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Brain and Music

**A contribution to the investigation of central auditory processing with
a new electrophysiological approach**

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Dekan: Prof. Dr. M. Schlegel
Gutachter: Prof. Dr. Angela D. Friederici
Prof. Dr. Erich Schröger
Dr. Mari Tervaniemi

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Table of Contents

Prelude on a Research Project	1
1 Ear, Nerves, and Hearing	7
2 Music-theoretical background	15
2.1 How major keys are related	15
2.2 The basic in-key functions in major	18
2.3 Neapolitan sixth chords	19
2.4 Secondary dominants	20
3 Subjective measures of music perception	23
3.1 Context-dependent representation of pitch	23
3.2 The representation of key-relatedness	25
3.3 The representation of chord-functions	27
3.4 The developing and changing sense of key	28
3.5 Hierarchies of harmonic stability	30
3.6 Musical expectancies	34
4 From EEG to ERPs	37
4.1 Electro-encephalography (EEG)	37
4.2 The 10-20 system	39
4.3 Obtaining event-related brain potentials (ERPs)	41
5 Magnetoencephalography	45
5.1 Forward solution and inverse problem	46
5.2 Volume conductor models	47
5.3 MEG vs. EEG	47
6 ERP-correlates of auditory processing	51
6.1 Exogenous components: N1 and P2	51
6.2 Mismatch Negativity, N2b (and P3)	52

7	ERP-correlates of language processing	55
7.1	Semantic processes: N400	55
7.2	Syntactic processes: (E)LAN and P600	58
7.2.1	Early Negativities	58
7.2.2	P600	59
8	ERP-correlates of music processing	63
8.1	One-part stimuli (melodic processing)	63
8.2	Multi-part stimuli (chord processing)	66
9	Experiment 1	69
9.1	Introduction	69
9.2	Methods	72
9.2.1	Subjects	72
9.2.2	Stimuli	73
9.2.3	Procedure	73
9.2.4	EEG measurements	74
9.2.5	Data-Analysis	74
9.3	Results	75
9.3.1	Musical context build-up	75
9.3.2	Neapolitan chords	75
9.3.3	Secondary dominants	80
9.3.4	Deviant instruments	81
9.3.5	Summary	81
9.4	Discussion	81
9.4.1	Building up a musical context	81
9.4.2	Processing unexpected chords	83
9.4.3	Effects of position	85
9.4.4	Late positivity and P3-effects	86
9.4.5	Secondary dominants	87
10	Experiment 2	89
10.1	Introduction	89
10.2	Methods	90
10.3	Results	90
10.3.1	Clusters	90
10.3.2	Effects of position	93
10.3.3	Degree of violation: Clusters vs. Neapolitans	93
10.3.4	Secondary dominants	95
10.3.5	Deviant Instruments	97
10.3.6	Summary	97

10.4 Discussion	99
10.4.1 Processing strong musical violations	99
10.4.2 Effects of position	99
10.4.3 Effects of degree of violation	100
10.4.4 Secondary dominants	101
10.4.5 Deviant instruments	101
11 Experiment 3	103
11.1 Introduction	103
11.2 Methods	103
11.3 Results	104
11.3.1 Behavioral Data	104
11.3.2 ERP-effects	104
11.3.3 ERPs: Effects of position	108
11.3.4 Effects of task-relevance	108
11.3.5 Secondary dominants	110
11.3.6 Deviant Instruments	111
11.3.7 Summary	111
11.4 Discussion	112
11.4.1 Effects of position	112
11.4.2 Effects of task-relevance	112
11.4.3 Effects of (non-) detection	113
11.4.4 Secondary dominants	114
11.5 Supplementary behavioral study	115
11.5.1 Methods	115
11.5.2 Results	116
11.5.3 Discussion	117
12 Experiment 4	119
12.1 Introduction	119
12.2 Methods	120
12.3 Results	120
12.3.1 Neapolitan chords	120
12.3.2 Effects of probability	122
12.3.3 Secondary dominants	123
12.3.4 Deviant instruments	124
12.3.5 Summary	126
12.4 Discussion	127
12.4.1 Effects of probability	127
12.4.2 Deviant instruments	129

13 Experiment 5	131
13.1 Introduction	131
13.2 Methods	134
13.2.1 Subjects and Stimuli	134
13.2.2 Procedure	134
13.2.3 EEG measurements and data-Analysis	135
13.3 Results	135
13.3.1 Modulations	135
13.3.2 Chord-Inversions	139
13.3.3 Deviant Instruments	140
13.3.4 Summary	142
13.4 Discussion	143
13.4.1 Modulations vs. in-key chords	143
13.4.2 ERAN vs. MMN	147
13.4.3 Chord inversions	147
13.4.4 Deviant instruments	147
14 Experiment 6	149
14.1 Introduction	149
14.2 Methods	150
14.2.1 Subjects and Stimuli	150
14.2.2 Procedure	151
14.2.3 EEG measurements	151
14.2.4 Data-Analysis	151
14.3 Block 1: Ignore condition	152
14.3.1 Results	152
14.3.2 Discussion	156
14.4 Block 2: Attend condition	159
14.4.1 Results	159
14.4.2 Discussion	162
15 Experiment 7	165
15.1 Introduction	165
15.1.1 Musical syntax as reflected in ERPs	166
15.2 Methods	167
15.2.1 Subjects and stimuli	167
15.2.2 Procedure	167
15.2.3 MEG recording	168
15.2.4 Postprocessing	169
15.2.5 Modeling and Data-Analysis	170
15.3 Results	171
15.4 Discussion	175

16 Summary and General Discussion	181
A Color Figures	201
B Supplementary ERPs	215
C Brain anatomy	219

Prelude on a Research Project

How is music like language and so what if it is? (Joseph B. Swain)

The linguistic sign unites, not a thing and a name, but a concept and a sound-image. The latter is not the material sound, a purely physical thing, but the psychological imprint of the sound, the impression it makes on our senses. The sound-image is sensory, and if I happen to call it 'material' it is only in that sense, and by way of opposing it to the other term of the opposition, the concept, which is generally more abstract (Ferdinand de Saussure)

Is language the interpreting system of all other systems, linguistic and non-linguistic? (Emile Benveniste)

How and where does the brain process music? Besides being motivated by a general interest in music-psychology, investigating this issue with the present study particularly aimed at exploring differences and similarities between the neural processing of music and language. The means of investigation were electrophysiological measures, namely event-related brain potentials (ERPs) obtained with both electro- and magnetoencephalography (EEG and MEG).

Up to now, electrophysiological reflections of language perception have been extensively investigated. Semantic and syntactic processing has been found to be reflected in ERP-components like N400, LAN, ELAN, and P600. In contrast, only little is known about the neural correlates of music perception. Thus, for the most part it is still unknown which cognitive processes and brain regions are activated by the processing of both music and language (and which specifically by either of them).

It may be speculated that at least some brain structures might be employed for the processing of both language and music, since both language and music have many features in common. Undoubtedly, both music and language are means of communication (e.g. Swain, 1997; Raffmann, 1993; Paynter et al., 1997; Sloboda, 1985). In a linguistic sense, both language and music are ‘sign systems’ which may be conceived as mechanisms that aid generating and understanding messages. Both the musical *and* the linguistic sign unite a sound-image and a concept, that is the ‘psychological imprint of the sound’ (Ferdinand de Saussure, in Innis, 1986).

The term ‘sign system’ refers to rules according to which (acoustic) information can be interpreted. That is, in both language and music, rules serve the attribution of meaning to information. Analogies between the structural perception of language and music have been stressed within the theory of ‘Generative Theory of Music’ (Lerdahl & Jackendoff, 1999), in which linguistics and music theory are methodologically connected in order to describe a ‘musical grammar’ (see also Bernstein, 1976; Raffmann, 1993; Swain, 1997).

Up to now, however, only little is known about how (and with which structures) the brain processes syntactic aspects of music. This contrasts the substantial amount of literature concerned with syntactic language processing. In electrophysiological studies, for example, these processes have been found to be reflected electrically in components like ELAN, LAN, and P600. In order to investigate the processing of a musical ‘syntax’, the present study initially simply took advantage of the psychological reality of musical syntax as demonstrated by the brain’s ability to expect musical events to a higher or lower degree (i.e. to identify ‘wrong’ notes, see e.g. Krumhansl & Kessler, 1982; Bharucha & Krumhansl, 1983; Bharucha & Stoeckig, 1986).

Like language, music also has a semantic dimension that refers to the meaning of signs. In both language and music, the meaning of a sign has to be ‘extracted’ by an active process of interpretation, whereby the meaning of signs has to be seen as lying in their systematic relation to each other (for thoughts about meaning in music see e.g. Sloboda, 1985; Raffmann, 1993; Swain, 1997; Paynter et al., 1997). That is, in both language and music, the meaning of an acoustic event does depend on its context in relation to the other acoustic

events with which it is used. In other words: Independently of whether a person sings, plays an instrument, or speaks a sentence, a succession of acoustic events is normally supposed to constitute a context that can be understood by another person.

The cognitive processes of interpreting information, that is of building up a context and integrating appropriate new information into it, are substantial for understanding music as well as language. These processes are connected to the semantics of signs within sign systems and have been well studied with respect to language perception. In electrophysiological studies, for example, these processes have been found to be reflected electrically in the so-called N400. With respect to the perception of music, investigating how and where such processes are reflected in the brain has remained elusive.

The present study was conducted to provide a step forward clarifying which cognitive processes and structural components of the brain are involved in the perception of both language *and* music, and which processes and components are rather specific for each of them. Therefore, ‘syntactic’ and ‘semantic’ aspects of music processing were investigated in particular. Empirically observing the brain might provide answers to theoretical questions like whether or not music is also a language, whether or not the interpretation of signs within different sign systems might nevertheless use the same neural resources, or whether or not ‘language is the interpreting system of all other systems’ (Emile Benveniste, in Innis, 1986).

Six EEG-experiments and one MEG-study were carried out. To ensure that results enable a broad generalization, participants of all experiments were ‘non-musicians’. That is, no participant had ever had musical lessons, or learned playing an instrument or singing (besides normal school education).

Experiment 1 was performed to exploratively investigate electrophysiological reflections of the build-up of a musical context and the processing of musical expectancy violations. Neapolitan sixth chords and secondary dominants were employed as such ‘violations’. Both chord types are prominent stylistic means in western tonal music. Neapolitans as well as secondary dominants elicited particular early and late ERP-effects, though the participants did not have a task connected to the harmonic dimension of the stimulation. These ERP-effects, as working labels termed ‘early right anterior negativity’ (or ERAN) and ‘N5’, were hypothesized to be dependent on the musical expectancy induced by a musical context.

To test the hypothesis that the degree of musical expectancy determines the processing of music, a second experiment was conducted. In that experiment, the same experimental paradigm as in Experiment 1 was employed, except that the Neapolitan chords were replaced by highly dissonant half-tone clusters. It was found that clusters elicited virtually the same ERP-components as Neapolitan chords and secondary dominants, though distinctly larger in amplitude.

In both Experiments 1 and 2, the decisive harmonic stimuli were not task-relevant. Participants were even not informed about the presence of either Neapolitan chords or clusters. Hence, it was interesting to investigate the influence of task-relevancy on both ERAN and N5. Therefore, in a third experiment, participants were presented with the same experimental stimuli as in Experiment 1 but asked to detect the Neapolitan chords. The potentials of the N5, but not those of the ERAN, were affected by the task-relevancy.

ERAN and N5 were consistently found in Experiments 1-3, contrary to previous published studies concerned with the investigation of music perception. Since in some of these studies the probability of unexpected musical events was 0.5 (contrary to Experiments 1-3, where the probability of Neapolitans and clusters was 0.25), a fourth experiment was conducted in order to clarify whether ERAN and N5 are affected by the probability of unexpected chords. The experimental paradigm was similar to Experiment 3, except that Neapolitan chords occurred with a probability of 0.5. Both ERAN and N5 decreased in amplitude, indicating that the Neapolitan chords were perceived as less unexpected when presented with such a high probability.

Up to now, the ERAN and N5 have been discussed with the concepts 'expectancy', 'integration', and 'context'. These concepts are also important issues in the investigation of language perception. As noted earlier, the link between music and language was of major interest for the present study. Because ambiguity resolution is a hallmark in language processing research, ambiguity in music processing is an interesting domain to explore. In Experiment 5 it was therefore investigated how a change of key is reflected in the ERPs. Modulating chords (following an ambiguous 'pivot chord') elicited, like Neapolitans and clusters in the previous experiments, both ERAN and N5. Additionally, a particular slow-going effect was found to correlate in time with the change of key. This effect was taken to reflect working memory processes connected to a restructuring of harmonic expectancies.

The comparison of Experiments 1 and 3 allowed an investigation of the task-relevancy of chords. The influence of attention on music processing, however, had remained elusive. This issue was studied in Experiment 6, in which experimental stimuli similar to those employed in Experiment 1 were presented to the participants under the instruction to read a book and to ignore the music. It was found that Neapolitan chords elicited distinct ERAN and N5 even under ignore conditions, the amplitudes of the ERPs varying according to principles of music theory.

The last experiment of the present study aimed on localizing the neural generators of the ERAN using MEG. An early activation was found to be reflected in the MEG-data as the magnetic counterpart of the ERAN. The best dipole solution of this activation yielded generators in the lower part of the right and left (right stronger than left) pars opercularis. In the left hemisphere, this brain structure is classically called 'Broca's area'. The Broca's area is known to be involved in syntactic language processing. Results of Experiment 7 thus suggest that music is partly processed in the same brain structures than language. Besides, unexpected chords, theoretically taken as violation of musical syntax, empirically turned out to be processed similar to syntactic violations in language.

Results of the present study reveal brain responses elicited by the processing of music, which have to my knowledge not been reported before. These brain responses followed the principles of music theory. Given that participants were 'non-musicians', the present findings support the hypothesis of an implicit musicality of the human brain, which is observable even under ignore conditions. Results provide evidence for interesting parallels between the processing of music and language, which give rise to new perspectives pertaining the investigation of the cognitive processing of communicatively relevant auditory information.

Chapter 1

Ear, Nerves, and Hearing

The human ear has striking abilities of detecting and differentiating sounds. It is sensitive to a wide range of frequencies, intensities, and has a fairly fine-grained temporal resolution (for detailed descriptions see e.g. Klinke & Hartmann, 1983; Moore, 1982; Pickles, 1982; Cook, 1999).

The ear consists of three parts: the external (outer), the middle, and the internal (inner) ear. Sound (i.e. alternating compression and rarefaction of air) reaches the pinna and travels through the external auditory meatus to the tympanic membrane. The sound causes the tympanic membrane to vibrate. The vibrations are amplified by the middle ear (namely the three ossicles malleus, incus, and stapes), and transmitted to the oval window of the cochlea (composing with the vestibular apparatus the inner ear, see top of Fig. 1.1).

The cochlea has three fluid-filled compartments, the scala tympani, the scala media, and the scala vestibuli (which is continuous with the scala tympani at the helicotrema). Scala media and scala tympani are separated by the basilar membrane. The organ of Corti rests on the basilar membrane and is the sensory transduction apparatus of the ear. The vibration of the stapes results in varying pressures on the fluid in the scala vestibuli, causing oscillating movements of scala vestibuli, scala media (including basilar membrane), scala tympani, and both the round and the oval window (for detailed descriptions see e.g. Pickles, 1982; Kelly, 1991; Schmidt, 1997; Klinke & Hartmann, 1983; Moore, 1982).

The organ of Corti (located on the basilar membrane) contains the sensory receptor cells of the inner ear, the hair cells (bottom of Fig. 1.1). There are two types of hair cells, inner

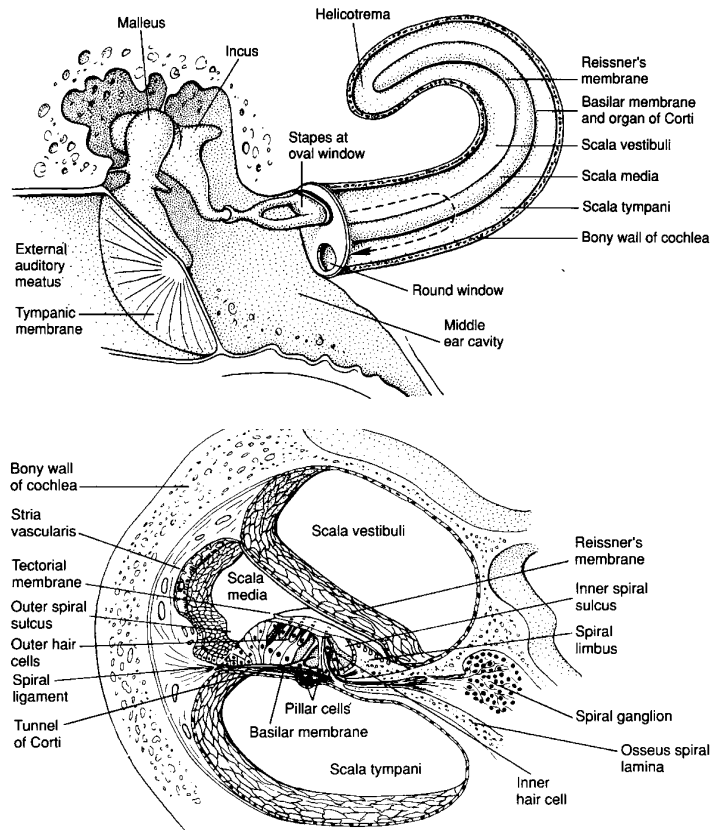


Figure 1.1: Top: The major parts of the human ear. In the Figure, the cochlea has been uncoiled for illustration purposes. Bottom: Anatomy of the cochlea (both figures from Kandell et al., 1991).

hair cells and outer hair cells. On the apical surface of each hair cell is a bundle of around 100 stereocilia. Above the hair cells is the tectorial membrane that touches the longest stereocilia of the outer hair cells. The sound-induced movement of the scalae (see above) causes a relative movement of tectorial and basilar membrane (and of the fluid between both membranes), resulting in a deflection of the stereocilia of both inner and outer hair cells. The deflection of the stereocilia is the adequate stimulus of a hair cell, which then depolarizes (or hyperpolarizes, due to the direction of deflection) by opening an inward current.

