $M = 0.45$ µV, $SEM = 0.19$ µV) than in the right hemisphere (anterior: $M = 0.40$ µV, $SEM = 0.23$ µV; posterior: $M = 0.16$ µV, $SEM = 0.18$ µV) and at anterior compared to posterior scalp regions. Even though its amplitude was relatively small, a significant main effect of syntactic regularity ($F_{(1,39)} = 5.29$, $p = 0.027$), and an interaction of attention × regularity ($F_{(1,39)} = 9.28$, $p = 0.004$) was revealed. In addition, a main effect of subgroup was found, reflecting the enlarged amplitudes (specifically of the ERP response to the supertonics) in the NM group.

Language experiment

ELAN: An ELAN – i.e. a negative amplitude difference in response to the syntactically incorrect compared to correct sentences around 150 to 200 ms after onset of the critical word – was observed mainly in the MT children. It had a latency of around 160 ms and was most prominent at the electrodes of the left-anterior ROI ($M = -0.94$ µV, $SEM = 0.24$ µV), much smaller in the right-anterior ROI ($M = -0.26$ µV, $SEM = 0.20$ µV), and there was almost no difference in the posterior ROIs (left: $M = 0.01$ µV, $SEM = 0.16$ µV; right: $M = 0.01$ µV, $SEM = 0.21$ µV). The ELAN amplitude in the MT group (left-anterior: $M = -1.32$ µV, $SEM = 0.34$ µV; right-anterior: $M = -0.69$ µV, $SEM = 0.33$ µV) was much larger than in the NM group (left-anterior: $M = -0.55$ µV, $SEM = 0.35$ µV; right-anterior: $M = 0.17$ µV, $SEM = 0.22$ µV). This was also reflected in the scalp distribution of this ERP component (see Figure 12-2): Whereas in the MT children, an ELAN could be clearly observed at the frontal scalp electrodes, the amplitude was considerably smaller in the NM children.

An ANOVA with the within-subject factors syntactic regularity (syntactically correct vs. incorrect sentences), anterior-posterior distribution, hemisphere, attentiveness (fixation cross *vs*. silent movie), and the between-subjects factor subgroup (MT vs. NM) was used to evaluate these ERP responses. An overview of the results can be found in Table 12-2 (column 3). The ANOVA revealed interactions of syntactic regularity × anterior-posterior distribution, of syntactic regularity × anterior-posterior distribution × hemisphere, and of syntactic regularity × hemisphere. These interactions are due to the larger amplitudes in response to the syntactic violation which was most prominent at the left anterior electrodes. Planned comparisons to investigate the site of effect revealed, firstly, a significant difference in the left-anterior ROI ($F_{(1,39)} = 14.93$, $p < 0.001$) when both groups are considered, and, secondly, a significantly larger ELAN amplitude for the MT group in the right-anterior ROI ($F_{(1,39)} = 4.58$, $p = 0.039$). Since the ELAN amplitude (in the anterior ROIs) was much larger in the MT group compared to the NM group, it was expected to find an interaction of syntactic regularity × subgroup. However, this interaction was minimally above the significance threshold ($p = 0.052$).

To account for the lack of interaction of syntactic regularity × subgroup in the above ANOVA, a further assumption was tested: As the ELAN develops until around 12 to 13 years of age (for sentences with passive mode construction; Hahne et al., 2004), it was not expected to find an ELAN in all children. A further ANOVA with the same factors as the ANOVA above, but with age (in months) as a covariate was computed. In this ANOVA, the interaction of syntactic regularity × subgroup was clearly significant ($F_{(1,38)} = 5.91$, $p = 0.020$). Further, it revealed an interaction of syntactic regularity × anterior-posterior distribution × hemisphere ($F_{(1,38)} = 4.21$, $p = 0.047$) indicating a significant difference between the two experimental conditions that was most obvious in the left-anterior ROI, and an interaction of syntactic regularity × anterior-posterior distribution × hemisphere × age ($F_{(1,38)} = 4.96$, $p = 0.032$) demonstrating an influence of age on the ELAN amplitude.[29]

Since the ANOVA with age as a covariate found an interaction of syntactic regularity × subgroup, the ELAN amplitude was further evaluated in two ANOVAs (with the same within-subject factors as above) separately for each of the two sub-groups. In the *MT group*, the *ANOVA with age as a covariate* revealed an interaction of syntactic regularity × anterior-posterior distribution × hemisphere ($F_{(1,19)} = 9.50$, $p = 0.006$) and an interaction of syntactic regularity × anterior-posterior distribution × hemisphere × age ($F_{(1,19)} = 11.29$, $p = 0.003$). The *ANOVA without age as a covariate* revealed a main effect of syntactic regularity ($F_{(1,20)} = 7.22$, $p = 0.014$), an interaction of syntactic regularity × anterior-posterior distribution ($F_{(1,20)} = 7.53$, $p = 0.012$), and of syntactic regu-

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[29] It was not possible to use planned comparisons within this ANOVA since it is, to my knowledge, not possible to account for a between-subjects factor and a covariate at the same time. Thus, results of the planned comparisons from the ANOVA without age as covariate are presented in Figure 4.

larity × anterior-posterior distribution × hemisphere ($F_{(1,20)} = 25.30$, $p < 0.001$). Essentially, the same results as in the ANOVA with age as covariate were observed, namely a significant ELAN was found which was most prominent at left-anterior scalp sites. In the former ANOVA, it was further shown that the ELAN amplitude was further influenced by the age of the participants. The user-defined contrasts revealed a significant difference between the experimental conditions for both anterior ROIs in the MT group (left: $F_{(1,20)} = 14.97$, $p = 0.001$; right: $F_{(1,20)} = 8.08$, $p = 0.010$). In the *NM group*, neither main effects nor interactions with syntactic regularity were found (in both ANOVAs, with and without age as covariate).

Later sustained negativity: During the time period in which the ELAN develops, a later sustained negativity (LSN) in response to a violation of linguistic syntax can be found, which is regarded as a predecessor of the ELAN (cf. Hahne et al., 2004). It appears as a negative amplitude difference between the responses to the syntactically incorrect vs. the correct sentences with a later onset and a more sustained time course than the ELAN (see Figure 12-1). Such negative difference was found, most prominent in the left-anterior ROI ($M = -2.19$ µV, $SEM = 0.24$ µV), slightly smaller in the right-anterior ROI ($M = -1.83$ µV, $SEM = 0.26$ µV), whereas in the posterior ROIs almost no difference was observed (left: $M = -0.16$ µV, $SEM = 0.21$ µV; right: $M = -0.39$ µV, $SEM = 0.24$ µV). In contrast to the ELAN (that was strongly left-lateralized), this ERP component was distributed more bilaterally in the anterior ROIs. Its amplitude was much larger in the MT group (left-anterior: $M = -2.79$ µV, $SEM = 0.33$ µV; right-anterior: $M = -2.57$ µV, $SEM = 0.35$ µV) than in the NM group (left-anterior: $M = -1.60$ µV, $SEM = 0.35$ µV; right-anterior: $M = -1.10$ µV, $SEM = 0.39$ µV). This can be seen in the chart in the bottom-right panel of Figure 12-3. The scalp topographies (see Figure 12-2) also reflect the considerably larger amplitude of the LSN in the MT compared to the NM children. Moreover, the distribution at anterior scalp sites was more bilaterally in the MT group whereas it was more focused to the left hemisphere in the NM group.

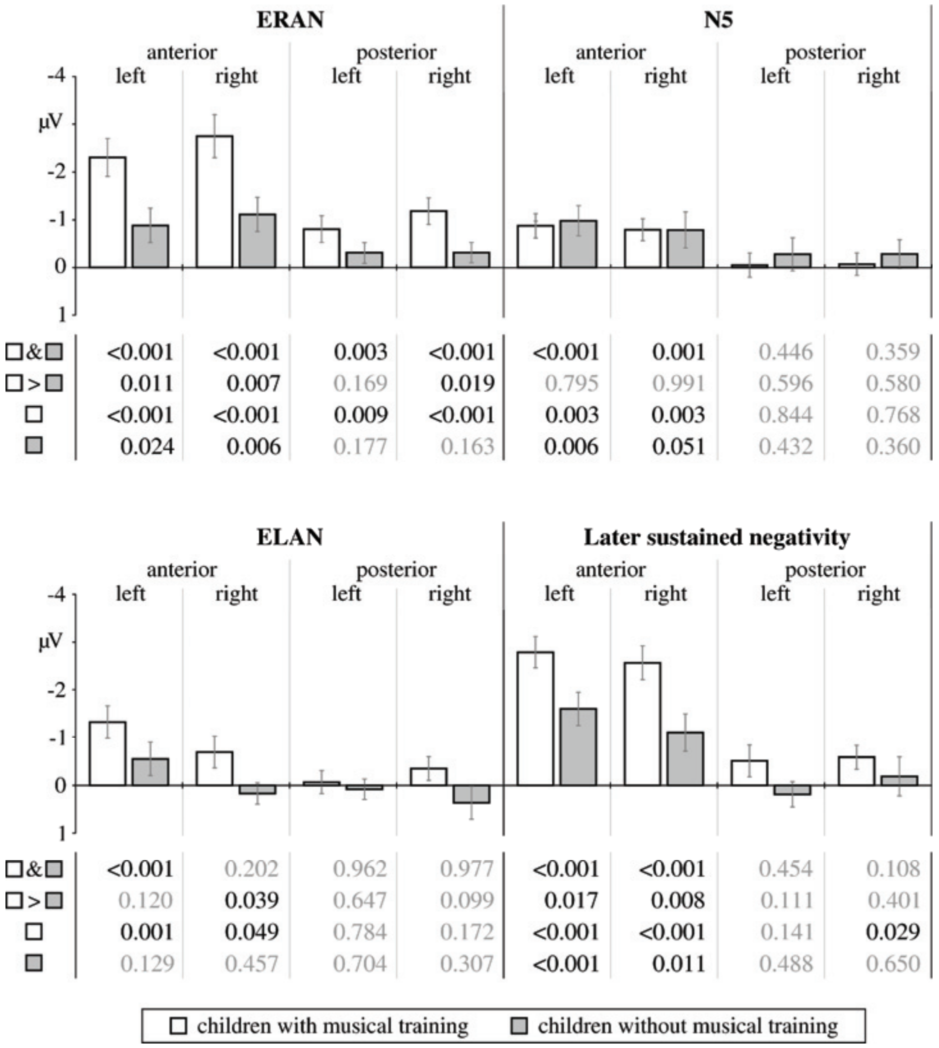
An overview of the results of the ANOVA used to evaluate this ERP component is given in Table 12-2 (column 4). It revealed a main effect of syntactic regularity, as well as interactions of syntactic regularity × subgroup, of syntactic regularity × subgroup × hemisphere × attention, of syntactic regularity × anterior-posterior distribution, and of syntactic regularity × anterior-posterior distribution × hemisphere. These results reflect that the LSN was most prominent at anterior sites (with a slight lateralization to the left hemisphere). MT children had a larger amplitude and a different lateralization of the LSN. Planned comparisons revealed that this ERP component was significant in both anterior ROIs but not for the posterior ROIs when both groups were considered (left-anterior: $F_{(1,39)} = 84.36$, $p < 0.001$; right-anterior: $F_{(1,39)} = 48.59$, $p < 0.001$). Furthermore, the component's amplitude was significantly larger in the MT group compared to the NM group in both anterior ROIs (left: $F_{(1,39)} = 6.24$, $p = 0.017$; right: $F_{(1,39)} = 7.74$, $p = 0.008$).

The ANOVAs for each group revealed a main effect of syntactic regularity (MT: $F_{(1,20)} = 41.03$, $p < 0.001$; NM: $F_{(1,19)} = 5.11$, $p = 0.036$) as well as an interaction of syntactic regularity × anterior-posterior distribution (MT: $F_{(1,20)} = 51.18$, $p < 0.001$; NM: $F_{(1,19)} = 26.03$, $p < 0.001$) in both groups. This indicates that a significant LSN was found in both groups which had a larger amplitude at anterior sites. In the MT group, an interaction of syntactic regularity × hemisphere × attention ($F_{(1,20)} = 6.07$, $p = 0.023$) was found, whereas in the NM group interactions of syntactic regularity × region × attention ($F_{(1,19)} = 4.91$, $p = 0.039$) and of syntactic regularity × region × hemisphere ($F_{(1,19)} = 8.54$, $p = 0.009$) were observed.

12.4 Discussion

The present experiment compared the processing of musical and linguistic syntax in 11-year old children that either received musical training or not. The charts in Figure 12-3 give an overview of the results of this experiment. Obviously, the amplitudes of the ERAN, the ELAN, and the LSN were considerably larger in the MT group compared to the NM group. The table below each chart contains the results from the user-defined contrasts that were employed to determine in which ROI the difference between the two experimental conditions (either irregular *vs*. regular chord or incorrect *vs*. correct sentences). It is indicated in which ROI a component was significant, either when both groups are considered (first row), or when the MT group (third row) and the NM group (fourth row) were evaluated separately. The second row indicates, if a larger amplitude was observed in the MT group compared to the NM group.

The ***ERAN*** was found in both groups (MT and NM). It had a bilateral but slightly right-lateralized distribution at anterior scalp sites. Its latency is slightly delayed compared to adults with a peak at around 240 ms. Like in the MT group of the 9-year old children, an enlarged ERAN amplitude was found in the MT group of the 11-year old children. It is also in accordance with the evidence from an earlier study which found an enlarged ERAN amplitude in adult musicians compared to non-musicians (Koelsch, Schmidt et al., 2002). However, this finding is remarkable given that the children in the MT group did play an instrument not longer than for around 5 years, and that the ERAN amplitude in the eleven-year old children with MT was increased to 253% compared to the children with NM. The ERAN in the MT group seems to be more widely extended over the scalp, presumably due to its larger amplitude. The enlarged ERAN amplitude likely reflects the more comprehensive knowledge of music-syntactic regularities in children with MT. In accordance with a number of studies that report improved auditory processing in musicians (see chapter “Musical Training”), this mainly implicit knowledge might have contributed to an improved music-syntactic processing reflected by the enlarged ERAN amplitude.



	ERAN				N5			
	anterior left	anterior right	posterior left	posterior right	anterior left	anterior right	posterior left	posterior right
☐&▨	<0.001	<0.001	0.003	<0.001	<0.001	0.001	0.446	0.359
☐>▨	0.011	0.007	0.169	0.019	0.795	0.991	0.596	0.580
☐	<0.001	<0.001	0.009	<0.001	0.003	0.003	0.844	0.768
▨	0.024	0.006	0.177	0.163	0.006	0.051	0.432	0.360

	ELAN				Later sustained negativity			
	anterior left	anterior right	posterior left	posterior right	anterior left	anterior right	posterior left	posterior right
☐&▨	<0.001	0.202	0.962	0.977	<0.001	<0.001	0.454	0.108
☐>▨	0.120	0.039	0.647	0.099	0.017	0.008	0.111	0.401
☐	0.001	0.049	0.784	0.172	<0.001	<0.001	0.141	0.029
▨	0.129	0.457	0.704	0.307	<0.001	0.011	0.488	0.650

Figure 12-3 Summary of the results from Experiment IV: Amplitudes of the investigated ERP components from the music experiment (ERAN and N5; upper panel) and from the language experiment (ELAN and LSN; bottom panel). The tables below each chart indicate in which ROI the difference of the experimental conditions (either irregular vs. regular chord or syntactically incorrect vs. correct sentences) was significant: for the mean of both groups (first line), for the MT children (third line), and for the NM children (fourth line). The (second line) indicates whether the difference in the MT children was significantly larger than this in the NM children.

An ***N5*** usually follows the ERAN. It is taken to reflect processes of harmonic integration. It was observed equally in both groups. This is in accordance with an earlier study investigating the processing of musical syntax in adult musicians (Koelsch, Schmidt et al., 2002) and with the results of Experiment III that also did not show group differences in the N5 amplitude.