The inner hair cells then release chemical transmitter (presumably glutamate) at their basal ends where the hair cells are contacted by the peripheral branches of axons of bipolar neurons whose cell bodies lie in the spiral ganglion and whose central axons constitute the auditory nerve. The transmitter released at the base of the cell excites the peripheral ter-

terminal of the sensory neuron, and this in turn initiates action potentials in the cell's central axon in the auditory nerve. Oscillatory changes in the potential of a hair cell thus result in oscillatory release of transmitter and oscillatory firing in the auditory nerve (for detailed descriptions see e.g. Pickles, 1982; Schmidt, 1997; Klinke & Hartmann, 1983). The duration of an acoustic stimulus is encoded by the duration of activation of an auditory nerve fiber.

Different frequencies of sounds are selectively responded to in different regions of the cochlea. Each sound initiates a traveling wave along the length of the cochlea that starts at the oval window, and passes along the cochlea to the helicotrema. Due to the mechanical properties of the basilar membrane (which vary along the length of the cochlea), different frequencies of sound produce different traveling waves with peak amplitudes at different points along the basilar membrane. Higher frequencies result in peak amplitudes closer to the base of the cochlea, lower frequencies in peaks near the apex of the cochlea (in the region of the helicotrema; for further description see e.g. Pickles, 1982; Kelly, 1991; Schmidt, 1997; Klinke & Hartmann, 1983).

The outer hair cells distinctly amplify the peak of a traveling wave, resulting in a sharp peak of the wave at the frequency-characteristic place on the basilar membrane. This dynamic activity of the outer hair cells enables the ear to a high frequency-selectivity which is a prerequisite of both language and music perception.¹

Corresponding to the tuning of an inner hair cell that an auditory nerve fiber innervates, an individual nerve fiber is most sensitive to a particular frequency of sound, its so-called characteristic frequency. Nevertheless, an individual auditory nerve still responds to a range of frequencies since a substantial portion of the basilar membrane moves in response to a single frequency. The sound pressure level (SPL, for explanation and medical relevance see e.g. Pickles, 1982; Kelly, 1991; Schmidt, 1997) is then encoded (1) by the firing rate

¹Interestingly, outer hair cells achieve the changes in tuning of the local region in the organ of Corti by increasing or decreasing the length of their cell bodies (thereby affecting the mechanical properties of the organ of Corti). This change in length is an example of the active processes occurring within the organ of Corti while processing sensory information. Besides, the outer hair cells are innervated by efferent nerve fibers from the central nervous system, the changes in length are thus hypothesized to be at least partly top-down influenced. That is, the dynamics of the cochlea (determining the processing of acoustic information) may be influenced by the brain.

of the afferent nerve fibers, and (2) in case that the SPL exceeds the firing-opportunities of a single cell, by the firing rate of neighbored nerve fibers. The brain thus decodes the spatio-temporal (i.e. two-dimensional) pattern consisting of the individual firing rates of all activated auditory nerves (each with its characteristic frequency) into information about frequency and intensity of a stimulus.

The cochlear nerve enters the central nervous system in the brain stem (cranial nerve VIII). Within the brain stem, information originating from the hair cells is sent up via both contra- and ipsilateral connections between the nuclei of the central auditory path (for a detailed description see Nieuwenhuys et al., 1995). For example, some of the secondary auditory fibers that originate from the ventral cochlear nucleus project to the ipsilateral superior olivary nucleus and to the medial superior olivary nucleus of both sides (both superior olivary nuclei project to the inferior colliculus). Other secondary auditory fibers project to the contralateral nucleus of the trapezoid body (that sends fibers to the ipsilateral superior olivary nucleus; see Fig. 1.2). The pattern of contra- and ipsilateral connections is important for the interpretation of interaural differences in phase and intensity for localization of sound.

The inferior colliculus is connected with the medial geniculate body of the thalamus. The cells in the medial geniculate body send most of their axons via the radiatio acustica to the ipsilateral primary auditory cortex (for a detailed description see Nieuwenhuys et al., 1995).

Generally, the primary auditory cortex (comprising Brodman's areas 41 and 42, see Appendix B) corresponds to the transverse gyrus of Heschl (or gyrus temporalis transversus, see Appendix B) which is part of the superior temporal gyrus (STG). The primary auditory region is surrounded by the auditory association areas of the STG laterally, and by the cortex of the circular sulcus medially (which contains a second auditory representation, for detailed information see e.g. Pandya, 1995).

The functional significance of the auditory cortex is thought to be mainly the discrimination, identification, auditory memory, and presumably conceptualization of sounds and sound patterns (for a detailed description see e.g. Pickles, 1982).² In addition, the human cortex contains several functional areas in the temporal and frontal lobes related to the per-

²For interesting links of these properties to the cytoarchitecture of the auditory cortex see e.g. Pickles

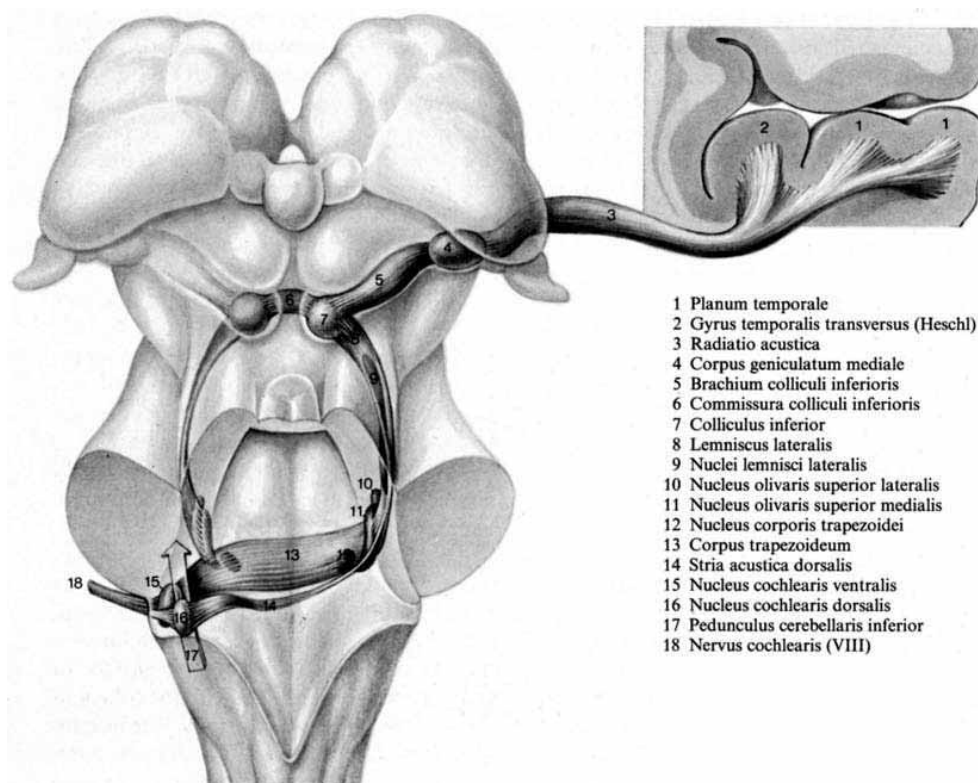


Figure 1.2: Dorsal view of nerve, nuclei, and tracts of the auditory system (from Nieuwenhuys et al., 1995).

ception of sounds (e.g. Wernicke's area and Broca's area which are both important for the perception of speech sounds).³

At a cognitive level, the perception of pitch is of fundamental importance for the perception of music. Pitch is a 'morphometric medium' (e.g. Attneave & Olson, 1971; Shepard, 1999), that is pitch is a medium capable of bearing forms. For example, pitch patterns like melodies or harmonies can be moved up and down in pitch, and still be recognized

(1982); Kandell et al. (1991); Gazzaniga (1996); for an overview of the anatomy of the auditory cortex see e.g. Pandya (1995).

³For the functional significance of temporal and frontal lobe areas with respect to (1) auditory sensory memory functions see e.g. Näätänen (1992); Alho (1995); Opitz et al. (1999b,a), (2) music perception see Liegeois-Chauvel et al. (1998); Zatorre et al. (1994); Peretz et al. (1994); Samson & Zatorre (1993); Zatorre et al. (1992); Zatorre (1984, 1985, 1988); Zatorre & Samson (1991); Samson & Zatorre (1988); Peretz (1990); Gaschler-Markefski et al. (1998), and (3) language perception see for review Friederici (1998); Zatorre et al. (1996).

as being the same pattern. In that sense, the representation of pitch corresponds to the log frequency scale. What is relevant for psychological relations between pitches is the ratios of their physical frequencies, not their arithmetic differences (for a detailed description see e.g. Krumhansl, 1979).⁴

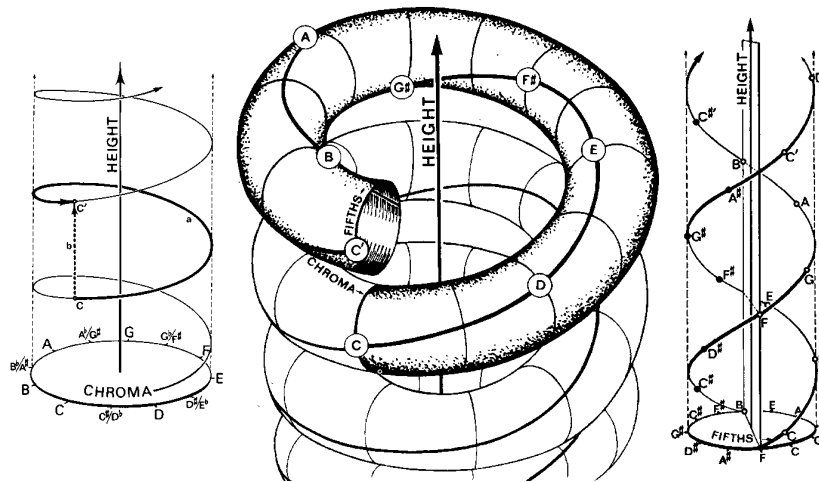


Figure 1.3: Left: Helical configuration of tones accounting for the increased similarity between tones separated by an octave. Pitch height is the vertical dimension, the chroma circle is the projection onto the horizontal plane (from Shepard, 1965). Middle: Five-dimensional configuration capturing pitch height, chroma, and the relationships of perfect fifths and octaves. Right: Double helix wound around a cylinder, illustrating the representation of fifth-relationship within the double-helical structure. Both middle and right figure from Shepard (1982b).

Importantly, the perceived distance between two tones is not only dependent on the (physical) frequencies of both tones, but influenced by numerous factors. For example, tones separated by octaves (see Chapter 2 for examples) are perceived as ‘somewhat identical’, though different in pitch height. Pitch can thus not be captured on a rectilinear scale of pitch. It can approximately be captured by placing the pitches on a spiral (or ‘helix’), with the octaves lying on a vertical line (left of Fig. 1.3). The vertical position on the pitch helix represents the pitch height, the position within an octave around the cylinder defined by the helix represents the chroma of a pitch.

⁴see also Fechner (1873); other than logarithmic representations have also been described with special experimental paradigms, see e.g. Stevens et al. (1937); Ellis (1965); for summaries see Shepard (1982a, 1999).

For an appropriate capture of pitch, however, the musical importance of the perfect fifth⁵ (similar to the importance of the octave) should also be taken into account.⁶ A configuration that represents more adequate height, chroma, and the relationships of octaves and fifths is a double-helix wound around a helical cylinder (middle and right of Fig. 1.3; see also Chapter 3 and Shepard, 1982a; Deutsch, 1982).

⁵See Chapter 2 for explanation and examples of intervals and the circle of fifths.

⁶For an illustration: two tones separated by intervals like octave or fifth are perceived as more closely related compared to two tones separated by a minor second, though the latter tones are closer related with respect to their physical frequency.

Chapter 2

Music-theoretical background

2.1 How major keys are related

In music theory, the distance of two single tones is called an *interval*. When the relation between the frequencies of two tones is 1:2, the interval is called an octave (e.g. c' and c'' , Fig. 2.1). The higher tone of two tones building an octave is perceived twice as high than the lower one.



Figure 2.1: Octave interval built by the tones c' (left) and c'' (right).

In the tempered intonation, the octave-range is divided into twelve equally-spaced *semitone*-steps.¹ As long as no tone is transposed an octave above or below, the division of the octave-range into twelve semitone steps leads to a set of twelve different tones. These tones build the *chromatic scale* and are the basic elements of western tonal music (Fig. 2.2).

¹Non-tempered scale-systems which distinguish for instance between the tones *f sharp* and *g flat* are more complicated and will be neglected here. For detailed descriptions see e.g. Eggebrecht (1967); Apel (1970); Eggebrecht (1972); Dahlhaus & Eggebrecht (1978, 1979); Dahlhaus (1980).

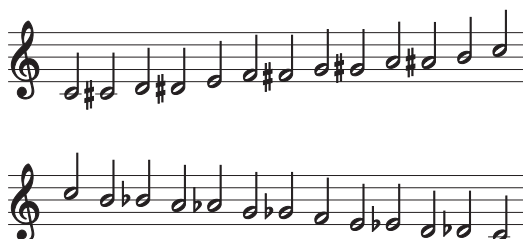


Figure 2.2: Ascending (top row), and descending (bottom row) chromatic scale: the octave ($c' - c''$) is divided into 12 semitone steps. In the tempered intonation, where e.g. c sharp is the same tone as d flat, such a division of an octave leads to twelve different tones (c'' is the octave of c' and thus not counted).

The interval of two tones which are one semitone step distant from each other is generally called a minor second. Two semitone steps build a major second (i.e. a whole tone), three semitone steps a minor third, four a major third, etc. (Fig. 2.3). By combining mainly semi- and whole-tone steps in various ways within an octave-range, several scales can be constituted. These scales normally comprise seven tone-steps. During the last centuries, three scales have become most prominent in western tonal music: a major scale, and three minor scales (harmonic minor, melodic minor, and minor without raised sixth and seventh degrees).² The major scale consists of two tetrachords, each tetrachord with a degree progression of $1-1-\frac{1}{2}$ (i.e. whole tone step - whole-tone step - semitone step). Both tetrachords are separated by a whole-tone step (Fig. 2.4).



Figure 2.3: Examples of intervals, from left: minor second, major second, minor third, major third, perfect fourth, perfect fifth.

Since a major scale comprises seven tone-steps (e.g. in C major: $c-d-e-f-g-a-b-c$), and an octave can be divided into twelve semitone steps, there are always four tones of the chromatic scale which do not belong to a given major scale.³

²Though especially in Jazz-music, old scales like doric, phrygic, lydian etc. are often employed.

³For example: C major does not comprise the tones c sharp (or d flat), d sharp (or e flat), f sharp (or g flat), g sharp (or a flat), and a sharp (or b flat).



Figure 2.4: Example of two tetrachords building the *C* major scale. The two tetrachords are separated by one whole-tone step.

A tonal key exactly determines the tones which belong to this key. For example, the *C* major key determines exclusively the tones of the *C* major scale as belonging to *C* major (no further tones belong to *C* major). Two different major keys never consist of exactly the same tones, though they may have tones in common. Importantly, each initial major key has exactly two neighboring major keys which consist of the same tones *except one* in respect of the initial key. For example, *C* major shares six tones with *G* major (*c-d-e-g-a-b*). The missing (seventh) tone of *C* major is *f*, the missing tone of *G* major is *f sharp* (being one semitone step distant from *f*). The other key which has six tones in common with *C* major is *F* major.⁴

Because both *G* major and *F* major share six tones with *C* major (more than any other major key), they are from a music-theoretical point of view the most closely related major keys of *C* major. In *C* major, *G* major is called the dominant key, *F* major the subdominant key. Vice versa, *C* major is the subdominant key of *G* major, and the dominant key of *F* major. In *F* major, the tone *c* is the fifth scale-tone above *f*. The interval between *f* and *c* is called a (perfect) *fifth*. Analogously: the fifth scale-tone in *C* major is *g*, the interval between *c* and *g* is also a fifth.⁵

The keys which are closest related to an initial key have each for their part a further closest related key (since each major key has exactly *two* neighbored major keys consisting of the same tones except one). Continuing the example: *G* major has (besides the subdominant key *C* major) also a dominant key, which is *D* major. *D* major can be distinguished from *G* major by the tone *c* which belongs to *G* major, but not to *D* major. Note that *d* is the fifth scale-tone of *G* major, the interval *d-g* is (again) a fifth.

⁴These six tones are: *c-d-e-f-g-a*; the missing (seventh) tone is *b* in *C* major (*b flat* in *F* major, respectively).

⁵Notably, the relationship between keys can not only be described in terms of fifths, but also in terms of tetrachords: the second tetrachord of *F* major is the first tetrachord of *C* major, and the second tetrachord of *C* major is the first of *G* major

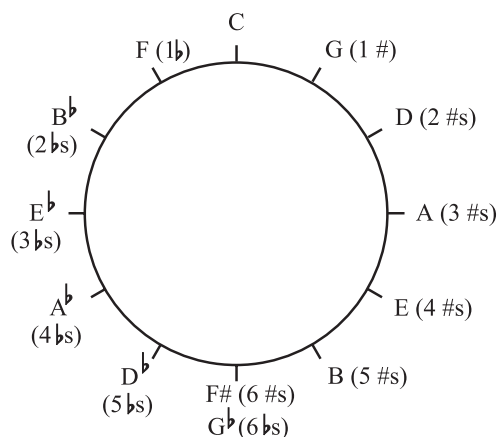


Figure 2.5: The circle of fifths (for major keys only).

The example showed that each initial major key has two closest related major-tonal neighbors (each having six tones in common with the initial key), two second-closest related neighbors (each having five tones in common with the initial key), two third-closest related neighbors, etc. Notably, the first scale-tone of an initial key (e.g. *c* in *C* major) is one fifth distant from the first scale-tone of both dominant and subdominant key (which are the closest related keys), two fifths distant from the second-closest keys, etc. The fifths-relatedness of major keys can nicely be described using the *circle of fifths* (Fig. 2.5).⁶

2.2 The basic in-key functions in major

The tones of a scale are also termed *degrees*. The tonic tone of a scale, e.g. in *C* major the tone *c*, is called the first degree, the second tone (in *C* major the tone *d*) is called second degree, etc. When a triad is built on a degree (by setting the in-key third on the degree, and then an in-key third onto that third), it is called *in-key chord*.

The triads built on the first, fourth, and fifth degree of a major scale are major chords, the triads built on the second, third, and sixth degree are minor chords. The triad on the seventh degree is a diminished chord. The in-key triad of the first degree is called tonic chord (or just: tonic). The tonic chord is the best representative of its key: (a) the root tone of the tonic chord is also the root tone of the key, (b) the tonic chord contains the fifth

⁶For an other description than the circle of fifths see Schönberg (1969).

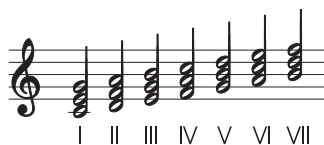


Figure 2.6: Chords built on the degrees of the *C* major scale, the degrees are indicated by roman numerals (chord functions from left: tonic, supertonic, mediant, subdominant, dominant, submediant)



Figure 2.7: Dominant seventh chord (left) and subdominant with Sixte ajoutée (right) in *C* major.

of the key (which is the third overtone of the root tone), and (c) the tonic chord contains the third of the key, which determines the tonal genus (major or minor). The in-key triad of the fourth degree is called subdominant, of the fifth dominant. The minor triad on the sixth degree is called submediant, on the second degree supertonic, and on the third degree mediant. Tonic, subdominant, dominant, mediant, etc. are called *chord functions* (Fig. 2.6). Chord functions can be signed by roman numerals of the degrees on which they are built (Fig. 2.6), as well as by letters (e.g. T for major tonic, S for major subdominant).

The triad on the fifth degree with an added minor seventh is called a *dominant seventh chord* (in *C* major: *g-b-d-f*, the interval *g-f* is a minor seventh, Fig. 2.7). The seventh is the *characteristic dissonance* of the dominant, and is within a progression of chords usually led into the third of a subsequent tonic chord. The characteristic dissonance of the subdominant is the *Sixte ajoutée*, a major sixth added to a major triad (usually subdominant, Fig. 2.7). According to Jean Philippe Rameau (1722) the three chords: tonic, dominant seventh chord, and subdominant with Sixte ajoutée build the harmonic center (‘Centre harmonique’) of a tonal key.

2.3 Neapolitan sixth chords

Each chord in root position (that is with the root tone in the base, see Fig. 2.8) can be inverted into a *sixth chord* by setting the base tone e.g. into the top voice, so that the third

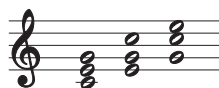


Figure 2.8: C major triad in root position (left), as sixth chord (middle), and as six-four chord (right).



Figure 2.9: Neapolitan chord in c minor (left), followed by the dominant (middle) and the tonic chord (right)

becomes the base tone of the new chord. A repetition of this procedure leads to a *six-four chord* with the fifth of the chord in the base (Fig. 2.8).

When inverted into a sixth chord, the mediant of a minor subdominant is called *Neapolitan sixth chord*. That is e.g. in either C major or c minor: the minor subdominant is *f - a flat - c*, the mediant of the minor subdominant is *d flat - f - a flat*, which is once inverted the sixth chord *f - a flat - d flat* (Fig. 2.9).

A Neapolitan sixth chord can also be interpreted as a minor subdominant with a minor sixth instead of a fifth. For an example: in either C major or c minor the minor sixth of a subdominant is *d flat*. When the fifth is replaced by a minor sixth, the minor subdominant is consisting of the tones *f - a flat - d flat*.

2.4 Secondary dominants

As described before, each in-key chord has a harmonic function within a tonal key. However, chords may be paraphrased in a way that they temporarily take over another function within another tonal key. In case that a chord takes over the function as a tonic, this might be indicated by a preceding dominant seventh chord of that temporary tonic. In other words, an in-key chord may be preceded by a dominant seventh chord, so that the in-key chord functions temporarily as a tonic. Such a dominant seventh chord, which alters the function of the subsequent chord, is called a *secondary dominant*.



Figure 2.10: Example for of a secondary dominant (in *C* major). From left: tonic, secondary dominant to the dominant, dominant, dominant seventh chord, and tonic.

For example: the dominant of *C* major (*g-b-d*) may be preceded by the dominant seventh chord of *G* major (*d-f sharp-a-c*). The tone *f sharp* does not belong to *C* major, but to *G* major. Moreover, a seventh (*d-c*) is the characteristic dissonance of the dominant. Thus, the *G* major triad (*g-b-d*), which was formerly functioning as dominant of *C* major, now functions as a tonic (possibly only temporarily). This function-change was induced by the dominant seventh chord of *G* major: *d-f sharp-a-c* (Fig. 2.10).

Chapter 3

Subjective measures of music perception

3.1 Context-dependent representation of pitch

As described in Chapter 2, from a music-theoretical point of view certain tones belong to a tonal key, whereas others do not. Moreover, within the group of tones which belong to a key, the notes that build the tonic chord represent the tonal key most unambiguously. In a series of experiments, Krumhansl (1979) found that these relationships between tones determine the psychological representation of musical pitch, rather than just the psycho-acoustic properties of tones (such as absolute pitch height or chroma).

In one of the experiments performed by Krumhansl (1979), musically trained participants were in each trial presented with a pair of tones after a tonal key had been established (by presenting a tonic chord or a major scale). The participants were asked to judge how similar the first tone of the tone-pair was to the second tone in the tonal system suggested by the preceding musical context.

A similarity matrix containing similarity-ratings of the tone-pairs revealed a considerable amount of structure: The tones of the tonic chord were judged to be more similar compared to the diatonic scale tones, and the diatonic scale tones were judged to be more similar compared to the non-diatonic tones.¹

¹That is, within *C* major tone-pairs consisting of tonic-chord tones only (like *c-e*, *c-g* or *e-g*) obtained the

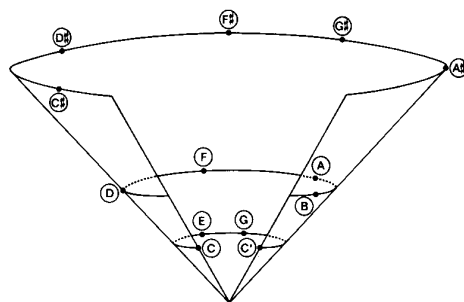


Figure 3.1: MDS of the averaged similarity-matrix, three-dimensional solution (from Krumhansl, 1979).

All data were scaled using a non-metric multidimensional scaling method (MDS). The best MDS-solution was obtained by a conical (three-dimensional) configuration (Fig. 3.1). The cone had a radius at the base equal to its height, the major triad components falling on a circular cross section of half the radius of the circular cross section containing the other (diatonic) scale tones, and one-quarter the radius of the circular cross section containing the non-diatonic tones. Results were taken to indicate that within a musical context, the tones of the tonic chord were perceived as more similar (or proximal) to each other compared to the other diatonic tones, and the other diatonic tones as more similar to each other compared to the non-diatonic scale tones.

With respect to a ‘meaning’ tones within a harmonic system, Krumhansl interestingly stated that ‘in an explicitly musical context, musical listeners perceive a complex pattern of interrelationships among the individual tones. [That is,] tones acquire meaning through their relationships to other tones’ (ibid., p.358, p.370). The degree of relationship between tones was determined by the function of each tone in respect to an established tonal key. Tonic tones were most structurally stable and closely related, followed by the other diatonic tones, and the non-diatonic tones. This finding indicates that the tones were psychologically represented within a tonal hierarchy that notably corresponds with music theory.

Another interesting finding of Krumhansl’s experiment (1979) was that the similarity ratings also depended on the order in which the two tones were presented. That is, an asymmetry was found in the ratings of tone-pairs: diatonic tones followed by a tonic-chord highest similarity ratings, whereas lower ratings were given to tone-pairs consisting of the remaining diatonic scale tones (like *d-f* or *a-h*), and only poor similarity ratings to tone-pairs consisting of at least one non-diatonic tone (like *c sharp-f sharp* or *c-f sharp*).

tone were rated as more similar than when presented in the reverse order.² Krumhansl (ibid.) suggested these asymmetries as reflecting a tendency for tones to move over time toward (rather than away from) the vertex of the conical configuration, that is towards the tonic. This explanation nicely describes a dynamic aspect of music in time and will become important with respect to the present study when discussing neural processes of integration of out-of-key notes into a musical context.

3.2 The representation of key-relatedness

The experiment from Krumhansl (1979) referred to a psychological structuring of tones within a (single) key. Changes in the perceived stability of tones are closely linked with the perception of the tonal stability of chords because a chord is the simultaneous sounding of tones (Krumhansl & Kessler, 1982). The perception of chords as tonal functions, as well as relations between different keys were investigated in a study from Krumhansl & Kessler (1982).

In a first experiment, musically trained subjects rated how well, ‘in a musical sense’ (ibid.), a probe tone fit into a preceding presented musical element (for a similar study see Krumhansl & Shepard, 1979).³ The presentation of a musical element was expected to induce the notion of a tonal key. From the judgment data, major and minor key profiles were obtained which indicate, how well tones like tonic, third, fifth, etc. are perceived as fitting into the according tonic key.⁴

By shifting two key profiles to the appropriate tonics (e.g. to *C* major and *a* minor), and then correlating the ratings of both profiles for each tone of the chromatic scale, measures of

²And, analogously, non-diatonic followed by diatonic tones, as well as non-diatonic followed by tonic-chord tones. For example: the tone-pair $b'' - c'''$ was judged to be more similar than the same tone pair presented in the reverse order ($c''' - b''$), the pair *c sharp-d* as more similar compared to *d-c sharp*, and the pair *f sharp-g* more similar than *g-sharp-f*.

³Musical elements were e.g. major or minor scales, major or minor chord sequences, or a dominant seventh chord.

⁴As to be expected from both music theory and the experiment from Krumhansl (1979), the tonic-tone received the highest ratings, the tones from the tonic-triad received higher ratings than the other diatonic scale tones, and the diatonic tones higher ratings compared to the non-diatonic tones.

interkey distance were calculated.⁵ The procedure of correlating key profiles was applied to all major-major, major-minor, and minor-minor key pairs, resulting in a correlation matrix of all major and minor keys.

This correlation matrix was analyzed using MDS. Interestingly, dimensions 1 and 2 of a four-dimensional solution yielded an arrangement of keys perfectly representing the circle of fifths (though of *either* major *or* minor keys, see below) which is suggested by music theory to describe interkey distances (Fig. 3.2).⁶

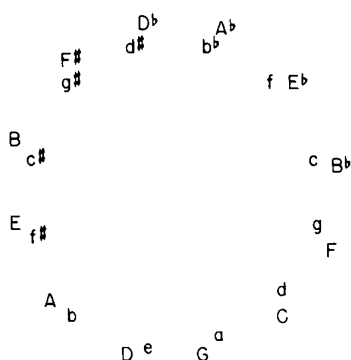


Figure 3.2: Dimensions 1 and 2 of the four-dimensional solution of the MDS-scaled key-correlation matrix (from Krumhansl & Kessler, 1982).

However, another solution was suggested by Krumhansl & Kessler (1982), in which all keys were arranged in a toroidal configuration. A flattened-out representation of this toroidal configuration is shown in Fig. 3.3. In this configuration, the pattern of interkey-distances becomes strikingly interpretable. ‘All keys separated by fifths fall on a path wrapping three times around the torus before joining up with itself again; the major keys fall on such path, and the minor keys on another, parallel path. These are lined up so that any major key is flanked by its relative minor on one side and its parallel minor on the other’ (Krumhansl & Kessler, 1982, p.345).

⁵For example: In the case of *C* major and *a* minor (*a* minor being the relative minor key of *C* major), the profiles gave a high correlation, in the case of *C* major and *F sharp* major (being only far related in the sense of the circle of fifths), the correlation was very low.

⁶Notably, in music theory minor keys are arranged within the circle of fifths with respect of their relative major key. The placement obtained from the key-correlation matrix is different, and suggested by Krumhansl & Kessler as reflecting a ‘compromise between the close tie of a major key to both its relative major and parallel minor keys’ (ibid., p.344).

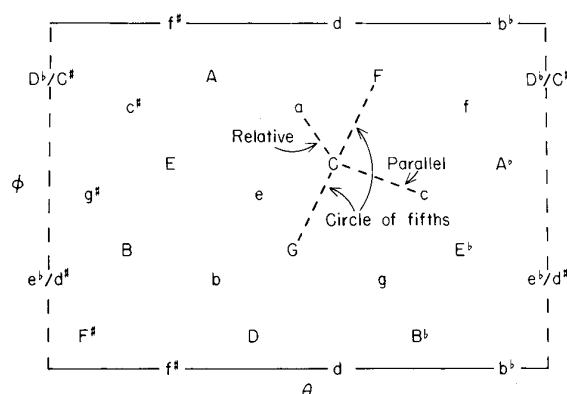


Figure 3.3: Flattened-out toroidal configuration of the multidimensionally scaled key-correlation matrix (from Krumhansl & Kessler, 1982). The opposite edges of the rectangle are identified. Examples of ‘relative’ and ‘parallel’ minor key refer to *C* major.

Compared to the circle of fifths, the torus has the advantage of depicting empirically obtained measures of psychologically represented interkey-relations. Interestingly, analyses of the empirical data led to a depiction of *all* interkey relations. In the circle of fifths, merely relations of immediately surrounding single major or minor keys are represented.⁷ The configuration shown in Fig. 3.3 can thus be taken as a spatial map of key regions and key distances. In respect of the present studies, this spatial map will become important for approaching the issues of how chords relate to different tonal centers and how the sense of key develops and changes as listeners hear sequences of chords.

3.3 The representation of chord-functions

The term ‘tonal key’ refers to a construct, in which relations of tones or chords to a given tonal center can be described. Whereas the chord-functions that constitute a particular key can un-ambiguously be specified, the determination of a prevailing key from a sequence of tones or chords is always ambiguous. Because a musical event (whether comprising merely a single note or a single chord, or long sequences of notes or chords) can always be interpreted in several ways (that is according to several ‘higher-graded’ tonal contexts), a tonal center is always an abstraction.

⁷For example, the *C* major key is (psychologically as well as from a music-theoretical point of view) closer related to its minor relative (*a* minor) than to its minor parallel (*c* minor).

That is, no key is explicitly inherent in a musical event. Even the key signature of the written score does not distinguish e.g. between major and minor modes. Listeners have to extract key information from a musical event by using knowledge about harmonic chord-functions of different musical keys.⁸ The data obtained by Krumhansl & Kessler (1982) allowed an investigation of the perceived relations of chords as functions with respect to different abstract tonal centers. Therefore, chord-profiles were calculated for major, minor, diminished, and dominant seventh chords.⁹

The profiles of major and minor chords correlated highly with a key profile when both chord profile and key profile were adjusted to the same reference tone, that is when a chord was the tonic of a key (e.g. the profile of a *C* major chord correlated highly with the profile of the *C* major key). The correlations between a chord and all keys were analyzed using an MDS-method, so that the psychological distance between a chord and all 24 keys could be determined (see *ibid.*, p.350 for further description).¹⁰ Results are illustrated for the *C* major, and *a* minor chords in Fig. 3.4. The results show, that the psychologically perceived position of a chord within the tonal system seems to be a compromise of the chords' function (derived analytically from music-theory) with respect to different keys. This finding is vital for a description of musical expectancy. With respect to the present study, this issue will become important when discussing the reflections of a violation of musical expectancies.¹¹

3.4 The developing and changing sense of key

Each chord has a tendency to be interpreted as the tonic of a key, the most simple solution from a functional point of view (instead of interpreting a chord in respect of another chord

⁸Similarly, for an analyst of a musical piece, there are often different (i.e. more or less plausible) ways of ascribing chord-functions to notes or chords.

⁹Fit-ratings for probe-tones were shifted to a reference chord, and then averaged across each of the following conditions: probe-tone preceded by a major chord, by a minor chord, by a diminished chord, and by a dominant-seventh chord.

¹⁰This procedure can be applied to $4 \times 12 = 48$ chords: four chord types were investigated, and each chord can be adjusted to each chromatic scale tone.

¹¹Interestingly, there seems to be a strong tendency for the *a* minor chord to the *A* major key, probably reflecting a general tendency for 'every passage in minor to be resolved in major' (Schenker, 1956).

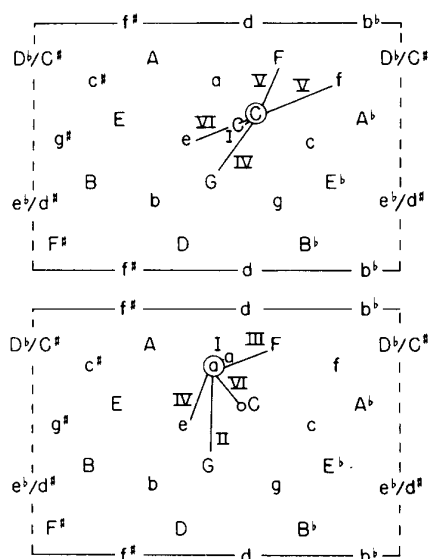


Figure 3.4: Placement of *C* major, *a* minor, and *b* diminished chord in the toroidal configuration (from Krumhansl & Kessler, 1982) Interestingly, the *C* major chord is not only located near the *C* major key, but also drawn slightly toward the *F* major key (and *f* minor key, respectively), in which it plays the important functional role of the dominant. The slightly weaker harmonic function of subdominant (of *G* major) is reflected in a greater distance between the *C* major chord and the *G* major key. Analogously, the position of the *a* minor chord in the key distance map reflects its role as mediant (in *F* major), as submediant (in *C* major), as supertonic (in *G* major), and as subdominant (in *e* minor).

functioning as tonic). Schenker (1956) stated that ‘not only at the beginning of a composition but also in the midst of it, each [chord] manifests an irresistible urge to attain the value of the tonic for itself’ (p.256, also in Krumhansl & Kessler, 1982). This ‘tonicization’ is enhanced when a chord is preceded by its own dominant (especially by a dominant seventh chord), and during ‘sections of greatest key ambiguity and instability’ (Krumhansl & Kessler, 1982).