Comparable to other experiments of this work, an early difference in auditory processing was found in this experiment. A discussion of the possible functional significance of this difference can be found in the chapter "Experiment II".

An ***ELAN*** was found for the MT group whereas in the NM group the ELAN was not significant. These results confirmed our expectations that musical training might lead to an improved processing of linguistic syntax. The ELAN is proposed to reflect processes of fast and fairly automatic syntactic structure building and was most prominent at left-anterior scalp sites, which is in accordance with results from earlier studies in adults (e.g. Hahne & Friederici, 1999). As this ERP component develops until 12 to 13 years and the processes that are reflected by it are still developing, it was not clear if it would be present in 11-year old children. For this reason, the age of the children was an important additional variable to account for the amplitude size of the ELAN and to disentangle influences of musical training and of development and their interaction.

The ***LSN*** was significant in both groups, but had an enlarged amplitude in the MT group. This ERP component had an onset around 400 ms and a sustained time course. It was relatively bilaterally distributed (but was slightly larger in the left hemisphere). In contrast to the ELAN, which was only found in the MT group, a LSN was found in both groups. However, the amplitude of the LSN component is almost two times as large in the MT group as in the NM group.

Usually a P600 follows the ELAN which was not observed in this experiment. However, this result was expected and in accordance with the results of Experiment III. A more detailed discussion can be found in the chapter on "Experiment III".

Both the presence of an ELAN and the enlarged amplitude of the LSN in MT children indicated a transfer effect from the music- to linguistic-syntactic processing. It nicely demonstrates that musical training may influence particular processes in another cognitive domain (as language). This transfer effect may be accounted for by the following assumption: The enlarged ERAN amplitude in MT children indicates that their music-syntactic processing is more elaborated which is reflected larger amplitudes of their neurophysiological correlates. The overlap in the neural resources underlying the processing of musical and linguistic syntax (see the chapters on "Music Perception", "Language Perception", and "Music and Language") makes it likely that transfer effects may be found. This might have led to a more proficient processing of linguistic syntax in MT children. On a more abstract level, this transfer effect might be related to the processing of sequential information that is involved in both the processing of musical and linguistic syntax. These assumptions also apply to other experiments of this work, and are elaborated in the chapter “General Discussion”.

12.5 Conclusion

The main finding of this experiment was the establishment of the ELAN in MT children which could not be observed in NM children. In addition, the ERAN and the LSN had an enlarged amplitudes in MT children compared to NM children. This indicates that MT children had an improved processing of musical syntax as well as a transfer effect from music to language leading to an superior processing of linguistic syntax. This improvement is presumably due to the heightened implicit and explicit knowledge of music-syntactic regularities in MT children. It resulted in an improved function of the neural correlates that underlie music-syntactic processing. Moreover, the transfer effect was most presumably due to the strong overlap in the neural resources underlying music-syntactic and linguistic-syntactic processing.

13 Experiment I – IV: Development of the Neural Correlates of Music-Syntactic Processing

One main aim of the present work was to investigate the neural correlates of music- and linguistic-syntactic processing in children of different age groups (2½-, 5-, 9-, and 11-year old children). However, for two reasons this overview will be mainly focussed on the development of music-syntactic processing. Firstly, developmental aspects of processing linguistic syntax were subject of a recent study (Hahne et al., 2004) whereas no earlier study investigated the development in the processing of musical syntax. Secondly, whereas data on the processing of musical syntax were acquired from all four age groups, data on the processing of linguistic syntax were measured only in two age groups (9- and 11-year old children). Thus, this overview will specifically focus on the development of the neural correlates of music-syntactic processing.

As outlined in the previous chapters and the chapter “Music perception”, a violation of music-syntactic regularities usually elicits two ERP components: the ERAN and the N5. An overview of the development of these ERP components will be given in this chapter. It will consider the amplitude size and the peak latency of these components. Figure 13-1 summarizes the amplitude size in the different age groups for the two components – in the left panel for the ERAN, and in the right panel for the N5. Since the experiments in all age groups contained a non-attentive part (where the children watched a movie) these data will be used for the present developmental comparison.

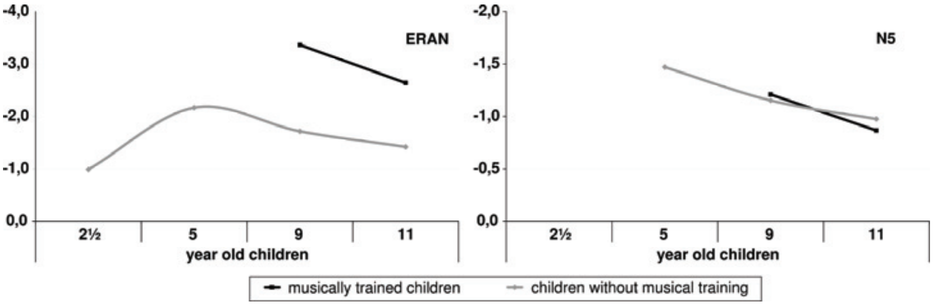


Figure 13-1 Developmental course of the amplitude size of ERAN (left panel) and N5 (right panel). Black solid lines represent data from musically-trained children, grey solid lines these from children without musical training

ERAN: The ERAN is taken to reflect early and fairly automatic processes of syntactic structure building (cf. Koelsch, 2005). It was observed in all age groups. For the children with typical language development and without musical training (NM) the ERAN amplitude was relatively small in the 2½-year-olds (*M* = -0.99 µV; *SEM* = 0.52 µV;

mean of the anterior ROIs). It was largest in the 5-year-olds (*M* = -2.17 µV; *SEM* = 0.32 µV). Later, the amplitude size decreased, i.e. it was smaller in the 9-year-olds (*M* = -1.72 µV; *SEM* = 0.59 µV) and smallest in the 11-year-olds (*M* = -1.42 µV; *SEM* = 0.37 µV). In the children with musical training (MT), the same pattern as for the NM children was observed, even though the amplitude size of the ERAN was much larger: The amplitude size also decreased from the 9-year old children (*M* = -3.36 µV; *SEM* = 0.74 µV) to the 11-year old children (*M* = -2.64 µV; *SEM* = 0.47 µV).

A mixed-model ANOVA for repeated measures with the within-subject factors syntactic regularity (regular tonics *vs*. irregular supertonics), anterior-posterior distribution, and hemisphere, and the between-subjects factors age group (2½-, 5-, 9-, and 11-year old children) and subgroup (NM *vs*. MT) was used to statistically evaluate the ERAN amplitude size. It revealed a main effect of syntactic regularity ($F_{(1,124)} = 70.66$; $p < 0.001$), and interactions of syntactic regularity × anterior-posterior distribution ($F_{(1,124)} = 42.76$; $p < 0.001$) and syntactic regularity × subgroup ($F_{(1,124)} = 4.25$; $p = 0.041$). This indicates that an ERAN was observed that had an anterior distribution and was larger in the group of musically trained children. This is in well accordance with the results that were observed when the experiments are considered separately. Notably, no significant interactions of syntactic regularity × age group were found. This demonstrates that the ERAN, once established, remained relatively stable and had a comparable amplitude size in the different age groups. However, it seems as if the scalp distribution slightly changes with age. The main effect of anterior-posterior distribution ($F_{(1,124)} = 21.67$; $p < 0.001$) indicates that the processing of both regular and irregular chord functions mainly takes place in anterior brain regions. The interaction of anterior-posterior distribution × age group ($F_{(3,124)} = 4.49$; $p = 0.005$) may reflect a shift towards anterior electrodes as the children grow older. Descriptively, this can be observed when the scalp topography of the ERAN in the group of 5-year old children (Figure 10-4) is compared with that of the group of 9- or 11-year old children (Figures 11-3 and 12-2).

The peak latencies of the ERAN in the NM group were largest for the 2½-year old children (left-anterior: 280 ms; right-anterior: 275 ms), decreased for the 5-year old children (left-anterior: 234 ms; right-anterior: 233 ms), further decreased for the 9-year old children (left-anterior: 198 ms; right-anterior: 199 ms), and were similar for the 11-year old children (left-anterior: 197 ms; right-anterior: 201 ms). For the MT group, the latencies slightly decreased compared to the NM children. As in the NM group, they were similar for the 9-year old (left-anterior: 185 ms; right-anterior: 183 ms) and the 11-year old children (left-anterior: 185 ms; right-anterior: 180 ms). The latencies in the 9- and 11-year old children were similar to those in adults (see, e.g., Koelsch et al., 2007).

N5: The N5 was proposed to reflect processes of harmonic integration (see, e.g., Koelsch et al., 2000). It could not be observed in the 2½-year old children. For the older children, the development of its amplitude was essentially the same as for the ERAN amplitude. In the NM children it was largest in 5-year old children (M = -1.47 µV; SEM = 0.52 µV), decreased for 9-year old children (M = -1.15 µV; SEM = 0.89 µV), and was smallest in 11-year old children (M = -0.98 µV; SEM = 0.43 µV). In MT children, the amplitude size of the N5 was similar to the size in NM children: it was slightly higher in 9-year-olds (M = -1.21 µV; SEM = 0.53 µV) and decreased in 11-year-olds (M = -0.87 µV; SEM = 0.34 µV).

An ANOVA with the same factors as above (but without the group of 2½-year old children, for which no N5 was observed) revealed a main effect of syntactic regularity ($F_{(1,88)} = 14.32$; $p < 0.001$), and an interaction of syntactic regularity × anterior-posterior distribution ($F_{(1,88)} = 19.73$; $p < 0.001$).[30] This indicates that an N5 with an anterior scalp distribution was observed in the investigated age groups. No significant interactions of syntactic regularity × age group were observed. It demonstrates that the amplitude of the N5 remained relatively stable during development. In all age groups, the N5 had a more sustained time course than the ERAN and often no clear peak could be observed. Thus, it was difficult to clearly determine the peak latencies. These were therefore not analyzed.

To sum up, the inspection of the developmental time course of amplitude size and peak latency of ERAN and N5 revealed a high amount of stability of these ERP components. However, descriptively differences were observed for the amplitude size of both components: The amplitudes of both ERAN and N5 were largest for the 5-year old children and decreased in the 9- and the 11-year old children. Moreover, the results of the ANOVAs, that were used to evaluate ERAN and N5 in the different age groups, nicely replicated the general pattern of results from the single experiments.

Friederici (2005) reviewed neurophysiological markers of language acquisition and proposed a high amount of stability of many ERP components that reflect particular aspects of language processing. These components, once established, appear relatively similar to these of older children and adults. A similar proposal can be made for the ERP components that reflect music-syntactic processing, for which a high developmental stability was demonstrated in this overview.

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[30] Furthermore, a main effect of anterior-posterior distribution ($F_{(1,88)} = 97.34$; $p < 0.001$), and interactions of anterior-posterior distribution × age group ($F_{(2,88)} = 3.62$; $p = 0.031$) and anterior-posterior distribution × hemisphere ($F_{(1,88)} = 12.11$; $p = 0.001$) were found.

14 General Discussion

14.1 Summary: Results of Experiment I to IV

The experiments of this work investigated the processing of musical and linguistic syntax in children of different age groups. Moreover, the influence of musical training and language impairment on these processes was evaluated. The main results of these experiments will be summarized briefly.

Experiment I investigated the processing of musical syntax in ***2½-year old children***. EEG measures were recorded while the children were listening to chord sequences that ended either on a regular chord (a tonic) or a harmonically irregular chord. Two subgroups listened to different irregular chords: In one subgroup ($N = 37$) supertonics, in another subgroup ($N = 32$) Neapolitan sixth chords were used as irregular chords. This manipulation was introduced to compare the effect the combination of either a slight acoustical violation (the supertonic only minimally deviates acoustically from the regular chord) or a stronger acoustical violation (the Neapolitan sixth chord introduced more saliently acoustical deviants, namely two out-of-key notes) with a violation of the harmonic regularities.[31] In adults and older children (Koelsch et al., 2003; Koelsch et al., 2000) the irregular chords elicit, compared to the regular chords, an ERAN (around 200 ms; reflecting fast and automatic syntactic structure building) and an N5 (around 500 ms; reflecting processes of harmonic integration).

The main finding of this experiment was that an ERAN was observed in the 2½-year old children. This reflects that the neural correlates of music-syntactic processing are at least partially present in children of that age. Essentially the same results were obtained in the two subgroups (that had either supertonics or Neapolitan sixth chords as irregular chords). The relatively small size of the ERAN amplitude and the lack of the N5 indicate that these processes are – at least to some degree – still in development. Currently, the processing of musical syntax was not investigated in younger children than 5-year-olds. For the first time the present study demonstrated that music-syntactic processing can be observed even in much younger, 2½-year old children.

In ***Experiment II*** the processing of musical syntax in ***5-year old children*** and the influence of language impairment on these processes was investigated. To this end, children with typical language development (TLD; $N = 20$) and with Specific Language Impairment (SLI; $N = 15$) were compared. Deficiencies in the processing of linguistic syntax were a main characteristic of children with SLI (see the chapter "Language Impairment"

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[31] For a discussion of these issues see the section "Methods" in the chapters on Experiment I and II as well as Koelsch, Jentschke, Sammler, and Mietchen (Koelsch et al., 2007).

and Leonard, 1998 for a review). Thus, we investigated, whether these deficiencies could also be found for the processing of musical syntax. EEG measurements were recorded while the participants listened to chord sequences that ended either regularly (on a tonic) or irregularly (on a supertonic). Further, behavioural tests (a language development test, tests on musical abilities, and a non-verbal intelligence test) were performed to enable a more detailed description of the participants' characteristics. The main finding was that an ERAN and an N5 could be demonstrated in children with TLD. In contrast, neither of these ERP components was observed in the group of children with SLI. However, these differences between the two groups were, most presumably, not due to problems in basic auditory processing mechanisms in the children with SLI: Both groups did not differ in their ERP response to the onset of the chord sequence. Instead, the group difference was rather due to the deficient processing of syntax for both, music and language, in the children with SLI. Other findings from the same experiment add further weight on this assumption: [1] The ERAN amplitude was correlated with the subtests of the language development test. [2] The considerable difference in the ERP responses to a violation of musical syntax between the two groups of participants allowed classifying a large number of participants (77.1 %) according to their ERAN amplitude size in a linear discriminant analysis. Taken together, the results from Experiment II strengthen the view that the shared neural correlates of processing syntax in music and language may lead to a considerable interaction of these processes. This assumption will be more thoroughly discussed below (see 14.3).

In ***Experiment III*** the processing of musical and linguistic syntax was compared in ***9-year old children*** that either received musical training (MT; $N = 19$) or did not (NM; $N = 13$). In these children, the ERP responses to a violation of musical syntax were acquired in one experimental session, and the ERP responses to a violation of linguistic syntax in another session. The stimuli of the music experiment were the same as in Experiment II. The stimuli of the language experiment were sentences with passive mode construction that ended either syntactically correct or incorrect. These sentences were used in a large number of earlier studies with adults (e.g, Friederici et al., 1993) and children (e.g., Hahne et al., 2004).

The main finding was an enlarged ERAN amplitude in the children with MT compared to the NM group. This finding is in accordance with an earlier study (Koelsch, Schmidt et al., 2002) that found a comparable enlargement of the ERAN in adult musicians. It should be mentioned that the children in that age group learned an instrument not longer than approximately 39 months. It is remarkable, that such a comparably short period of training can lead to a considerable change in the brain correlates of music-syntactic processing. It was neither expected, nor observed that the amplitude size of the N5 differed between the two groups. In the language experiment, an ELAN was not present in any of the two groups.[32] The amplitude of the later sustained negativity (LSN; which reflects a violation of the linguistic syntax and is regarded as a precursor of the ELAN in children) did not differ between the two groups (MT *vs*. NM). This indicates that the relatively short period of musical training might not be sufficient to evoke transfer effects between music-syntactic and linguistic-syntactic processing (that would be indicated by differences in the ERP responses between the two groups). Influences of the education and the socio-economic status of the parents and the intelligence of the children were statistically controlled – correlation analyses revealed no interaction of these factors with the amplitudes of the ERP components that were investigated.