Krumhansl & Kessler (1982) also investigated how a sense of key develops or changes during listening to a sequence of chords. Some sequences consisted of in-key chords only, and were employed in order to investigate a developing sense of key, since a tonal key was established and supported with progressing in-key chords. During other chord-sequences, the initial key was left, and another key was established. Such a change between keys is in musical terms called ‘modulation’ (for another study employing modulating sequences as stimuli see Berent & Perfetti, 1993).

With respect of the present study, it is interesting to note that during in-key chord sequences, participants perceived tones (which are elements of chords) more and more with respect of their stability within the established key (and less with respect to the last heard chord only). Besides, the sense of key tended to be stronger than just the sense dependent on the relative functional proximity of chords. That is, the sense of key increased towards the end of a cadence, entailing a perception of chords according to their stability within the established key. This increase might reflect that a musical context build-up (music-theoretically inherent in the cadences) was psychologically represented in listeners.

It was also found that during modulating sequences, listeners gradually shifted their key sense from the region of the first key toward the region of the second key. Notably, some residual effect of the first key was maintained throughout the entire sequence. These findings are important with respect of Experiment 5, where the processing of tonal modulations will be investigated with electrophysiological measures.

3.5 Hierarchies of harmonic stability

In a prominent study, Bharucha & Krumhansl (1983) investigated the mental representation of the organization of harmonic information (see Krumhansl et al., 1982b,a, for a similar studies). They summarized their results by stating six principles that describe hierarchies of harmonic stability which govern the perceived relationships between chords. Some of these principles were found to be dependent, and some to be independent of a tonal context.

Similarity ratings were obtained (from musically trained subjects) for test chords that either followed a *C* major context, or a *F sharp* major context, or were presented without any context.¹²

Applying a multidimensional scaling method to the data, it was found that chords from the same key were judged to be more closely related to each other than chords not from the same key (independent of whether the test chords were preceded by a tonal context or not). This context-independent effect was taken to reflect a principle that was termed *key*

¹²Subjects had to rate how well the second chord followed the first chord with respect to the previously heard cadence. This judgment was taken by Bharucha & Krumhansl (1983) as a similarity rating.

Membership. This principle states that ‘chords from the same key are perceived as more closely related than chords that are not from the same key’ (ibid., p.70).

In order to formally state the harmonic principles, Bharucha & Krumhansl (1983) denoted the psychological distance between two directly succeeding chords C_1 and C_2 by $d(C_1, C_2)$, the set of the seven in-key chords by K , and the membership of a chord C in K by $C \in K$ ($C \notin K$ means that the chord C is not from K). The set of the three chords tonic, dominant, and subdominant was referred to as the *harmonic core*. The harmonic core was denoted by S . d_K refers to the psychological distance between chords when a key K was instantiated by a preceding context. Formally, the principle of key Membership was written as:

$$d(C_1, C_2) < d(C_3, C_4), \text{ where } C_1, C_2 \in K, \text{ and there does not exist} \\ \text{any } K' \text{ such that } C_3, C_4 \in K'.$$

It was also found that the I, V, and IV chords occupied central positions within each key. That is, the chords of the harmonic core clustered together, surrounded by the other four chords from the same key. This pattern was also found to be independent of harmonic context. Thus, independent of a tonal context, chords in the harmonic core were perceived as more closely related to each other than were the other chords from the key but not in the core. This effect was taken to reflect a principle termed *Intrakey Distance*, formally written as:

$$d(C_1, C_2) < d(C_3, C_4), \text{ where } C_1, C_2 \in S, \quad C_3, C_4 \notin S, \text{ and} \\ C_1, C_2, C_3, C_4 \in K, \quad C_3 \neq C_4.$$

Besides, in the no-context-condition, chords were separated into two sets (corresponding to the two keys from which they were drawn). In the *C major* context condition, the chords from *C major* were pulled closer together, and the chords belonging to *F sharp major* were more dispersed than in the no context condition. In contrast, in the *F sharp major* context the chords from *F sharp major* were pulled together, and the *C major* chords were more separated. Thus, two chords were perceived as most closely related when they were in the context key, moderately related when no tonal context was provided, and more distantly related if neither chord was the context key. This effect was described by the principle of *Contextual Distance*, formally written as (ibid., see also Krumhansl et al., 1982a):

$$d_K(C_1, C_2) < d(C_1, C_2) < d_{K'}(C_1, C_2), \quad \text{where } C_1, C_2 \in K, \\ C_1, C_2 \notin K'.$$

Interestingly, two chords from the same key were perceived as more closely related if the first chord was not in the harmonic core (and the second chord was in the harmonic core) than when they were heard in the reverse temporal order. This asymmetry was reduced in magnitude when the chords were out of the context.¹³ This asymmetry-effect was termed by Bharucha & Krumhansl (1983) as the principle of *Intrakey Asymmetry*, formally written as:

$$d(C_1, C_2) < d(C_2, C_1), \quad \text{where } C_1 \notin S, C_2 \in S, \text{ and } C_1, C_2 \in K.$$

When both test chords were from different keys, the highest ratings were given when there was no context. Importantly, higher ratings were given to pairs ending on a chord that belonged to the preceding tonal context compared to pairs ending on a chord that did not belong to the preceding context. That is, a pair of chords was judged as more closely related when the first chord was out of the context key (and the second chord was in the context key) than when they were heard in the reverse temporal order. This asymmetry-effect turned out to be context-dependent, since the tonal context tended to increase the perceived distance between chords belonging to different keys (the ratings did virtually not differ when there was no context). The principle describing this effect was termed as the principle of *Contextual Asymmetry* (see also Krumhansl et al., 1982a), formally written as:

$$d_K(C_1, C_2) < d_K(C_2, C_1), \quad \text{where } C_1 \notin K, \text{ and } C_2 \in K.$$

In another experiment, Bharucha & Krumhansl (1983) participants recognized a particular chord more easily, when it was out of the context key than when there was no tonal

¹³Both temporal orders were influenced in virtually the same way by the preceding harmonic context, indicating a context-independence of the asymmetry-effect.

context or when it was in the context key.¹⁴ This effect was described by the sixth principle: *Contextual Identity* (ibid., see also Krumhansl et al., 1982a), formally written as:

$$d_K(C_1, C_1) < d(C_1, C_1), \text{ and } d_K(C_1, C_1) < d_{K'}(C_1, C_1), \text{ where} \\ C_1 \in K, \text{ and } C_1 \notin K'.$$

The six empirically supported principles proposed by Bharucha & Krumhansl (1983) as governing the perceived distances between chords were taken to indicate that the internal representation of harmonic relationships was highly regular and structured. Some of the principles even hold in the absence of an established tonal context, whereas other principles describe relationships that are altered by a tonal context. Similarly to the studies from Krumhansl (1979) and Krumhansl & Kessler (1982), the study from Bharucha & Krumhansl (1983) demonstrated that ‘chords, like single tones, are subject to influences of the tonal context in which they are embedded’ (ibid.).

With respect of the present study, it is important to note that a major finding of the study of Bharucha and Krumhansl (1983) was that when a tonal context was introduced, the representations of in-key chords were made more stable, and those of chords containing out-of-key notes less stable. Generally, in western tonal music ‘the more stable tones appear more frequently, in prominent positions, and with rhythmic stress’ Bharucha & Krumhansl (1983). According to Bharucha and Krumhansl (1983), harmonically stable chords function as cognitive reference points for the system as a whole. Besides, the perception of structure of music (which is a prerequisite of building a representation of a musical context and thereby a prerequisite for the understanding of music) highly relies on the perceiver’s ability to organize the individual musical events in terms of the hierarchies of harmonic stability reflected by the six principles.

¹⁴Trials consisting of two chord-sequences each. These two sequences were either identical or different with respect to a single target chord being either diatonic or nondiatonic. Besides, sequences were either composed in a way that all chords were in-key (except possibly a target chord) and a musical context was built up towards the end of the sequences (tonal condition), or they consisted of randomly ordered chords from different keys. Participants (musically trained) had to make same / different judgments about the chord-sequences presented in each trial. Recognition errors were taken to reflect the perceived relatedness between the target chords.

3.6 Musical expectancies

The perception of musical relations within a hierarchy of tonal stability enables a listener to perceive and appreciate tension and release. For example: moving away from a tonal center to unstable chords (or keys) is perceived as tensioning, returning to the stable tonal center as releasing. The course of tension and release during a musical piece is an important dimension of a musical context.

Dissonance as well as a tone (or chord) that is harmonically unrelated to a musical context can produce or enhance tension. Since the perception of tension is only possible with the experience (i.e. knowledge) of relaxedness, musical expectancy in form of anticipated relaxedness is vital to our musical experience. The interplay between expectancies, as they unfold over time, and the varying degrees to which they are fulfilled or violated are broadly considered as fundamental for the appreciation of music (e.g. Meyer, 1956; Schönberg, 1969; Bharucha, 1984; Jones, 1981, 1982; Bharucha & Stoeckig, 1986, 1987).¹⁵

The generation of musical expectancies while listening to major-minor tonal music considerably relies on the representation of a hierarchy of harmonic stability in the brain of a listener. In a study from Bharucha & Stoeckig (1986) it was shown that a harmonic context primes the processing of chords that are related to this context (relative to chords that are unrelated to this context).¹⁶ Subjects (whether or not musically trained) responded faster and more accurate to harmonically related chords compared to unrelated chords. This result was taken to reflect that a chord generates expectancies for related chords to follow.

Bharucha & Stoeckig (1987) also found evidence for the hypothesis that musical expectancies are generated at a cognitive level (rather than already on a sensory level), by activation spreading through a network that represents harmonic relationships (for similar results obtained with the presentation of chord-sequences see Bigand & Pineau, 1997; Bigand et al., 1999). Notably, the brain's ability to expect musical events to a higher or lower

¹⁵With respect of the present study it is important to note that the expectancy of an acoustic event is not just determined by tonal, i.e. harmonic features, but also e.g. by the timbre of a sound (Platel et al., 1997; Tervaniemi et al., 1997; Schröger, 1998).

¹⁶In a priming paradigm, subjects had to make a speeded true/false decision about a chord following a prime chord to which it was harmonically either closely or distantly related.

degree may be taken as a reflection of a psychological reality of musical syntax (e.g. Swain, 1997).

Chapter 4

From EEG to ERPs

4.1 Electro-encephalography (EEG)

The human cerebral cortex is crucially involved in the performance of cognitive functions. Such functions are for example perception (of motion, depth, form, color, pitch height, loudness, sound, etc.), voluntary control of movement, motor planning, learning and memory operations (encoding, retrieval, recognition, comparison, etc.), perception and production of language (and music), thought (e.g. problem solving), emotion, affect, and motivation.

The cerebral cortex contains different types of nerve cells that can be divided into two major classes: pyramidal and nonpyramidal cells (based e.g. on morphology and neurotransmitter content).¹ The pyramidal cells are excitatory neurons² and represent circa 80 percent of the cortical neurons. Pyramidal cells are oriented parallel to one another, and their apical dendrites are oriented perpendicular to the surface of the cortex.

When active, the pyramidal cells and their dendrites produce an excitatory postsynaptic potential (EPSP) by an ionic current flowing inward through the synaptic membrane and outward along the extrasynaptic membrane. Exhibiting postsynaptic potentials develop over a time period of some milliseconds and have a decay of 10-30 ms.³

¹For detailed descriptions see e.g. Kandell et al. (1991); Braitenberg & Schütz (1993); Birbaumer & Schmidt (1996); Schmidt (1997).

²Their transmitter is thought to be glutamate

³Inhibiting postsynaptic potentials are distinctly slower in duration (70-150 ms).

Notably, cortical functions are assumed to be dependent on the operations of populations of neurons rather than on the actions of any single neuron. Neurons presumably build populations because the synaptic strength of a population of neurons is larger than that of synaptic connections of single adjacent neurons. Such a population of neurons is called a *cell assembly*.

The EPSPs produced by single pyramidal cells effectively summate (due to their synchronous activity and similar geometric orientation within a cell assembly). The resulting electric current can be measured extracellularly, even from some centimeters distance. The extracellular record of electric current originating from brain activity is called the *electroencephalogram* (EEG).⁴

EPSPs generated in the cerebral cortex contribute most to the currents recorded with the EEG. Interestingly, the action potentials (the largest potentials generated by neurons) are actually thought to contribute only little to surface potentials, because the action potentials can (due to their short latency) only hardly summate over time as effectively as the (slower) EPSPs (for detailed descriptions see e.g. Kandell et al., 1991; Schmidt, 1997).

The transmission of sensory information from the peripheral sensory system through the sensory pathways is also capable of producing measurable electric potentials, though extremely smaller than those originating from cerebral activity. For auditory stimuli, for example, so-called *brainstem-responses* that originate from the activation of various nuclei in the brainstem (and are thus associated with the transmission of sensory [auditory] information) can also contribute little to the EEG (for detailed description of these responses in the auditory modality see Näätänen, 1992).

However, there is much neural activity that is not measurable with the EEG. Neural activity might for example be insufficiently synchronous (for the discussion of open and closed fields see Nunez, 1981). Moreover, in several brain structures (e.g. the thalamus), neurons (even when associated in an assembly) hardly have similar geometric orientations. Hence, their activity is invisible to distant recording electrodes (e.g. Rugg & Coles, 1995).

To measure the EEG, at least two electrodes have to be used: An active electrode which is placed over a site of neuronal activity, and an indifferent electrode which is placed at

⁴The term EEG was first introduced by Hans Berger in 1929 for the electric measurement of *human* brain activity.

some distance from this site and serves as reference electrode. Though reduced by the electrical resistance of brain tissue, meninges, skull, liquor, and skin, the flow of electric current is measurable even outside the head. In both clinical applications and cognitive psychology, numerous active electrodes are usually situated over different parts of the scalp (and connected to a single reference electrode). The EEG is usually applied as a non-invasive method (though intracranial recordings may be used in clinical applications). The active electrodes are often placed according to a conventional schemes, e.g. the 10-20 system (see below). The frequencies of the EEG normally vary between 0-80 Hz, and the amplitudes of a scalp-recorded EEG usually vary between 1-100 μV (microvolt).

4.2 The 10-20 system

The locations of electrodes for scalp-recorded EEGs are generally described with reference to the 10-20 system (Jasper, 1958, Fig. 4.1). In this system, electrode positions are specified with respect to their proximity to particular brain regions (F: frontal, C: central, P: parietal, O: occipital, T: temporal), and to their locations in the lateral plane (odd numbers: left, even numbers: right, the subscript z for midline). The Cz electrode, for example, is located on the midline over the central lobe, the T8 electrode is positioned over the right temporal lobe. The principle electrode locations are defined with respect to the relative distances along the anterior-posterior axis (from nasion over the vertex to inion), and the coronal axis (from the left post-auricular point over the vertex to the right post-auricular point). Most other locations are defined in relation to these principal locations.

Fig. 4.1 shows the electrode positions according to the 10-20 system. The outer circle is drawn at the level of the nasion and the inion. The inner circle represents the temporal line of electrodes. Tracing along the anterior-posterior line from nasion to inion, after 10 percent of this line the inner circle crosses midline, after another 20 percent the Fz electrode is located, after another 20 percent the Cz electrode (vertex), etc. Due to the need of larger numbers of electrodes, the American Society for Electroencephalography has established an extended version of the 10-20 system (Sharbrough, 1991, Fig. A.1).

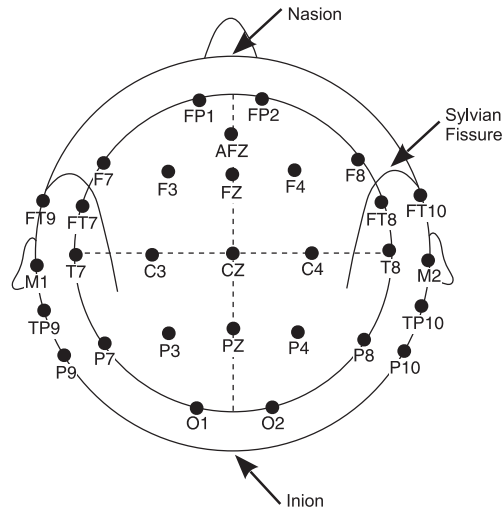


Figure 4.1: Electrode positions according to the 10-20 system. M1 and M2 are mastoidal electrodes.

It is common to apply electrodes at both left and right mastoidal sites⁵, these electrodes are often employed as reference electrodes. When needed, electrodes can be placed wherever useful: placement of nasopharyngeal or sphenoidal electrodes for example enhances detection of activity in the medial temporal lobes, originating e.g. in structures of the limbic system such as the hippocampus.

For the detection of neural generators of the auditory system it is often useful to place a reference electrode onto the nose: One reason is that generators in the auditory cortex are often located within the temporal lobe next to the sylvian fissure (see Fig. 4.1 and Appendix B). The apical dendrites of the pyramidal neurons of these generators are oriented perpendicular to the surface of the cortex. When an electric potential is generated, it projects with one polarity above, and with the complementary polarity beyond the sylvian fissure (i.e. approximately parallel to the line mastoid-Fz). To observe maximal amplitudes of both negative and positive potentials at both the left and the right hemisphere, a reference electrode is ideally placed onto the anterior-posterior line within the plane that draws through the sylvian fissure. This can best be realized with a nose-electrode (see Fig. A.2).

⁵That is behind the left and right ear.

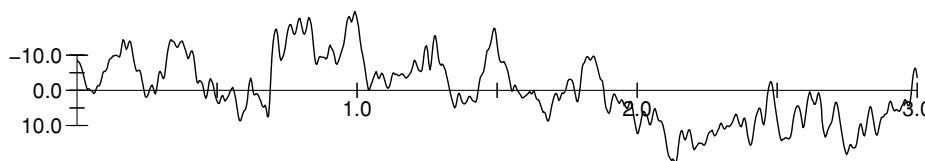


Figure 4.2: Spontaneous EEG over 3 seconds, from Cz.

The electrodes employed in the present EEG-studies are shown in Fig. A.2. Since these experiments investigated the processing of auditory musical information, most of the electrodes were placed at temporal and frontal sites, whereas only few electrodes were positioned at parietal and occipetal sites.

4.3 Obtaining event-related brain potentials (ERPs)

A 'spontaneous EEG' (i.e. an EEG recorded without experimental stimulation) over three seconds, obtained from the vertex, is shown in Fig. 4.2. Though no stimulation was present, distinct brain activity with amplitudes from around -20 to $20 \mu\text{V}$ is observable. This activity is called *noise*, and generated by a vast number of operations permanently performed by a living brain. When a stimulus is presented, the subsequently recorded brain potentials are composed of brain activity reflecting the processing of the stimulus, and the brain potentials reflecting brain activity which is not connected to the presentation of the stimulus. The potentials which correlate in time with the presentation of a stimulus are called *signal*.

The signal of one single trial (i.e. from a single stimulus presentation) is usually not larger than the spontaneous EEG itself and can thus not be distinguished from the noise (see Fig. 4.3, left diagram of the top row). However, when the same stimulus (or similar stimuli) are presented repeatedly, the signal in the brain potentials following each trial correlates with the presentation of the stimuli, whereas the noise does not.

It is possible to extract the signal from the noise by averaging the potentials of each trial (and thereby to increase the signal-to-noise ratio). That is, for each corresponding sampling point of all trials, arithmetic mean and standard-deviation of the electric potentials are calculated. Thereby, the stimulus-correlated signal remains, whereas the uncorrelated

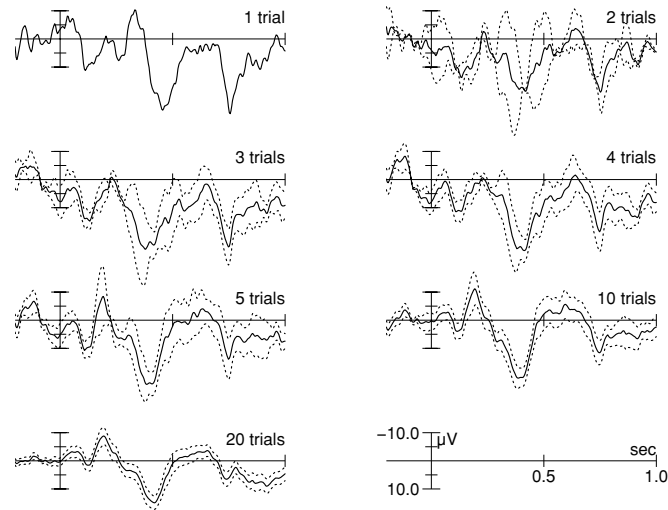


Figure 4.3: ERP of a single trial (top row, left), and ERPs of 2-20 averaged similar trials (solid lines). The standard error of mean is indicated by the dotted lines. The vertical line indicates the onset of the stimulus.

noise is averaged out. A brain response that becomes visible by the averaging of trials (time-locked to the presentation of a stimulus) is called an *event-related potential* (ERP).

In Fig. 4.3 is shown how the brain activity before the onset of the stimulus (indicated by the vertical line) approximates the zero-line with increasing number of averaged trials, reflecting that brain activity which did not correlate with the presentation of the stimuli was averaged out of the ERP-data. Besides, it is shown how the standard error of mean of the event-related potentials decreases with increasing number of averaged trials.

ERPs reflect brain activity with a high temporal resolution. With a sampling rate of 250 Hz, for example, time-intervals of 4ms duration can be investigated. It is important to note that most ERP-components are presumably generated not only by a single neural source, but by a set of generators (e.g. Näätänen & Picton, 1987; Scherg & Picton, 1991). The waveforms of all generators superimpose linearly at the scalp, that is each electrode senses activity from each source (to a greater or lesser extent, depending on the distance to the source, for mathematical depiction see e.g. Scherg & Picton, 1991). Besides, the spatial distribution of the electric potentials over the scalp is considerably influenced by the orientations of the neural sources (e.g. oriented tangentially or radially to the surface

of the head). Hence, even though the electric potential of a component is often largest at a particular electrode site this does thus not yield at all that the neural generator of this component is located in the head just beyond this electrode.

Chapter 5

Magnetoencephalography

A particular interest within brain research is applied to the identification of the functional significance of circumscribed brain regions. This can be achieved by the localization of neural generators underlying cognitive processes. With this respect, it is important to note that EEG measurements are considerably influenced by the volume conducting properties of whole the head, because the electric currents induced by the brain potentials have to pass the brain tissues and the skull in order to reach the skin surface. The low conductivity of the skull causes severe attenuation of the potential values and blurring of their spatial distribution (Elbert, 1998; Hämäläinen et al., 1993; Gevins & Rémond, 1990; Scherg, 1990; Näätänen, 1992; Knösche, 1997).

Electric activity of the brain, however, also produces magnetic fields (as a magnetic field is produced by an electric current through a wire). Though these neuromagnetic fields are extremely weak¹, they can be measured using magnetoencephalography (MEG).² Event-related magnetic fields (ERFs) are thought to be the magnetic equivalent of the electric ERP (for discussion see Näätänen, 1992; Hämäläinen et al., 1993). One important advantage of

¹For a rough illustration: The order of magnitude of an ERF (see below) is around 100 femtotesla (fT), that is 100×10^{-15} tesla. This is about one billionth of the earth's magnetic field (which has a strength of 70 μ tesla, i.e. 70×10^{-6} tesla).

²MEG measures magnetic fields using superconducting quantum interference devices (SQUIDs), which contain coils of superconducting wire. The SQUID is cooled by liquid helium to sustain the superconducting state. In principal, magnetic fields generated in the head (given a particular orientation and a certain strength) produce via the SQUID a voltage proportional to the magnetic flux through the area of the detection coil (for a detailed description see e.g. Williamson, 1989; Hämäläinen et al., 1993).

MEG is that the magnetic field caused by a source is mostly influenced by the conductivity profile of the tissue surrounding the source, whereas EEG source localization is dependent on a correct volume conductor model between a source and all electrodes. That is, an appropriate volume conductor model is more complicated to construct for the source localization with EEG compared to MEG data.

A neural source is well represented by a short segment of current which is, as a model, usually referred to as an equivalent current dipole (ECD). The localization of a source of a magnetic field relies on the law of Biot and Savart (e.g. Bleaney & Bleaney, 1976), which specifies the contribution made by the current density at each point in space to the field at a given point of observation. According to the Biot-Savart law, the magnetic field generated from a current dipole is tangential to a circle centered on a straight-line extension of the current's direction. The field is thus parallel to a plane that is perpendicular to the dipole. The orientation of the field can be predicted by the right-hand rule.

In order to determine the focus of electrical activity in the brain (e.g. by calculating ECDs) from MEG data, the magnetic field has to be measured from a number of locations (in the present study by 148 SQUIDS). The data from all sensors can be interpolated, resulting in a topographical map representing the spatial distribution of the amplitudes and polarities of the magnetic field at a certain latency for a particular experimental condition. By doing so, it is possible to determine the loci of the extrema of the magnetic field strength. Given, for example, a dipolar magnetic field-pattern, it is then possible to derive the localization of the electric activity.³

5.1 Forward solution and inverse problem

Given a volume conductor model and a sensor configuration, the magnetic field or electric potential that would arise from a certain source can be predicted with the Maxwell equations. This prediction is usually referred to as the forward solution.

In contrast, when electric potentials or magnetic fields are measured outside the head, the measured information can be used to reconstruct the cerebral current sources underlying

³The generator is located between the two maxima, the distance between the two maxima determines the distance of the generator.

the (electric) brain activity. This reconstruction is usually referred to as the bioelectromagnetic inverse problem. Importantly, the solution to this problem is generally not unique, because different classes of source configurations (e.g. each consisting of a different number of dipoles) can give rise to the same measured electric potential or magnetic field. A reliable solution of the inverse problem is thus subjected to a reliable forward solution which, in turn, depends on both an appropriate volume conductor model (see below) and an assumption of a reasonable source configuration (especially with respect to the number of sources; for detailed descriptions see e.g. Hämäläinen et al., 1993; Elbert, 1998).

5.2 Volume conductor models

To calculate measured electric potentials or magnetic fields as a function of an electric activity inside the head, it is necessary to construct a volume conductor model which determines the positions and the values of the different conductivities of the different tissues of the head (such as brain, liquor, skull, and scalp). Therefore, several methods have been developed. A crude approximation is the assumption of the human head as a homogeneous conducting sphere, usually referred to as the single sphere model. Attempts to create more realistic representations of the structure of the human head led to the multiple spheres model, in which the head is seen as consisting of a number of shells (representing tissues like brain, liquor, etc.).

The method used in the present study is the boundary element method (BEM) which is applied to individual, realistically shaped models of the main inter-tissue boundaries within the head (Fig. A.3).⁴

5.3 MEG vs. EEG

Besides the points already mentioned before, there are some more differences between source localization with MEG and EEG data which are worth to be mentioned.

⁴Such as scalp surface, inside and outside boundaries of the skull, surface of the brain, etc.

- When a dipole is oriented radially to the skull surface, the topographical map representing the spatial distribution of the amplitudes and polarities of the magnetic fields may not show focal maxima of the magnetic field, even when a BEM is used. This is mainly due to the orientation of the SQUIDS placed over the head, which only register magnetic fields that pass a detection coil of the SQUID.⁵ This effect also contributes to the phenomenon that deeper sources are hardly measurable with MEG, since with growing depth (i.e. when moving towards the center of the volume conductor) neural sources become radially oriented with respect to the head surface (Hämäläinen et al., 1993; Näätänen, 1992; Elbert, 1998).
- Multiple and /or distributed sources may add their electric potentials (and lead to a considerable qualitative difference between different experimental conditions in the ERPs) whereas magnetic fields easily compensate each other (so that no magnetic field is measurable outside the head).
- Using MEG, early cognitive processes can best be investigated (within approximately 250 ms after the onset of a stimulus). Physiologically, the number of neural activation foci increases with progressing time after stimulus onset. Thus, the magnetic fields often either compensate each other, or an extremely high signal-to-noise ratio is required for a reliable source reconstruction.
- MEG is usually more sensitive to cortical generators (whereas EEG is also capable of measuring potentials from subcortical sources; cf. Hämäläinen et al., 1993).
- The acquisition of MEG data is more sophisticated (and hence more expensive) compared to the acquisition of EEG data.
- EEG-data can easily be grand-averaged across subjects (the electrode configuration is due to the application of electrodes on the head surface individually scaled, and the electric potentials blur to a greater degree over the head compared to the magnetic fields). A grand-average often leads to significant qualitative differences between the ERPs elicited in different experimental conditions. In contrast, it is highly problematic to simply average ERFs across subjects. Subjects differ with respect to their head

⁵Though three-dimensional vector devices will appear soon which better support measuring radial magnetic field components.

size, and their positioning within the sensor. The magnetic fields (which are more focal compared to the widely distributed electric potentials) thus hardly overlap across subjects.

- Hence, considerably more trials have to be employed per subject in the MEG in order to obtain reliable results per subject. This may lead to repetition effects, or experimental sessions with inconvenient duration. In order to obtain a signal-to-noise ratio reasonable for dipole-fitting, it is suggested here as a rule-of-thumb that the amount of trials obtained across all subjects in an EEG-experiment should therefore approximately equal the amount of trials obtained by a single subject with MEG measurement.⁶
- MEG measurements can be performed more quickly, because usually only a little number of electrodes (e.g. for measuring the EOG) is applied.
- Whether EEG and MEG measure the same neuronal activity is still a matter of debate (for discussion see Näätänen, 1992, p.89-90).

⁶It is also suggested that the signal-to-noise ratio for a two-dipole solution should exceed a value of at least 10 (and considerably more for solutions employing more than two dipoles).

Chapter 6

ERP-correlates of auditory processing

The following chapter provides a brief introduction of the most important ERPs elicited during the processing of auditory information. It is important to note that most of the descriptions of ERP-components hold only for the auditory modality, especially with respect of latency and scalp topography.

6.1 Exogenous components: N1 and P2

In general, a predominant classification divides ERP components into exogenous and endogenous components (Donchin et al., 1978). The exogenous components are mainly determined by the external stimulus characteristics, whereas the endogenous components mostly depend on intentions and actions of a subject. The earliest exogenous components are the auditory brainstem responses, which occur within the first 10-12 ms after the onset of a stimulus (for review see Näätänen, 1990, 1992). The brainstem-responses are followed by the so-called middle-latency responses which are also categorized as exogenous components and generated in the primary auditory cortex. Their latency is from around 9-50 ms after stimulus onset (Picton, 1980; Celesia & Puletti, 1971). Late exogenous components are, for example, P1, N1 and P2. These late exogenous components are considerably larger in amplitude compared to the early and middle-latency responses.

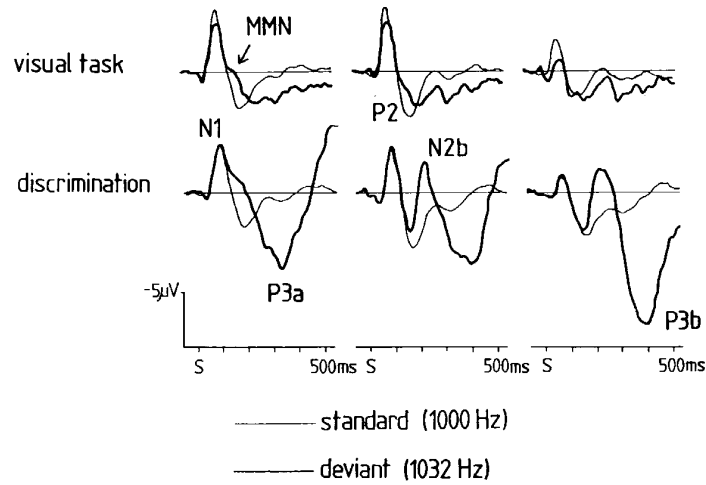


Figure 6.1: ERPs of auditory standard and deviant stimuli while performing a demanding visual task (top row), or while trying to discriminate deviant stimuli among standard stimuli (bottom row). Recorded from Fz (left column), Cz (middle), and Pz (right). Adapted from Näätänen (1990).

The N1 denotes a negativity that normally peaks around 100 ms after the onset of a stimulus (for review see Näätänen & Picton, 1987; Näätänen, 1990, see also Fig. 6.1). The N1 is usually preceded by a small P1 (peaking around 50 ms), and a larger P2-wave (around 200 ms). Both N1 and P2 do not represent a single cerebral event, since both components differ in scalp distribution due to experimental manipulations (Näätänen & Picton, 1987). That is, most presumably both N1 and P2 are generated by a set of neural generators (Näätänen & Picton, 1987; Scherg & von Cramon, 1986; Scherg, 1990). The N1 is thought to correspond with a transient detection, since the N1 is evoked by abrupt changes in the level of energy impinging on the sensory receptors (Clynes, 1969).¹

6.2 Mismatch Negativity, N2b (and P3)

In contrast to the previously described exogenous components, ‘an ERP-component called the mismatch negativity (MMN) appears to provide a physiological measure, although an indirect one, of the actual sensory information processed in the brain’ (Näätänen, 1992, see Fig. 6.1). The human brain permanently encodes physical features of the auditory

¹That is, the N1 can also be elicited by the offset of a stimulus, as well as by a change in tonal frequency or intensity of a continuous auditory stimulation (for review see Näätänen & Picton, 1987; Näätänen, 1992).

environment into neural memory representations stored in auditory sensory (or 'echoic') memory. Involved in indicating changes in regularities inherent to the acoustic input is a special sensory memory mechanism, which is reflected electrically as the MMN. That is, the MMN is elicited by deviant auditory stimuli in a repetitive auditory environment of discrete standard stimuli (for reviews see Näätänen, 1992; Schröger, 1998).

The MMN usually overlaps the N1 and the P2 waves (which are elicited by both standard and deviant stimuli) and has a fronto-central, mostly right-hemispheric preponderant scalp distribution. The MMN is elicited by many kinds of stimulus change, for example changes in frequency (e.g. Sams et al., 1985), intensity (Näätänen et al., 1987, e.g.), spatial location (Paavilainen et al., 1989), stimulus duration (Näätänen et al., 1989), phonetic features (Näätänen et al., 1997), and timbre (Tervaniemi et al., 1997). When nose-reference is used, the MMN inverts polarity at mastoidal sites.

Notably, the processes eliciting the MMN may be elicited even by unattended deviant stimuli (for detailed discussion see Schröger, 1998). Therefore, the MMN seems to reflect auditory feature encoding and mismatch-detection processes which operate automatically (or 'pre-attentively', i.e. independently of attention).

During active oddball paradigms, that is (only) when participants detect occasionally presented target stimuli among a series of standard stimuli, the MMN is usually followed by an N2b (for exception see Näätänen et al., 1982).² The N2b is typically maximal over central scalp electrodes and does not invert polarity at mastoid electrodes (Näätänen & Gaillard, 1983; Näätänen, 1990, see Fig. 6.1). The N2b is often followed by a positive-going ERP-component which is maximal around 300 ms and has a frontally predominant scalp distribution (for exception see Knight, 1990). This component is called the P3a (Squires et al., 1975; Ritter & Ruchkin, 1992; Näätänen, 1992).

A P3a might occur without a preceding N2b, in case that a deviant stimulus attracts the attention of a subject. The amplitude of the P3a is related to physical stimulus deviation (rather than to the dimension of task-relevancy, i.e. whether or not a stimulus has to be detected; Näätänen, 1992). When the deviant sound is a complex environmental sound (usually referred to as 'novel' sound), additional cognitive processes might be involved in the generation of a P3a, thus the frontally predominant ERP-deflection elicited by novel

²N2b may of course also be elicited without a preceding MMN.

sounds in the time-window of the P3a is often referred to as 'Novelty P3' (e.g. Courchesne et al., 1975; Cycowicz & Friedman, 1998, 1999; Spencer et al., 1999; Opitz et al., 1999b,a). The generation of both P3a and Novelty P3 is observable under both attend and ignore conditions.

The N2b-P3a-complex is usually followed by another positive ERP-component with a latency slightly longer than the latency of the P3a and with a parietal amplitude maximum, the P3b (or just P3, see Fig. 6.1). The P3b reflects the decisional processes during the conscious recognition and detection of a target-stimulus(Donchin et al., 1978).³

³Though the P3 does not necessarily reflect conscious processing (Donchin & Coles, 1998). For an interpretation of the P3 as reflecting processes of context updating see Donchin & Coles (1988, 1998)

Chapter 7

ERP-correlates of language processing

As described in the previous chapter, auditory perception can be investigated with ERPs. At least partly due to this property, ERPs have also become an interesting tool for the investigation of both language perception and production, especially with respect of the processing of semantic (content) and syntactic (structural) information.