Experiment IV investigated the processing of musical and linguistic syntax in ***11-year old children*** that were either musically trained (N = 21) or not (N = 20). The experimental paradigm was the same as in Experiment III. Two main findings were obtained in this experiment: Firstly, an enlarged amplitude size of the ERAN was found in MT children compared to the NM children (similar to the results in Experiment III). Secondly, a group difference was observed in the neural correlates of the processing of linguistic syntax: for children with MT both a significant ELAN amplitude size as well as a significantly enlarged amplitude size of the LSN was found. Most remarkably, an ELAN was present in the group of children with MT but not in the group of children with NM. That is, musical training may lead to earlier established processes of fast and automatic structure building that are reflected in the ELAN. In addition, the amplitude size of the LSN was enlarged in MT children. Both findings suggest that musical training may not only leads to an improved music-syntactic processing but also to a similar improvement for linguistic- syntactic processing. This again, emphasizes the strong overlap of the neural correlates of musical and linguistic syntax processing. Some accounts to this difference will be discussed in more detail below (see 14.3). Most presumably, these differences in the ERP responses between the two groups of children (MT *vs*. NM) can not be accounted for by external variables as the education and the socio-economic status of their parents or the intelligence of the children – these variables were matched and did not differ between the two groups.

Table 14-1 provides an overview of the investigated ERP components and if these were observed in the different subgroups and age groups. Both, ERAN and N5 reflect music-syntactic processing. An ERAN was found in the children of all age groups. It was ab-

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[32] It should be mentioned that we did not expect to find an ELAN because this ERP component was demonstrated to develop for sentences with passive mode construction until around 13 years of age (cf. Hahne et al., 2004).

sent in the children with specific language impairment. The ERAN amplitude in 9- and 11-year old MT children was significantly larger than in NM children. An N5 was not present in 2½-year old children, but in all children of the older age groups (5-, 9-, and 11-year-olds). It was not present either in the children with SLI. As expected, musical training did not influence the amplitude size of the N5. The ELAN and the LSN reflect linguistic-syntactic processing. The LSN is regarded as a precursor of the ELAN, which reflects fast and automatic structure building processes. The LSN reflects the detection of a syntactic violation during the period in which the ELAN develops (cf. Hahne et al., 2004). In accordance, an ELAN was not observed in the 9-year old children. In the 11-year old children an ELAN was demonstrated, but only in the MT children. The LSN was present in 9- and 11-year old children. In the 9-year old children its amplitude size did not differ between children with MT and with NM. In contrast, for the 11-year old children with MT the LSN amplitude was significantly larger than in children with NM. It may be assumed that the amount of musical training the 9-year old children received was not sufficient to evoke the transfer effects that were found in the 11-year old children.

Table 14-1 Summary of the main results of the present work: In 2½- and 5-year old children the processing of musical syntax was investigated (reflected in the ERP components ERAN and the N5; the table cells for the language ERP components are empty) whereas in 9- and 11-year old children the processing of musical and linguistic syntax (reflected in the ERP components ELAN and LSN) was compared.

Experiment		ERAN	N5	ELAN	LSN
I	2½-year old children	N	–	not investigated	
II	5-year old children	N, ~~S~~	N, ~~S~~		
III	9-year old children	M > N	M = N	–	M = N
IV	11-year old children	M > N	M = N	M	M > N

NOTE: The capitals in the table cells denote in which of the different groups of children the investigated ERP components were significant. "N" denotes the children with typical language development and without musical training, "M" the children with musical training, and "S" children with SLI. "=" indicates that the amplitude of the respective ERP component was of the same size in both groups, ">" that the component was significantly larger in one group.

14.2 Influences of Musical Training, Language Impairment, and Development on Processing Musical and Linguistic Syntax

Influences of Language Impairment: A main characteristic of children with SLI is their deficient syntactic processing. In Experiment II was found that these deficiencies were not restricted to language perception but also for music perception: In children with SLI, no ERP response to a violation of music-syntactic regularities was observed. However, these ERP responses are present in children of the same age with TLD and even in younger (2½-year old) children. Several accounts to the deficiencies in music-syntactic processing in children with SLI are conceivable. Two will be briefly discussed. Firstly, the deficiencies may be due to an impairment of more domain-general processes that are involved in both the processing of musical and linguistic syntactic regularities. There are some candidate processes, e.g., deficits in the procedural memory system (Ullman & Pierpont, 2005), in working memory processes (Baddeley, 2003; Baddeley et al., 1998), or in grammar processing mechanisms (van der Lely, 2005; van der Lely et al., 1998). Secondly, the deficiencies of children with SLI, demonstrated for the processing of syntax in both domains (music and language), might be due to the strong overlap in the neural resources underlying these processes (for discussion, see 14.3).

Influences of Musical Training: Influences of musical training were found for the processing of both, music and language. For both age groups (9- and 11-year old children) an enlarged ERAN amplitude was observed in MT children. This is in accordance with a large number of studies, demonstrating brain plasticity in response to musical training (for a detailed overview, see the chapter “Musical Training”). The same result revealed an earlier study, investigating the processing of musical syntax in adult musicians (Koelsch, Schmidt et al., 2002). Most presumably, musicians have a larger implicit and explicit knowledge about the music-syntactic regularities that underlie Western tonal music. Their enlarged representations of these regularities and of harmonic relatedness may account for the enlarged ERAN amplitude.

In 11-year old children with MT an ELAN was found (which is lacking in the group with NM). The LSN – regarded as a precursor of the ELAN, but also reflecting the detection of violations of the linguistic syntax – had a significantly larger amplitude size in the children with MT. This demonstrates that musical training may contribute to an improved processing of linguistic syntax and moreover, to an earlier establishment of the fast and automatic processes of syntactic structure building. Most presumably, these differences were not elicited by personality variables of the children, such as the socioeconomic status, the education of their parents, or the intelligence scores of the children. These variables were either matched (in the 11-year old children) or statistically controlled for (in the 9-year old children). Instead, these transfer effects rather rely on the overlap of the neural correlates of syntax processing in music and language (that will be discussed in 14.3).

Currently, there are not many studies regarding transfer effects into other cognitive domains due to musical training. Among these studies, some demonstrated such an influence on language processing (see the chapter "Musical Training"). Most studies employed behavioural methods and only recently, some studies investigated such transfer effects with neurophysiological methods in order to provide a better understanding of the underlying neural mechanisms. These studies found a beneficial effect of musical training on the processing of prosody (Magne et al., 2003, 2006; Moreno & Besson, 2006; Schön et al., 2004). The present work, focussing on the processing of musical and linguistic syntax, adds some further knowledge regarding such neural mechanisms and is among the first to specify neural correlates of such transfer effects from the music to the language domain.

Development of the neural correlates of music-syntactic processing: To investigate the development of music-syntactic processing, the ERP data from children of several age groups (2½, 5, 9, and 11 years) were directly compared. The youngest age group, for which an ERAN could be demonstrated, were 2½-year old children. It is likely that the ERAN is still developing at this age. In 5-year-olds (with TLD) the ERAN was more stable and had an enlarged amplitude size compared to the 2½-year old children. Later, the amplitude size decreased with increasing age. The latency of the ERAN shortened with age. An N5 was not observed in the 2½-year old children. In 5-year old children (with TLD) it was present and its amplitude size was largest. It also decreased as the children's age increase. Taken together, these findings indicate a high amount of continuity in the neural correlates of music-syntactic processing. This is comparable to the development of language perception, for which Friederici (2005) also proposed a high amount of continuity.