7.1 Semantic processes: N400

Semantic processes were found to be reflected in the ERP as a negative component elicited around 400 ms after stimulus presentation (Kutas & Hillyard, 1980). This component is broadly distributed over the posterior part of both hemispheres and referred to as the N400, or just 'N4' (for review see Kutas & Kluender, 1991; Kutas & Van Petten, 1994; Friederici, 1998).

In the study from Kutas & Hillyard (1980), subjects were required to read sentences comprised of about seven words, with each word being presented individually at a rate of 1 second. Infrequently, the final word was either semantically inappropriate but syntactically correct, or larger in letter size but semantically correct. As shown in Fig. 7.1, semantically deviant final words elicited an N400, while words in larger type ('physically

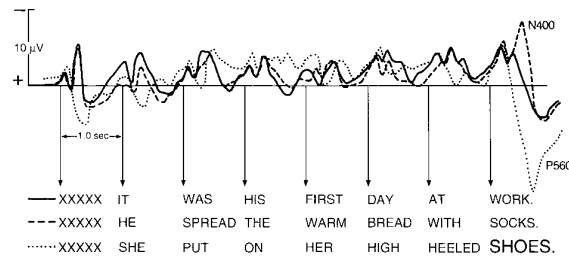


Figure 7.1: ERPs to sentences ending with a non-anomalous, semantically anomalous, or physically anomalous word. An N400 was elicited by the semantically anomalous words (from Kutas & Hillyard, 1980).

deviants') were associated with the classic P3b (maximal around 560 ms). Neither component was evident when a sentence terminated with a word that was both semantically and physically congruous with the preceding words. The N400 was thus suggested to reflect semantic processing.

The amplitude of the N400 is sensitive to the semantic expectation built up by the preceding context for a given word. Kutas et al. (1984) showed that semantically anomalous words had a smaller N400 when they were related to the expected ending than when they were not. While the expected ending [*eat*] to the sentence stimulus *The pizza was too hot to ...* showed no N400, the ending *drink* showed a small N400, and the semantically unrelated ending *cry* elicited a large N400.

Fischler et al. (1983) showed that the N400 is sensitive to the associative strength between entries in the mental lexicon, rather than to the propositional content of a statement. Subjects were asked to verify a set of simple semantic propositions (e.g. *A robin is a bird* or *A robin is not a car*). The truth of a statement did not affect the N400, the association between the two content words on the other hand did. The N400 is also sensitive to interpretable false statements. In an experiment from Fischler et al. (1985) subjects had to learn a set of statements such as *Matthew is a lawyer*. False statements such as *Matthew is a dentist* presented a day after the practice session elicited an N400.

The N400 seems to be a controlled (rather than automatic) process. In a semantic priming paradigm, Chwilla et al. (1995) observed that different levels of processing (assessed by changing the task demands) affected the amplitude of the N400 priming effect (which was only present in a lexical decision task compared to a physical task). These results were taken to indicate that an N400 priming effect is only evoked when the task performance

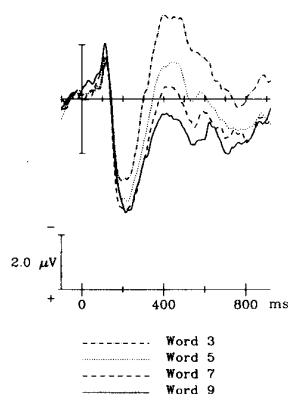


Figure 7.2: Amplitude-decline of the N400 elicited by semantically correct open class words during sentence comprehension (from Van Petten & Kutas, 1990).

induces the semantic aspects of words to become part of an episodic trace of the stimulus event.¹

Van Petten & Kutas (1990) showed that the amplitude of the N400 elicited by open class words (i.e. nouns, verbs, etc.) is inversely correlated with the word's ordinal position in relatively simple English sentences (Fig. 7.2). This finding was interpreted as a reflection of the build up of constraints imposed by a partial sentence upon individual succeeding words.

Brown & Hagoort (1993) claimed that the processing nature of the N400 is related to lexical-semantic integration processes. That is, once a word has been accessed in the mental lexicon, its meaning has to be integrated into an overall representation of the current word or sentence context. The easier this integration process, the smaller the amplitude of the N400. However, whether the N400 reflects processes of lexical access and/or processes of lexical integration is still an issue for psycholinguistic modeling (for discussion see Friederici, 1998).

¹The hypothesis of the N400 being a controlled process was supported by a study from Gunter & Friederici (1999). Similar to the study from Chwilla et al. (1995), an N400 was present under a grammatical judgment task, but distinctly attenuated under a physical task. An interesting finding of the study from Gunter & Friederici (1999) was that the N400 was (somewhat unexpectedly) elicited by *syntactic* violations (verb inflection and word category violation). Nevertheless, according to the authors, the N400 was still triggered by semantic expectations Gunter & Friederici (1999).

In an experiment from Holcomb & Neville (1990), legal pseudowords elicited an N400, whereas ‘backward words’ (words spelled or played backward) showed no evidence of an N400 response (neither in the visual, nor in the auditory modality). Holcomb & Neville (1990) thus claimed that the N400 is language specific, i.e. that the N400 is elicited only by linguistic stimuli.² This hypothesis has been supported by the results of ERP-studies investigating music-processing, where so far no N400 has been found (see Chapter 8). However, N400-like effects were found in priming studies to pairs of related and unrelated pictures (Barrett & Rugg, 1990; Holcomb & McPherson, 1994), during the retrieval of object forms (taken to reflect involvement of conceptual semantic integration processes, see Mecklinger, 1998), and during the processing of faces (for summary see Jemel et al., 1999).

7.2 Syntactic processes: (E)LAN and P600

It is generally agreed that sentence comprehension also requires an analysis of constituent structure, that is, an analysis of the relative ordering of words in the sentence and of the grammatical roles played by these words. Two ERP components have been found to reflect syntactic processes: a left anterior negativity (either present between 100 and 200 ms or between 300 and 500 ms) and a late positivity being maximal around 600 ms (or even later).

7.2.1 Early Negativities

In an experiment from Neville et al. (1991), the violation of phrase structure elicited a left anterior negativity (around 125 ms) which was followed by a left temporo-parietal negativity between 350 and 500 ms.³ Left anterior negativities (LANs) with a similar latency range have also been observed in correlation with the processing of subcategorization information (Osterhout & Holcomb, 1993; Rösler et al., 1993), with agreement violations (Coulson et al., 1998; Friederici et al., 1993; Gunter et al., 1997; Osterhout & Mobley, 1995), and for

²If the N400 is a generic mismatch response that responds to any kind of discrepancy between prime and target stimuli, then both kinds of non-words should have produced equivalent negativities.

³In specific, this left anterior negativity was evoked by a word category error, e.g. *Max's of proof the theorem*.

agreement errors in pseudoword combinations (Münte et al., 1997). Besides, a left anterior negativity was observed for the processing of function words as compared to open class words (Neville et al., 1992; Nobre & McCarthy, 1994). Most of the left anterior negativities displayed a centro-frontal or frontal maximum, often with a left-hemispheric dominance (for review see Friederici, 1998).⁴

Notably, during the processing of language, early syntactic processes reflected in the LAN and semantic processes reflected in the N400 are presumably carried out in parallel. In a 2 by 2 design employed in a study from Gunter et al. (1997), both LAN and N400 were found to become significant around the same time window (260 ms) but did not show an interaction.⁵

With regard to the left anterior negativities described in the literature it seems reasonable to distinguish the *early* left anterior negativity with a latency of about 100 to 300 ms (Friederici, 1998, ELAN, for review see), and the left anterior negativities with a latency of about 300 to 500 ms (LAN). The ELAN elicited during the presentation of connected speech has first been described by Friederici et al. (1993). In this experiment, word category violations (e.g. *Der Freund wurde im besucht / The friend was in the visited*) evoked an ELAN present around 180 ms, followed by a second negativity between 300 and 500 ms (Fig. 7.3).

The ELAN has so far been observed for the processing of phrase structure violations and closed class elements only. Since the ELAN was found to be independent of the influence of attentional factors, the ELAN is assumed to reflect highly automatic processes (Hahne & Friederici, 1999).

7.2.2 P600

The P600 is a late positivity of the ERP elicited by words that are difficult to integrate structurally into meaningful sentences. Its amplitude is maximal over parietal leads. The P600 has been found to be elicited by a variety of syntactic anomalies such as garden-path

⁴For the observation of the LAN in sentences whose processing required working memory see Kluender & Kutas (1993).

⁵An interaction between syntax and semantics was found, however, in the region of the P600.

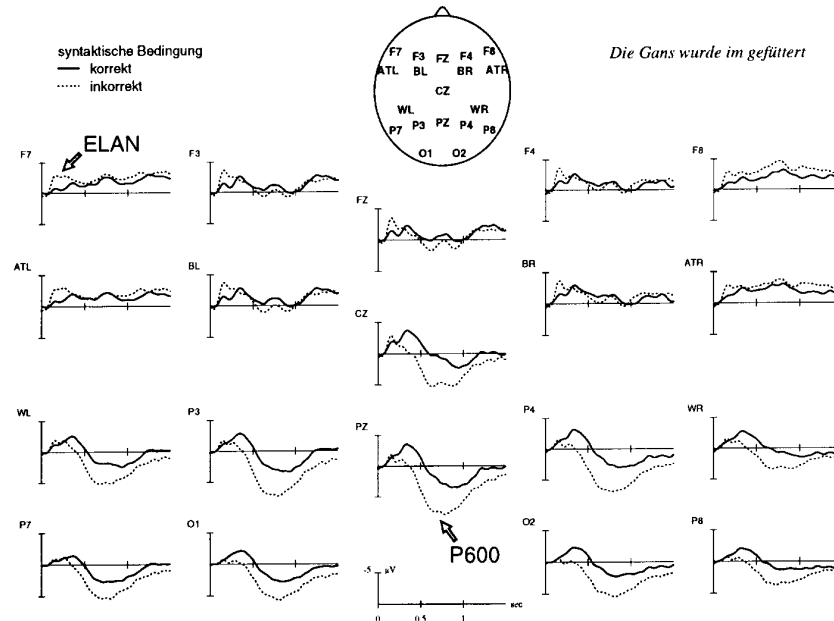


Figure 7.3: ERPs elicited by syntactic incongruity (dotted line) compared to ERPs elicited by syntactically correct words (solid line). The ELAN is best to be seen at F7 around 180 ms; (from Hahne, 1999).

sentences and other syntactically non-preferred structures (Friederici et al., 1996; Hagoort et al., 1993; Mecklinger et al., 1995; Osterhout & Holcomb, 1992, 1993; Osterhout et al., 1994), agreement violations (Coulson et al., 1998; Friederici et al., 1993; Gunter et al., 1997; Hagoort et al., 1993; Osterhout & Mobley, 1995), outright phrase structure violations (Friederici et al., 1996; Neville et al., 1991; Osterhout & Holcomb, 1992, 1993), and subadjacency violations (Neville et al., 1991; McKinnon & Osterhout, 1996). Whereas fairly automatic parsing processes seem to be reflected in the early negativities, fairly controlled later processes of reanalysis and repair may be reflected in the P600 component (Friederici, 1998; Hahne & Friederici, 1999; Gunter & Friederici, 1999).

It is important to note that it seems likely that the P600 is a type of P3b (Osterhout & Holcomb, 1995), calling into question the hypothesis of the P600 reflecting a pure *syntactic positive shift* (SPS, Hagoort et al., 1993). Evidence supporting the hypothesis that the P600 rather belongs to the P3-family was provided by a study from Gunter et al. (1997). In this study, the P600 was affected by the probability of violation (25% vs. 75%). This finding was taken as evidence that the P600 resembles the P3b.⁶

⁶However, studying the P600 is still capable of providing information about language processing (cf. Oster-

With this respect, it seems fairly plausible that a P600 is not specific for the processing of language, as demonstrated by an experiment from Patel et al. (1998). As will be described in the next chapter, this experiment revealed that both linguistic and musical structural incongruities elicited positivities that were statistically indistinguishable (though the positive component peaked earlier during the processing of music [600 ms] compared to language processing [900 ms]). This finding was suggested by the authors to indicate that the neural processes reflected in the P600 are not uniquely linguistic but index more general cognitive operations involved in the processing of structural relations in rule-governed sequences.⁷

hout & Holcomb, 1995).

⁷Though the P600 was larger in amplitude relative to ERP elicited by in-key target chords (which had also to be detected), it is important to note that the P3 is larger in amplitude to unexpected compared to expected targets (cf. Pritchard, 1981; Ritter & Ruchkin, 1992).

Chapter 8

ERP-correlates of music processing

8.1 One-part stimuli (melodic processing)

Only recently, ERP-researchers discovered the investigation of cognitive processes underlying the perception of music (for review see Besson, 1998).¹

In an initial study, Besson & Macar (1987) attempted to determine whether the N400 would be elicited by other than only linguistic deviations. Besides language and geometric patterns, scales and melody-excerpts (containing only the first few bars of a familiar melody) were presented to the participants which ended in 25% of all trials on an incongruous note. An N400 was elicited only by language stimuli, taken to support the hypothesis that the N400 indexes the further processing required by linguistic incongruities rather than by violations of arbitrary overlearned rules in general. This conclusion is critical, since the incongruous endings of scales and melodies were rather structural violations than violations of semantic expectancy (only the latter being connected to the N400).

Besson & Macar (*ibid.*) also reported a significantly larger N100 elicited by incongruous endings of scales and melodies, and a second negative deflection (especially present in the ERPs of deviant melody-endings), but both phenomena were only speculatively discussed. Auditory (and geometric) stimuli also elicited a P3b, due to unexpectedness of the less probable incongruous stimuli.

¹For the investigation of music processing as reflected in DC-potential recordings see e.g. Altenmueller et al. (1997); Pihan et al. (1997); Altenmueller (1986); Beisteiner et al. (1994); Beisteiner (1992).

A study from Verleger (1990) also investigated ERP-effects of melodic deviance. In contrast to the study from Besson & Macar (1987), melodies ended not only in the midst of the phrases (properly or with a deviant tone), but also at the end of a melody-phrase (with the final tone either having its proper or a deviant pitch). As in the study from Besson & Macar (1987), no N400 was found in any condition. Instead, P3-effects were found and suggested to correlate independently (a) with deviance and (b) with ending, the former reflecting arousal, the latter reflecting subjects' expectation of the closing stimulus.

Paller et al. (1992) performed an experiment similarly to the melody-condition of the study from Besson & Macar (1987), but allowing additional time for expectations to develop for the terminal note. As in the studies from Besson & Macar (1987) and Verleger (1990), deviant terminal notes did not elicit N400s, but P3-effects. Even in a condition, in which the P3-amplitude was minimized (employed in order to investigate if the P3 overlaps an N4), no N400 was evident.

In a prominent study from Besson & Faita (1995), familiar and unfamiliar melodies (i.e. single tones) with either congruous or incongruous endings (diatonic, non-diatonic, and rhythmic) were presented to both musicians and non-musicians. In one experiment of this study, participants had to detect the incongruous endings, and in another experiment, participants 'were told to listen to the phrases carefully to be able to answer questions at the end of each block' (Besson & Faita, 1995, p.1288). Since in both experiments incongruous endings were task-relevant, a P3b (reflecting the decisional processes connected to the detection of the incongruity) is to be expected to be present in the ERPs. Incongruous endings elicited positivities from around 300 ms post-stimulus onset and with a parietal maximum. These positivities were taken by Besson & Faita as 'late positive components' (LPCs). In the experiment where incongruous endings were to be detected, the LPCs showed a greater amplitude and a shorter latency for musicians than for 'non-musicians', presumably since familiar melodies were more familiar for musicians than for non-musicians and thus easier to detect for musicians.

In both experiments, the LPCs had a larger amplitude for familiar melodies than for novel melodies (presumably since incongruities ending familiar phrases were easier to detect), and for non-diatonic than for diatonic endings (Fig. 8.1). Diatonic incongruities ending unfamiliar melodies did not elicit an LPC (presumably since they are hardly to de-

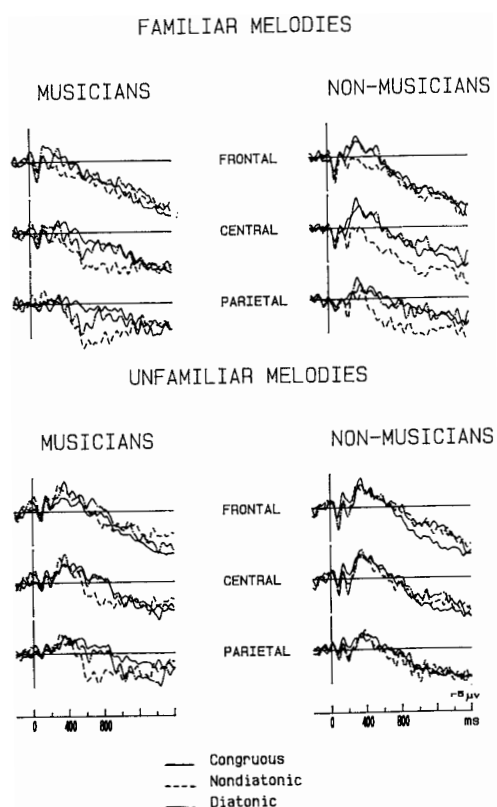


Figure 8.1: ERPs elicited by congruous and incongruous melody-endings, separately for musicians and non-musicians (from Besson & Faita, 1995). Participants were instructed to listen to the sequences and to answer infrequently asked questions about the melodies.

tect), whereas non-diatonic incongruities did (they were detectable for participants by the application of tonal rules).

Results indicate that the LPC is at least partly connected to the detectional processes of a music-structural violation (detectable mainly through specific, memory driven expectations), rather than to a genuine processing of music. This hypothesis is supported by the finding that the LPC was significantly larger in the first experiment (where the incongruous endings were to be detected).

However, negative components in the 200-600 ms range were found for incongruous endings (diatonic and non-diatonic), which differed neither between hemisphere, nor along the anterior-posterior dimension. Unfortunately, their functional significance could not be specified, since they were largest for incongruous endings of unfamiliar musical phrases.