As outlined in the chapter "Music Perception", there is currently no widely accepted and comprehensive model of how music perception develops. Some theoretical accounts propose that the acquisition of music-structural regularities develops until late childhood (i.e., 6 to 7 years of age; cf. Sloboda, 1985; Trainor & Trehub, 1994; Trehub, 2003b). Other accounts assume that these processes might be established earlier, specifically if implicit measures are used (Schellenberg et al., 2005). ERPs are such an implicit measure which allows observing neural correlates of music-syntactic processing in 2½-year old children. This result emphasizes that knowledge of music-syntactic regularities is present quite early in development and that the process of musical enculturation might not be that long lasting as presently assumed.

14.3 Commonalities between the neural correlates of processing musical and linguistic syntax

The summary of the present experiments strengthens the view that the neural correlates of processing musical and linguistic syntax strongly overlap. Thus, there might be a considerable interaction of these processes. This assumption is supported by both, the finding of deficiencies in children with SLI for both the processing of linguistic and musical syntax, and the presence of an ELAN and the enlarged amplitude of the LSN in the children with MT. The transfer effect that was demonstrated for the processing of linguistic syntax in children with MT may be explained by considering (at least) two possible mechanisms.

Focusing on the anatomical location, a large number of studies provided evidence for a strong overlap of the neural resources that are recruited in both tasks. It is thus conceivable that some task general processing components may be involved in both the processing of linguistic and musical syntax. One such component may be the procedural memory system (Ullman, 2004) which is assumed to play an important role in acquiring and performing skills involving sequencing. That is, it might be related to the processing and the storing of ordered sequences which rely on structures and regularities (as musical and linguistic syntax). The *inferior frontal gyrus* (IFG) was proposed as a neural basis for such processes (see Bornkessel et al., 2005; Gelfand & Bookheimer, 2003; Janata & Grafton, 2003; Mesulam, 1998).

Lashley (1951) suggested that sequencing and coordination of behaviour may be regarded as a form of grammar. Movements can be considered as communicative gestures, and might therefore be associated with language. The IFG (especially the *pars opercularis* and the adjacent *ventral premotor cortex*) is important for a wide range of motor functions (for a review, see Binkofski & Buccino, 2004; see also the chapter "Music and Language"). In the musical domain, it is involved in the processing of sequential sounds (Platel et al., 1997), sight reading (Sergent et al., 1992), and score reading while listening to the accuracy of a performance (Parsons, 2001). This region is also involved in the processing of temporal structures in order to predict future sequential events (Coull, 2004; Fuster, 2001; Rao et al., 2001; Schubotz et al., 2000), e.g., violations of previously encountered rhythmic patterns (Schubotz & von Cramon, 2001a), of specific event successions (Schubotz & von Cramon, 2001a), and of variations in pitch patterns (Gandour, Wong, & Hutchins, 1998).

Friederici, Fiebach, et al (2006) demonstrated a dissociation within the left *inferior frontal cortex* between the deep *frontal operculum* – responding to syntactic violations – and the inferior portion of the left *pars opercularis* (BA 44) – modulated by the complexity of well-formed sentences. This leads to another candidate process – working memory – that also relies (at least to some extent) on the IFG (e.g., Braver et al., 1997). Because language processing is realized as a sequential process, a word in a non-canonical position has to be identified as a moved element and to be kept active in working memory until its original position in the syntactic structure can be specified. More general, working memory functions may be a prerequisite to comprehend a musical or a sentential phrase, holding its elements in memory and building relations between these elements in order to detect their underlying structure and to build a coherent percept.

Turning to a more functional perspective, prosodic processing might interact with syntactic processing. It was demonstrated that prosodic cues are of considerable importance for language acquisition (Fernald, 1989; Papoušek, 1996), e.g., for word segmentation and the extraction of phrase structure. In adults, prosody is used for structural disambiguation, to guide parsing decisions, and to predict upcoming information in an utterance. A recent study by Eckstein (2005) indicated an influence of prosody merely on later processes than the early syntactic structure building (in adults). However, the processes of fast and automatic phrase structure building are thought to develop from later processes (cf. Hahne et al., 2004) for which a contribution of prosodic information may beneficial. The parts of the neural network in the inferior frontal cortex are not specific to the processing of syntax: The inferior part of the right IFG is also found implicated in prosody processing (cf. Friederici & Alter, 2004; see also M. Meyer et al., 2000; Wartenburger et al., 2007). Musical training, leading to an improved processing of musical syntax, might implicitly train this neural network (which is similar to the network used for syntactic processing). This could be an explanation for the transfer effects between musical and linguistic syntax processing. It may also open new perspectives for the treatment of language impairment.

14.4 Future perspectives

In this section some ideas will be proposed how the results of the present work might be extended in further studies. It is organized in three parts. One part contains methodological considerations, another part is related to theoretical issues, and a third part consists of some reasoning about how the knowledge gathered from this work may be utilized.

Methodological considerations: The use of additional evaluation methods might enable to gain further insight from the present data. Firstly, the analysis of frequency characteristics may provide additional knowledge of which kind of cognitive processes contribute to the processing of musical and linguistic syntax and if these processes differ between the groups of participants. The basic assumption is that particular classes of cognitive processes are related to certain frequency signatures. Recently, there are – to my knowledge – no studies that investigated the frequency characteristics of syntactic processing in music and language. However, such evaluation would have been beyond the scope of the present work. Profound knowledge about which cognitive processes can be related to a particular frequency signature is needed for a proficient interpretation of such data. A second method, coupling measures might enhance our understanding of which brain regions interact in which ways when musical and linguistic syntax are processed. However, since these coupling measures are based on relations between the scalp electrodes, they provide rather crude information about the localization of these processes. Only a limited number of electrodes were used in the experiments of the present work, since technical and practical limitations of the current measurement equipment did not allow for acquiring measurements from a larger number of electrodes. Thus, source localisation will not be possible. Finally, the scalp distribution of most of the ERP components that were investigated in this study was rather broad. The computations of surface Laplacian transformations (it is a measure current source density on the scalp obtained with spline functions) may help to specify more exactly the scalp site where these ERP responses are strongest.

Theoretical issues: Even though the present data allow for determining at which age first signs of processing musical syntax become established, this does not allow to investigate on which other basic processes these are grounded and how these processes become established. That is, currently it is not clear which processing stages are a prerequisite for the acquisition of music-syntactic regularities. For example, it is currently not known if it is necessary to extract the key in order to have a referential system, or if the acquisition of music-syntactic regularities might also take place on the basis of the computation of frequency relations between succeeding tones or chords. Such topics might be investigated using, e.g., MMN paradigms (Brattico et al., 2006; Fujioka et al., 2005) or modelling of these processes in neural networks (Bharucha, 1987; Tillmann et al., 2000).

Utilizing the knowledge gathered from this work: The results of the Experiments in this work demonstrate the strong relation between music and language: Both, the lack of ERP correlates of music-syntactic processing in the 5-year old children with SLI as well as the finding of an improved processing of both musical and linguistic syntax in the 11-

year old children with MT strengthens the view that a the processing of musical and linguistic syntax strongly interact. One may build on this knowledge to treat children with language impairment by means of music therapy. However, it has to be specified in more detail, which processes can be fostered in which way. Surely, it will not be sufficient to only play music to these children (because they have deficiencies in processing musical syntax as well). More likely, one has to tailor the task these children are confronted with in order to help them acquiring stepwise increasingly complex regularities. This, in some way, mirrors musical training which should provide a structured progression of challenges, geared precisely to learner's capacities in order to accelerate its progress. It remains to be specified in more detail, how exactly such treatment might be implemented.

The present results, demonstrating transfer effects from music to language, are intriguing. It indicates that musical training can influence processes in other domains than music perception. However, it is important to avoid the conclusion that music only gains its value, if it can produce significant non-musical cognitive benefits. Music can enrich a child's development in many ways. The narrow focus on cognitive development may prevent one from considering other important domains, including socio-emotional and physical development. Music has an intrinsic value as a great cultural invention, and as a vehicle for emotional expression and communication (see chapter on "Music Perception"). Further, the experience of developing mastery on an instrument is likely to positively influence a child's developing orientation to tasks requiring persistence (cf. Turner & Johnson, 2003). This in turn may help to create a stimulating and motivating environment that is conducive to wider learning.