In an experiment with sung melodies from Besson et al. (1998), stimuli infrequently ended either on a semantically incorrect word, and / or an incongruous note. While the semantically incorrect words elicited an N400, incongruous notes elicited an LPC. Interestingly, the processes reflected in both the N400 and the LPC were found to be independent from each other, suggesting that music can be processed independent from (or in parallel with) language.

8.2 Multi-part stimuli (chord processing)

In an ERP-study with multi-part stimuli (i.e. chords) conducted by Janata (1995), major cadences consisting of three chords were terminated equiprobably either by the tonic, the minor tonic, or a major tonic based on the tritone (IV#) of the original key (a chord perceived as dissonant and thus as unexpected). Musicians had to judge whether or not a cadence ended on 'the best possible resolution' (Janata, 1995).

In general, the degree of expectancy violation of a chord terminating a chord-sequence was reflected in the amplitude of positive ERP-peaks in two temporal regions: A P3a with a latency of 310 ms reflecting attentional processes, and a P3b peaking at 450 ms reflecting decisional processes (Fig. 8.2). A greater the violation was reflected in larger P3-peaks.

Hantz et al. (1997) recorded ERPs from musicians who were asked to judge whether or not novel musical phrases (consisting of single-tone- or harmonized melodies) were ended on the tonic ('closed endings'). Four different endings were employed equiprobably: tonic, open diatonic endings (i.e. the melody ended on a diatonic scale degree other than the tonic), open non-diatonic ('chromatic'), and white noise.

Negative drifts in the waveforms occurred over the course of the context series and were taken to reflect anticipation of closure. In general, deviant (open) endings were reflected by a negative deflection around 270 ms (maximal at Cz), followed by a positive peak around 470 ms relative to the 'closed' endings. The positive peak was maximal at Pz, and similarly to the study from Janata (1995) reflecting a P3b. Both early negativity and late positivity were heightened by the degree of deviance of the ending.

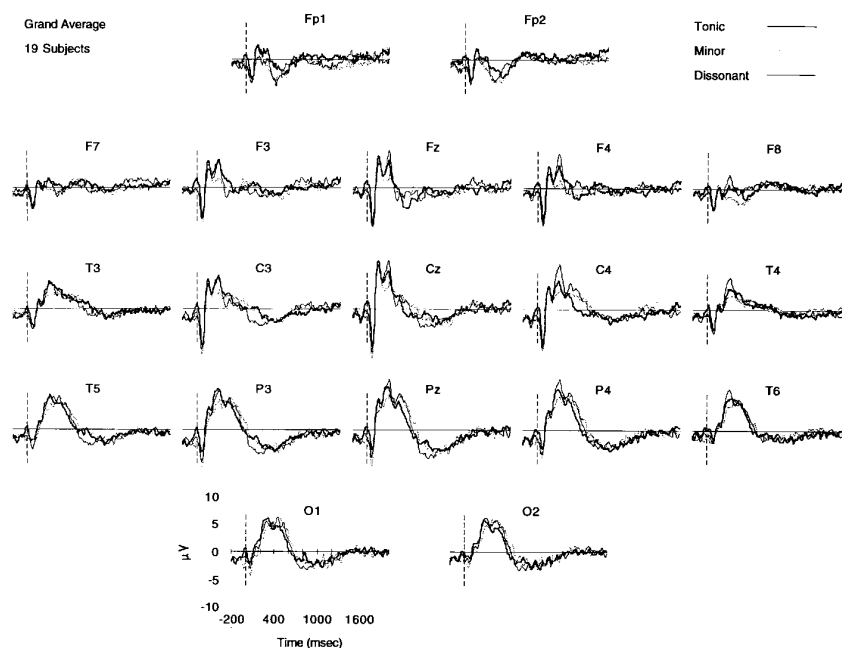


Figure 8.2: ERPs of chord-sequence endings (from Janata, 1995), positive is up.

In order to test the language-specificity of the P600 (see page 59), Patel et al. (1998) compared ERPs elicited by 'syntactic incongruities' in language and music, whereby harmonic incongruities were taken as grammatical incongruity in music. Target chords within polyphonic musical phrases were manipulated, so that the targets were either within the key of a phrase, or out-of-key (from a 'nearby' key or a 'distant' key, in view of the circle of fifths).

Both musical and linguistic structural incongruities elicited positivities with a latency of about 600 ms, which were maximal at posterior sites and statistically indistinguishable. Moderate and high degrees of structural anomaly differed in amplitude of the elicited positivities. Hence Patel et al. (1998) suggested that the P600 probably reflects more general knowledge-based structural integration during the perception of rule-governed sequences.

Additionally, a negative music-specific ERP component with a latency of around 350 ms and an anterior right-hemisphere lateralization was observed. This right antero-temporal negativity (RATN) was elicited by out-of-key target chords (Fig. 8.3). The RATN was taken to reflect the application of music-syntactic rules and working memory processes.

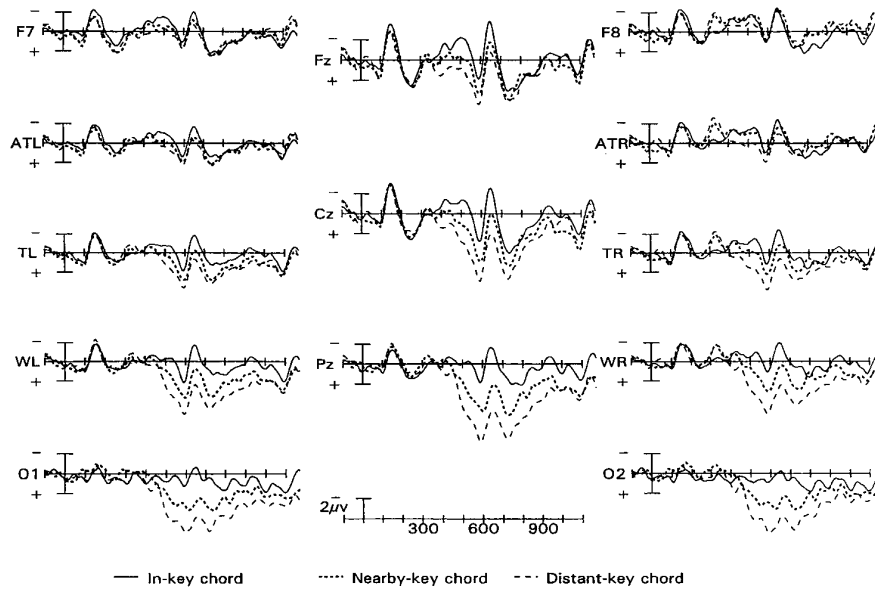


Figure 8.3: ERPs of the three target chord types (from Patel et al., 1998). Onset of the following chord is 500 ms after target onset.

In the studies from Janata (1995), Hantz et al. (1997), and Patel et al. (1998), stimuli were polyphonic, i.e. multi-part, and music processing was investigated under the condition to detect the experimental manipulations. Participants were highly trained musicians, hence results do not allow a broad generalization. In the study from Besson & Faita (1995), the processing of monophonic (i.e. one-part) melodies was compared between musicians and non-musicians under conditions in which participants had to respond overtly and under which participants did not have to give an overt response. However, still the decisive stimuli were never task-irrelevant. The probability of the incongruent stimuli varied between, but not within the mentioned studies (Besson & Faita, 1995; Janata, 1995; Hantz et al., 1997; Patel et al., 1998), thus an influence of probability on the processing of music remained unclear.

In contrast to these studies, the present study investigates how non-musicians process polyphonic musical information under both task-relevant and task-irrelevant conditions (Experiment 1 vs. 3), under both attend and ignore conditions (Experiment 6), and with varying probabilities of the decisive experimental manipulations (Experiment 3 vs. 4).

Chapter 9

Experiment 1

Context build-up and unexpected musical events

9.1 Introduction

The major aims of Experiment 1 were investigations of neural processes reflecting (a) the build-up of a musical context (b) the integration of musical information into a musical context, and (c) the violation of musical expectancies induced by a musical context. Investigating these issues aimed at exploring similarities and differences between music- and language-processing, especially in respect of the syntactic and semantic nature of music.

When a person sings, plays an instrument, or speaks a sentence, a succession of acoustic events is normally supposed to constitute a context which can be understood by another person. Hence, cognitive processes of both context build-up and integration of appropriate new information into a context are substantial for understanding music as well as language. In western tonal music, a musical context always refers to a tonal center (or tonal key), which is ideally represented by the tonic chord (in C major: c-e-g; see p. 18). Notably, the tonal center of a musical context is not explicitly inherent in each of its notes or chords, since every note or chord always belongs to several different keys. To understand a musical context, listeners have to extract a tonal center by perceiving musical relations between several notes (see Krumhansl & Kessler, 1982). Within a musical context, some musical events are more expected by listeners than others. The aesthetic violation of sound expectancies, musical



Figure 9.1: Examples of chord-sequences exclusively consisting of in-key chords.

surprises, ambiguity and disambiguation of musical events are perceived as appealing by most listeners. Composers expanded the repertoire of dissonances and ambiguities throughout the history of music, otherwise music would have become boring.

To investigate cognitive processes underlying the perception of music, an experimental paradigm was developed, in which the basic stimulus material consisted of chord-sequences, each chord sequence consisting of five chords. To investigate neural processes reflecting the build-up of musical context in specific, 25% of the chord-sequences consisted of in-key chords only (Fig. 9.1). They began and ended with a tonic chord, and built up a musical context towards the end of each cadence (in musical terms such a sequence is called a *cadence*). It was expected that during the presentation of a cadence, a tonal schema is activated in listeners, entailing the representation of a tonal key which specifies a hierarchy of harmonic stability (Bharucha, 1984, see p. 30).

To investigate neural processes reflecting both the violation of musical expectancy and a subsequent harmonic integration, in 25% of all chord-sequences, the chord at the third, and in 25% the chord at the fifth position was a ‘Neapolitan sixth chord’ (Fig. 9.2).¹ As described previously, Neapolitan chords contain out-of-key (i.e. ‘non-diatonic’) notes, and are thus perceived as more distant from the tonal center (and therefore as more unstable) compared to chords consisting exclusively of in-key notes. Chords with out-of-key notes interfere with an established stable tonal fabric. They violate the expectancy for tonally related chords to follow which may be experienced as a parsing failure requiring reinterpretation. Notably, the ability of listeners to identify wrong notes is by some theorists taken as demonstrating the psychological reality of a musical syntax (e.g. Swain, 1997).

Notably, the musical context (which induces musical expectancies for harmonically related chords to follow) was built up to a higher degree at the end compared to the middle of

¹For a music-theoretical description of Neapolitan chords see p. 19.



Figure 9.2: Examples of chord-sequences containing a Neapolitan sixth chord at the third position (top), and at the fifth position (bottom). Neapolitan chords are indicated by arrows.



Figure 9.3: Example of a chord-sequence containing a secondary dominant (the secondary dominant is indicated by the arrow).

a chord-sequence. The presentation of Neapolitan chords at both the third and the fifth position thus allowed to investigate a possible influence of the degree of specificity of musical expectancies on the processing of the Neapolitan chords.

Secondary dominants² were also presented within the chord-sequences (Fig. 9.3). They occurred with a probability of 25%, and were employed at the second position of a chord-sequence only. Secondary dominants were in the first line employed in order to prevent the stimulation from monotony. Nevertheless, secondary dominants were less closely related to the first chord of a chord-sequence (in the sense of the circle of fifths) compared to in-key chords. This difference might also be reflected in the ERPs.

Importantly, the chord-sequences were presented one after the other, in order to give the impression of a musical piece, rather than a presentation of single experimental stimuli (Fig. 9.4). Texture of chords followed the classical theory of harmony.

Chords were mainly played on a piano, but in 10% of the chord-sequences, an in-key chord at the second, third, fourth or fifth position was played on another (i.e. a ‘deviant’)

²See p. 21.

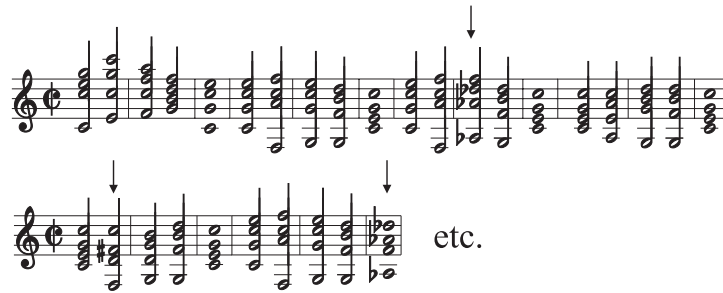


Figure 9.4: Example of directly succeeding chord-sequences as presented in the experiment.

instrument (e.g. marimba, organ, guitar). Participants were instructed to count these chords. This counting task was devised in order to direct participants attention towards the stimulation. Participants had no task connected to the detection of the Neapolitan chords. A conscious detection would have caused potentials (e.g. a P3b) which might have overlapped with components reflecting musical processing. Subjects were not informed about the presence of Neapolitan chords or their nature.

Though chords at the fifth position of a sequence were twice as long in duration than chords at the first to fourth position, all chords were presented with identical decay of loudness (so that Neapolitan chords at the third vs. fifth position were on average physically identical within the first 600 ms; see also Methods-section). To ensure that results enable to a broad generalization, participants were ‘non-musicians’.

9.2 Methods

9.2.1 Subjects

18 subjects (aged 20 to 30 years, mean 22.5, 9 females) participated in the experiment. Subjects were ‘non-musicians’, that is they never had musical lessons or learned to play an instrument besides normal school-education. All subjects were right-handed according to the Edinburgh Handedness Inventory (Oldfield, 1971). All subjects reported to have normal hearing.

9.2.2 Stimuli

A pool of stimuli consisted of 128 different chord-sequences (each sequence consisting of five chords). The first chord was always the tonic of the following chord-sequence; chords at the second position were tonic, mediant, submediant, subdominant, dominant to the dominant, secondary dominant to mediant, secondary dominant to submediant, secondary dominant to supertonic. Chords at the third position were subdominant, dominant, dominant six-four chord, Neapolitan sixth chord. Also chords at the third position, but only following a secondary dominant were mediant, submediant, and supertonic. Chords at the fourth position were dominant seventh chord; chords at the fifth position were tonic or Neapolitan sixth chord. All chords were presented in different chordings (tonic, third, fifth, and seventh in the top-voice). Secondary dominants were never followed by a Neapolitan chord at the third position. Neapolitan chords at the fifth position never followed a Neapolitan chord at the third position.

From the pool of 128 sequences, 172 chord-sequences were chosen randomly in a way that Secondary dominants, Neapolitan chords at the third position, and Neapolitan chords at the fifth position of a sequence occurred with a probability of 25% each (resulting in a total amount of 43 secondary dominants, 43 Neapolitans at the third, and 43 Neapolitans at the fifth position). Besides, each variation of a Neapolitan chord was in one cadence presented at the third, and in another at the fifth position.

Presentation time of chords 1 to 4 was 600 ms, of the fifth chord 1200 ms. Chords were presented via speakers and played under computerized control via MIDI on a synthesizer with approximately 60dB SPL. In 10% of the cadences an in-key chord at the second, third, fourth or fifth position was played by another instrument than piano (e.g. harpsichord, celesta, marimba). Cadences were played immediately one after the other, sounding like a musical piece.

9.2.3 Procedure

Participants were seated in a comfortable chair. They were instructed to keep their eyes open and to look at a fixation-cross. Participants were only informed about the deviant instruments, not about the Neapolitan chords or their nature. An example of a cadence played

on a piano and of a cadence in which one chord was played by a deviant instrument (organ) was presented to each participant before starting the EEG-measurement. Participants were instructed to ignore the harmonies and to count the deviant instruments. They were informed that they would be asked approximately every 2 minutes (i.e. after approximately 35 chord-sequences from the same key) about the number of deviant instruments, and report their answer by pressing a response button. This inquiry was employed five times during and at the end of the experiment. After an inquiry, the following chord-sequences were from another key (resulting in 5 sub-blocks from a different key). The duration of the experimental session was approximately 12 minutes.

9.2.4 EEG measurements

Measurements were performed in an acoustically and electrically shielded room. The EEG was recorded with Ag-AgCl Electrodes from 25 scalp locations of the 10-20-system, referenced to the left mastoid (see e.g. Pivik et al., 1993). Besides, the horizontal electro-oculogram (EOG) was recorded bipolarly between electrodes situated at the outer right and outer left canthus; the vertical EOG was recorded bipolarly between electrodes situated above and below the right eye. Sampling rate was 250 Hz (30 Hz low-pass). For elimination of artifacts caused by eye-movements, EEG-data were rejected off-line from the raw EEG whenever the standard deviation within any 200 ms interval of all data exceeded $35\mu V$ in the vertical, and $15\mu V$ in the horizontal electro-oculogram. For elimination of artifacts caused by drifts or movements, EEG-data were rejected off-line from the raw EEG whenever the standard deviation within any 500 ms interval exceeded $20\mu V$ at either one of the following electrodes: T7, T8, FT7, FT8, P7, P8, O1, and O2. On average, 9.4% of all trials were rejected from further data-analysis.

9.2.5 Data-Analysis

To test the lateralization of effects, repeated measurement ANOVAs were conducted comparing left vs. right frontal electrodes. Two regions of interest were computed: a region of left frontal electrodes (F7, F3, FT7, FC3) and a region of right frontal electrodes (F4, F8, FC4, FT8). To test the anterior-posterior distribution of effects, repeated measurement

ANOVAs were conducted comparing frontal vs. parietal electrodes. Two region of interest were computed: a region of frontal electrodes (F7, F3, Fz, F4, F8) and a region of parietal electrodes (P7, P3, Pz, P4, P8). If not separately indicated in the paper, variances of ERPs were analyzed by repeated measures as univariate tests of hypotheses for within subjects effects. After the statistical evaluation, ERPs were for presentation purposes digitally filtered using a 10 Hertz low-pass filter (51 points, FIR).