Abbreviations

ANOVA	Analysis of Variance
BA	Brodmann's area
EEG	Electroencephalography, Electroencephalogram
ELAN	Early Left Anterior Negativity
ERAN	Early Right Anterior Negativity
ERP	event-related potentials, event-related brain potentials
fMRI	functional Magnetic Resonance Imaging
GLM	General Linear Model
IFG	*inferior frontal gyrus*
LSN	Later Sustained Negativity in response to a syntactic violation, considered as a precursor of the ELAN
M	Arithmetic Mean
MEG	Magnetencephalography, Magnetencephalogram
MRI	Magnet Resonance Imaging
MT	Musical Training, musically trained
MTG	middle temporal gyrus
NM	without musical training, Non-Musically Trained
p	Probability of Error
P600	Postivity around 600 ms after the onset of the critical word (containing a syntactic violation), reflecting processes of syntactic reanalysis and repair)
r	Correlation Coefficient
ROI	Region of Interest
SEM	Standard Error of Mean
SLI	Specific Language Impairment
STG	*superior temporal gyrus*
TLD	typical language development
VBM	Voxel-Based Morphometry

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Appendix

Complete list of the sentences used in the language experiment

001	correct	Die Forelle wurde geangelt.
001	incorrect	Der Karpfen wurde im geangelt.
002	correct	Die Tante wurde geärgert.
002	incorrect	Die Mutter wurde im geärgert.
002	filler	Der Onkel wurde im Bett geärgert.
003	correct	Die Torte wurde gebacken.
003	incorrect	Der Kuchen wurde im gebacken.
004	correct	Das Baby wurde gebadet.
004	incorrect	Die Schwester wurde im gebadet.
004	filler	Das Kind wurde im Teich gebadet.
005	correct	Der Strohstern wurde gebastelt.
005	incorrect	Die Maske wurde im gebastelt.
006	correct	Der Schneemann wurde gebaut.
006	incorrect	Die Burg wurde im gebaut.
006	filler	Die Hütte wurde im Ferienlager gebaut.
007	correct	Der Postbote wurde gebissen.
007	incorrect	Der Polizist wurde ins gebissen.
008	correct	Die Trompete wurde geblasen.
008	incorrect	Die Posaune wurde zur geblasen.
008	filler	Das Waldhorn wurde zur Jagd geblasen.
009	correct	Das Spiegelei wurde gebraten.
009	incorrect	Das Fleisch wurde zum gebraten.
010	correct	Die Reise wurde gebucht.
010	incorrect	Die Fahrt wurde im gebucht.
010	filler	Der Urlaub wurde im Reisebüro gebucht.
011	correct	Die Höhle wurde gebuddelt.
011	incorrect	Die Grube wurde unterm gebuddelt.
012	correct	Das Hemd wurde gebügelt.
012	incorrect	Die Hose wurde am gebügelt.
012	filler	Die Bluse wurde am Freitag gebügelt.
013	correct	Das Karussell wurde gedreht.
013	incorrect	Die Schraube wurde im gedreht.
014	correct	Das Kind wurde geduscht.

014	incorrect	Das Nilpferd wurde am geduscht.
014	filler	Das Nashorn wurde am Morgen geduscht.
015	correct	Das Korn wurde geerntet.
015	incorrect	Das Getreide wurde im geerntet.
016	correct	Die Maus wurde gefangen.
016	incorrect	Der Fubball wurde vorm gefangen.
016	filler	Der Ball wurde vorm Tor gefangen.
017	correct	Der Hof wurde gefegt.
017	incorrect	Die Treppe wurde am gefegt.
018	correct	Der Geburtstag wurde gefeiert.
018	incorrect	Die Party wurde im gefeiert.
018	filler	Das Fest wurde im Garten gefeiert.
019	correct	Der Räuber wurde gefesselt.
019	incorrect	Der Cowboy wurde am gefesselt.
020	correct	Die Landschaft wurde gefilmt.
020	incorrect	Der Löwe wurde im gefilmt.
020	filler	Der Elefant wurde im Zoo gefilmt.
021	correct	Das Loch wurde geflickt.
021	incorrect	Die Hose wurde am geflickt.
022	correct	Das Geheimnis wurde geflüstert.
022	incorrect	Der Plan wurde im geflüstert.
022	filler	Der Name wurde im Versteck geflüstert.
023	correct	Der Lehrer wurde gefragt.
023	incorrect	Der Zauberer wurde im gefragt.
024	correct	Die Banane wurde gefressen.
024	incorrect	Das Stroh wurde im gefressen.
024	filler	Das Futter wurde im Stall gefressen.
025	correct	Das Fass wurde gefüllt.
025	incorrect	Die Tonne wurde beim gefüllt.
026	correct	Das Baby wurde gefüttert.
026	incorrect	Die Gans wurde im gefüttert.
026	filler	Die Kuh wurde im Stall gefüttert.
027	correct	Das Brot wurde gegessen.
027	incorrect	Das Eis wurde im gegessen.
028	correct	Der Tunnel wurde gegraben.
028	incorrect	Der Kanal wurde am gegraben.
028	filler	Das Loch wurde am Morgen gegraben.

029	correct	Die Wurst wurde gegrillt.
029	incorrect	Das Schnitzel wurde beim gegrillt.
030	correct	Der Bruder wurde gehauen.
030	incorrect	Der Freund wurde beim gehauen.
030	filler	Die Schwester wurde beim Streit gehauen.
031	correct	Das Zimmer wurde geheizt.
031	incorrect	Die Küche wurde am geheizt.
032	correct	Die Musik wurde gehört.
032	incorrect	Das Konzert wurde im gehört.
032	filler	Das Gebrüll wurde im Zelt gehört.
033	correct	Der Hund wurde geimpft.
033	incorrect	Die Kusine wurde vorm geimpft.
034	correct	Der Tiger wurde gejagt.
034	incorrect	Der Wolf wurde im gejagt.
034	filler	Der Wal wurde im Meer gejagt.
035	correct	Der Schatz wurde geklaut.
035	incorrect	Der Lutscher wurde im geklaut.
036	correct	Die Nuss wurde geknackt.
036	incorrect	Das Haselnuss wurde vorm geknackt.
036	filler	Die Walnuss wurde vorm Backen geknackt.
037	correct	Das Essen wurde gekocht.
037	incorrect	Das Ei wurde am gekocht.
038	correct	Die Oma wurde geküsst.
038	incorrect	Der Clown wurde am geküsst.
038	filler	Der Opa wurde am Abend geküsst.
039	correct	Die Glocke wurde geläutet.
039	incorrect	Das Glöckchen wurde vorm geläutet.
040	correct	Das Gedicht wurde gelernt.
040	incorrect	Das Alphabet wurde im gelernt.
040	filler	Das Gedicht wurde im Unterricht gelernt.
041	correct	Das Buch wurde gelesen.
041	incorrect	Das Märchen wurde im gelesen.
042	correct	Der Koch wurde gelobt.
042	incorrect	Die Freundin wurde im gelobt.
042	filler	Die Schülerin wurde im Unterricht gelobt.
043	correct	Der Brand wurde gelöscht.
043	incorrect	Das Feuer wurde beim gelöscht.

044	correct	Der Rasen wurde gemäht.
044	incorrect	Das Gras wurde am gemäht.
044	filler	Die Wiese wurde am Donnerstag gemäht.
045	correct	Das Bild wurde gemalt.
045	incorrect	Die Schnecke wurde im gemalt.
046	correct	Der Keller wurde gemauert.
046	incorrect	Die Garage wurde im gemauert.
046	filler	Die Wand wurde im Keller gemauert.
047	correct	Die Wohnung wurde gemietet.
047	incorrect	Das Haus wurde im gemietet.
048	correct	Die Farbe wurde gemischt.
048	incorrect	Das Müsli wurde fürs gemischt.
048	filler	Der Beton wurde fürs Fundament gemischt.
049	correct	Die Kuh wurde gemolken.
049	incorrect	Die Kuh wurde im gemolken.
050	correct	Die Wunde wurde genäht.
050	incorrect	Der Rock wurde am genäht.
050	filler	Das Kleid wurde am Samstag genäht.
051	correct	Die Schokolade wurde genascht.
051	incorrect	Der Pudding wurde vorm genascht.
052	correct	Die Tür wurde geöffnet.
052	incorrect	Der Behälter wurde im geöffnet.
052	filler	Die Dose wurde im Zelt geöffnet.
053	correct	Der Motor wurde geölt.
053	incorrect	Das Türschloss wurde im geölt.
054	correct	Die Tasche wurde gepackt.
054	incorrect	Der Rucksack wurde im gepackt.
054	filler	Der Koffer wurde im Hotel gepackt.
055	correct	Das Auto wurde geparkt.
055	incorrect	Der Bus wurde am geparkt.
056	correct	Die Kartoffel wurde gepellt.
056	incorrect	Die Mandarine wurde zum gepellt.
056	filler	Die Wurst wurde zum Abendbrot gepellt.
057	correct	Die Melodie wurde gepfiffen.
057	incorrect	Das Kinderlied wurde beim gepfiffen.
058	correct	Die Blume wurde gepflanzt.
058	incorrect	Der Strauch wurde im gepflanzt.

058	filler	Der Baum wurde im Wald gepflanzt.
059	correct	Das Obst wurde gepflückt.
059	incorrect	Die Birne wurde im gepflückt.
060	correct	Der Angriff wurde geplant.
060	incorrect	Die Reise wurde beim geplant.
060	filler	Der Ausflug wurde beim Mittagessen geplant.
061	correct	Die Zitrone wurde gepresst.
061	incorrect	Die Apfelsine wurde vorm gepresst.
062	correct	Die Nase wurde geputzt.
062	incorrect	Das Fenster wurde im geputzt.
062	filler	Der Stiefel wurde im Flur geputzt.
063	correct	Der Schmuck wurde geraubt.
063	incorrect	Der Videorekorder wurde beim geraubt.
064	correct	Die Pfeife wurde geraucht.
064	incorrect	Die Zigarre wurde beim geraucht.
064	filler	Die Zigarette wurde beim Fest geraucht.
065	correct	Die Kleidung wurde gereinigt.
065	incorrect	Der Teppich wurde vorm gereinigt.
066	correct	Der Verletzte wurde gerettet.
066	incorrect	Der Verunglückte wurde im gerettet.
066	filler	Der Matrose wurde im Sturm gerettet.
067	correct	Die Kugel wurde gerollt.
067	incorrect	Der Reifen wurde ins gerollt.
068	correct	Die Ärztin wurde gerufen.
068	incorrect	Die Tochter wurde zum gerufen.
068	filler	Der Arzt wurde zum Kranken gerufen.
069	correct	Das Holz wurde gesägt.
069	incorrect	Das Brett wurde im gesägt.
070	correct	Der Sand wurde geschaufelt.
070	incorrect	Der Lehm wurde vorm geschaufelt.
070	filler	Der Schnee wurde vorm Haus geschaufelt.
071	correct	Der Sack wurde geschleppt.
071	incorrect	Der Schrank wurde beim geschleppt.
072	correct	Die Tür wurde geschlossen.
072	incorrect	Das Geschäft wurde am geschlossen.
072	filler	Der Laden wurde am Samstag geschlossen.
073	correct	Die Tablette wurde geschluckt.

073	incorrect	Die Medizin wurde im geschluckt.
074	correct	Der Tee wurde geschlürft.
074	incorrect	Die Milch wurde vom geschlürft.
074	filler	Die Suppe wurde vom Löffel geschlürft.
075	correct	Der Weihnachtsbaum wurde geschmückt.
075	incorrect	Das Klassenzimmer wurde fürs geschmückt.
076	correct	Die Petersilie wurde geschnitten.
076	incorrect	Die Hecke wurde beim geschnitten.
076	filler	Das Haar wurde beim Frisör geschnitten.
077	correct	Der Brief wurde geschrieben.
077	incorrect	Die Postkarte wurde zum geschrieben.
078	correct	Die Straee wurde gesperrt.
078	incorrect	Die Autobahn wurde am gesperrt.
078	filler	Der Weg wurde am Mittwoch gesperrt.
079	correct	Die Brücke wurde gesprengt.
079	incorrect	Der Turm wurde am gesprengt.
080	correct	Die Fremdsprache wurde gesprochen.
080	incorrect	Die Nachricht wurde aufs gesprochen.
080	filler	Der Text wurde aufs Band gesprochen.
081	correct	Das Geschirr wurde gespült.
081	incorrect	Die Tasse wurde am gespült.
082	correct	Das Fahrrad wurde gestohlen.
082	incorrect	Der Fernseher wurde beim gestohlen.
082	filler	Das Radio wurde beim Einbruch gestohlen.
083	correct	Die Wand wurde gestrichen.
083	incorrect	Das Tor wurde am gestrichen.
084	correct	Der Pullover wurde gestrickt.
084	incorrect	Die Mütze wurde vorm gestrickt.
084	filler	Der Schal wurde vorm Winter gestrickt.
085	correct	Das Lied wurde gesungen.
085	incorrect	Das Wanderlied wurde im gesungen.
086	correct	Das Paket wurde getragen.
086	incorrect	Die Mappe wurde unterm getragen.
086	filler	Die Zeitung wurde unterm Arm getragen.
087	correct	Der Verlierer wurde getröstet.
087	incorrect	Der Pechvogel wurde am getröstet.
088	correct	Der Kaffee wurde getrunken.

088	incorrect	Der Saft wurde beim getrunken.
088	filler	Der Kakao wurde beim Essen getrunken.
089	correct	Der Sprung wurde geübt.
089	incorrect	Der Tanz wurde vorm geübt.
090	correct	Der Klassensprecher wurde gewählt.
090	incorrect	Der Kanzler wurde am gewählt.
090	filler	Der Präsident wurde am Sonntag gewählt.
091	correct	Der Betrüger wurde gewarnt.
091	incorrect	Der Verbrecher wurde beim gewarnt.
092	correct	Das Auto wurde gewaschen.
092	incorrect	Der Pullover wurde am gewaschen.
092	filler	Das T-Shirt wurde am Dienstag gewaschen.
093	correct	Die Medaille wurde gewonnen.
093	incorrect	Der Preis wurde im gewonnen.
094	correct	Der Ball wurde geworfen.
094	incorrect	Der Stock wurde ins geworfen.
094	filler	Der Stein wurde ins Wasser geworfen.
095	correct	Das Fleisch wurde gewürzt.
095	incorrect	Der Salat wurde beim gewürzt.
096	correct	Der Zahn wurde gezogen.
096	incorrect	Der Wagen wurde übers gezogen.
096	filler	Der Schlitten wurde übers Eis gezogen.

Curriculum vitae

Sebastian Jentschke
Max Planck Institute for Human Cognitive and Brain Sciences
Stephanstrasse 1a
04103 Leipzig

Personal Information

Date and place of birth	31.01.1974 in Sangerhausen, Germany
Family status	single, no children
Citizenship	German

Education

March 1997 – February 2003	Diploma in Psychology at the Johann-Wolfgang-Goethe University, Frankfurt, Germany *Title of thesis: “Memory for actions within life-span – Investigating memory performance and brain activity“* *Supervisor: Prof. Dr. Monika Knopf*
October 1997 – April 2001	Research assistant at the Department of Psychological Methods, Evaluation, and Research Methods, Johann-Wolfgang-Goethe University Frankfurt, Germany
November 2001 – February 2003	Research assistant at the Department of Developmental Psychology, Johann-Wolfgang-Goethe University Frankfurt, Germany
February 2003 – present	Ph.D. student in the Junior Research Group “Neurocognition of Music” at the Max Planck Institute for Human Cognitive and Brain Sciences, Leipzig, Germany *Title of dissertation: “Neural correlates of Processing Structure in Music and Language*

– Influences of Musical Training and Language Impairment”
Supervisors: Prof. Dr. Angela D. Friederici,
PD Dr. Stefan Koelsch

Selbstständigkeitserklärung

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Sebastian Jentschke
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