9.3 Results

9.3.1 Musical context build-up

ERP-waveforms of in-key chords are shown in Fig. 9.5. At frontal electrode sites, a negative ERP deflection was present around 550 – 600 ms after the onset of a chord. Especially at frontopolar, frontal, and frontocentral sites, the amplitude of this negative deflection depended on the position in the cadence: it declined towards the end of the cadence. This effect of position holds in particular for the last three in-key chords. An ANOVA employing position in the cadence (third vs. fourth vs. fifth chord) as within-subjects factor in the time window from 550 to 610 ms revealed an effect of position ($F(2, 32) = 4.42, p < 0.05$).³

In order to compare this effect of position in a cadence between two chords with identical harmonic function, ERPs of the in-key chords at the first and fifth position (both tonic chords) are shown in Fig. 9.6 (left). The negative ERP-deflection around 550 ms differed distinctly in amplitude between the tonic chord presented at the beginning compared to the tonic chord presented at the end of a cadence. The frontal predominance of this negative effect is illustrated in Fig. 9.6 (right).

9.3.2 Neapolitan chords

Chords at the fifth position: Brain responses of the chords at the fifth position of the chord-sequences are shown in Fig. 9.7 and Fig. A.4 (right). Compared to in-key chords, Neapolitan chords elicited from around 150 ms post-stimulus on a negative component in the ERP

³For ERPs of entire in-key chord-sequences (i.e. chords 1 – 5) from all experiments see Appendix A, those ERPs will be referred to in Experiment 5, but else not further discussed in the present study.

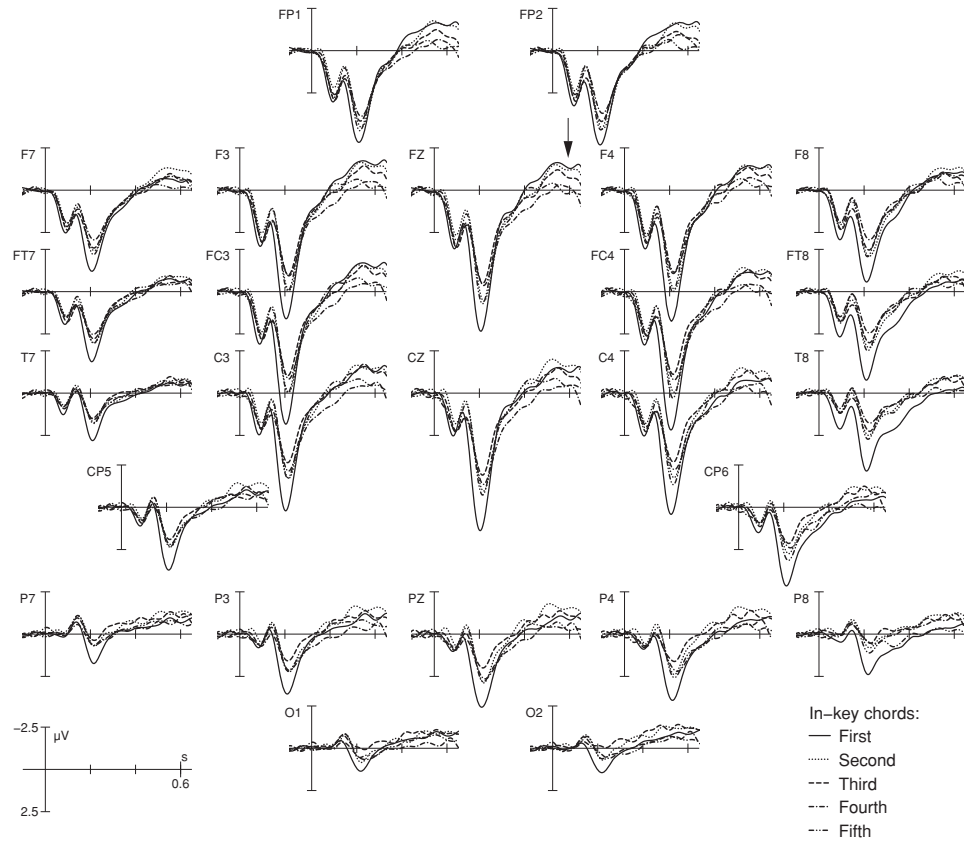


Figure 9.5: In-key chords, grand-average ERPs (first to fifth position). A late bilateral frontal negativity depended on the position of the chords in the cadence (indicated for the Fz-electrode by the arrow).

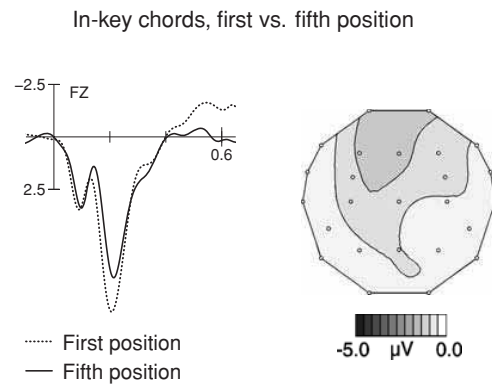


Figure 9.6: 1st vs. 5th chord (both tonic). Left: Grand-average ERPs. Right: Potential-map of the position-effect (difference-ERPs: chords at the fifth position subtracted from chords at the first position, view from top), interpolated over the time window from 550 – 610 ms.

which was right anteriorly predominant.⁴ A 2-factor ANOVA conducted for the 150 – 210 ms interval employing chord-type (two levels: in-key chords vs. Neapolitan chords) and anterior-posterior distribution (frontal vs. parietal electrodes) as factors, revealed an effect of chord-type ($F(1, 16) = 47.58, p < 0.0001$) and an interaction between the two factors ($F(1, 16) = 15.86, p < 0.005$). ANOVAs with factors chord-type and lateralization (left frontal vs. right frontal) revealed an effect of chord-type ($F(1, 16) = 55.53, p < 0.0001$), and an interaction between the two factors ($F(1, 16) = 7.79, p < 0.05$).

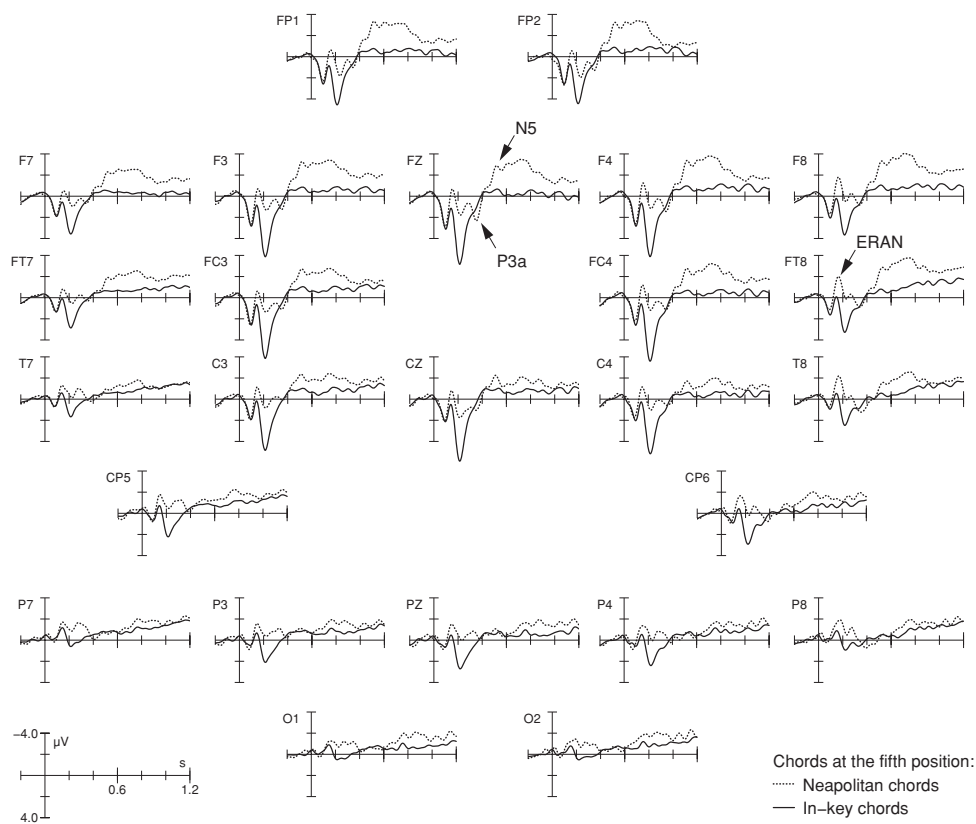


Figure 9.7: 5th position: Grand-average ERPs. Neapolitan chords elicited an early right anterior negativity (ERAN), a P3a, and a late bilateral negativity (N5).

Neapolitan chords at the fifth position also elicited a P3a (peaking around 350 ms), followed by a late negative component with an onset around 380 ms and peaking around

⁴In the following, the term *ERAN* refers to this early right anterior negativity.

550 ms. This late negative component was distributed bilaterally, and maximal at frontal sites.⁵ Two-factor ANOVAs (chord-type x anterior-posterior distribution) for the 550 – 610 ms interval yielded an effect of chord-type ($F(1, 16) = 7.05$, $p < 0.05$) and an interaction between the two factors ($F(1, 16) = 36.05$, $p < 0.0001$). Analogous ANOVAs with factors lateralization and chord-type yielded an effect of chord-type ($F(1, 16) = 18.01$, $p < 0.001$), and no interaction between the two factors.

Chords at the third position: ERPs of chords at the third position of the cadence are shown in Fig. 9.8. The waveforms of in-key chords compared to Neapolitan chords differed much less than those of the chords at the fifth position (see also Fig. A.4). Whereas Neapolitan chords at the fifth position elicited a distinct right anterior negativity with an onset of around 150 ms, this component was only weak, with a later onset, and less distinctly lateralized present in the ERP of the Neapolitan chords at the third position. Similarly, a P3a and a late bilateral negativity was merely slightly visible. In term, effects elicited by the Neapolitan chords at the third position were very similar, but smaller (and slightly later) than those elicited by the Neapolitan chords at the fifth position.

ANOVAs conducted for a 190 – 250 ms time interval employing factors chord-type and lateralization revealed a marginal effect of chord-type ($F(1, 16) = 4.03$, $p < 0.07$), but no interaction between the two factors (ANOVAs for the same time interval with factors chord-type and anterior-posterior yielded no effect). However, the lateralization is still visible in the ERPs, and will become significant when analyzed together with data of Experiment 3. Analogous ANOVAs for the late time interval (550 – 610 ms) also revealed a marginally significant effect of chord-type ($F(1, 16) = 4.06$, $p < 0.07$, no interaction between the two factors).

To test the differences in amplitude of the early and late negativities elicited by Neapolitan chords presented at the third compared to Neapolitans presented at the fifth position, two-factor ANOVAs were conducted with factors chord-type (in-key vs. Neapolitan chords) and position of chords in the cadence (3rd vs. 5th). ANOVAs for the 150-250 ms time interval (covering the relevant time window for the violation at the fifth and third position) revealed an effect of chord-type ($F(1, 16) = 62.65$, $p < 0.0001$) and an interaction between the two factors ($F(1, 16) = 17.61$, $p < 0.001$). The analogous ANOVAs for the

⁵In the following, the term *N5* refers to this late frontal negativity.

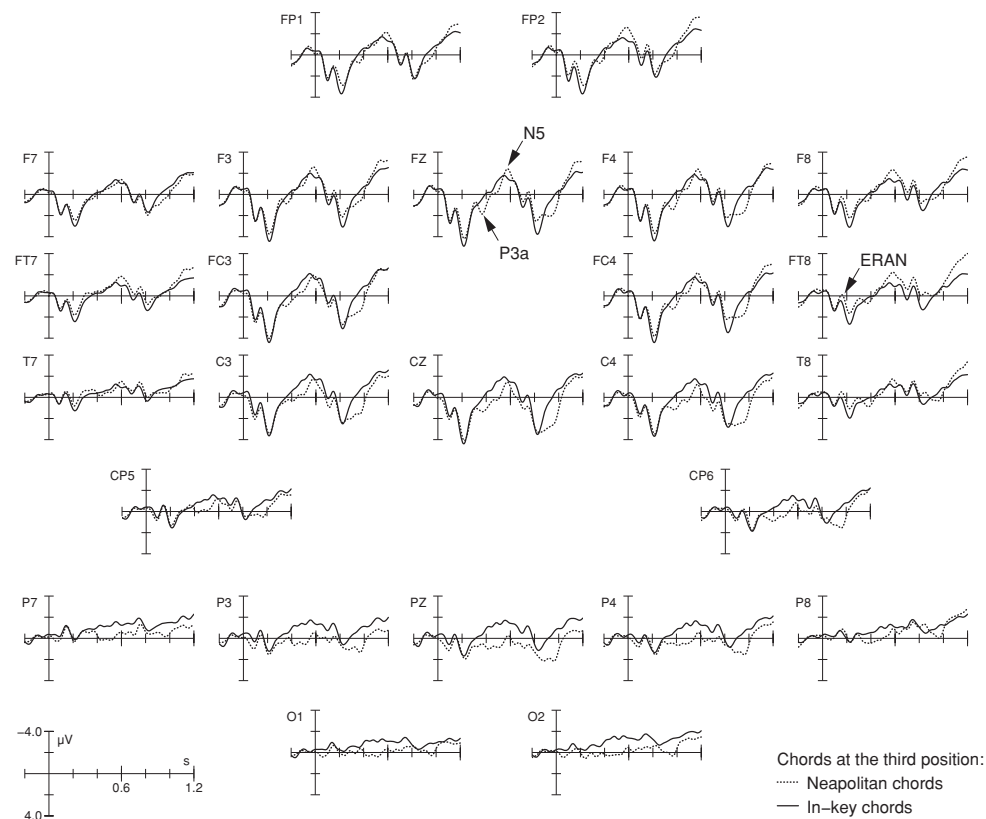


Figure 9.8: 3rd position, grand-average ERPs. Compared to in-key chords, Neapolitan chords elicited a small ERAN. The amplitude of the N5 did only slightly differ between Neapolitans and in-key chords.

550 – 610 ms interval also revealed an effect of chord-type ($F(1, 16) = 16.74, p < 0.001$), and an interaction between the two factors ($F(1, 16) = 21.30, p < 0.001$). ANOVAs thus indicate that both early and late negativities elicited by Neapolitan chords differed in amplitude between third vs. fifth position.

Neapolitan chords at the third position also elicited a posteriorly predominant positivity around 400-800 ms. An ANOVA with factor chord-type (in-key vs. Neapolitan chords) for posterior electrodes (P7, P3, Pz, P4, P8) revealed an effect of chord-type ($F(1, 16) = 9.34, p < 0.01$).

9.3.3 Secondary dominants

Brain responses to secondary dominants opposed to in-key chords are shown in Fig. 9.9 and Fig. A.5. secondary dominants tended to elicit a small, and widely distributed early negativity with an onset around 190 ms. The late bilateral frontal negativity observed for Neapolitan chords opposed to in-key chords was only tendentially present for secondary dominants.

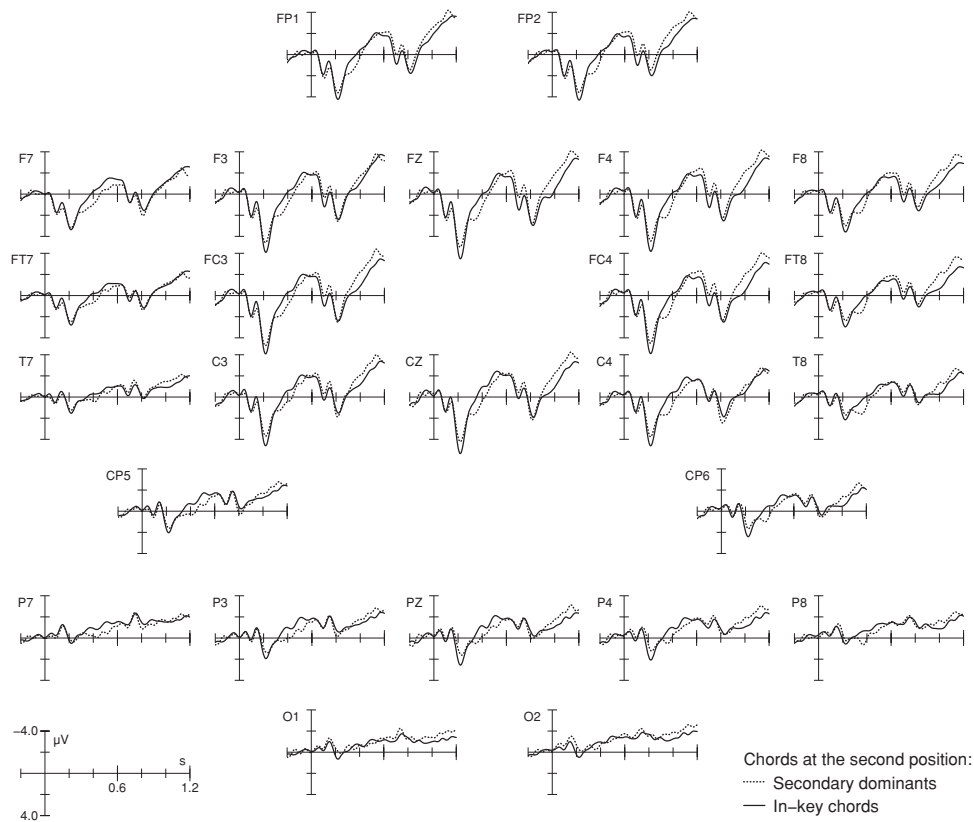


Figure 9.9: 2nd position, grand-average ERPs. Secondary dominants and in-key chords elicited similar ERPs, an early negativity was only slightly present. No statistical difference was revealed for the late (550 – 610 ms) time interval.

2-factor ANOVAs conducted for a 190 – 250 ms interval, employing chord-type (two levels: in-key chords vs. Secondary dominants) and anterior-posterior distribution (frontal vs. parietal electrodes) as factors, revealed a marginally significant effect of chord-type

($F(1, 16) = 4.45, p < 0.06$). No interaction was yielded between the two factors. Similarly, ANOVAs with factors chord-type and lateralization (left frontal vs. right frontal) revealed a marginally significant effect of chord-type ($F(1, 16) = 3.57, p < 0.08$), and no interaction between the two factors. Two-factor ANOVAs (chord-type x anterior-posterior distribution) for a 550 – 610 ms interval yielded no effect of chord-type, as well as the analogous ANOVAs with factors chord-type and lateralization.

9.3.4 Deviant instruments

Effects of chords which were infrequently played by another instrument compared to chords played on a piano will be evaluated together with data of Experiment 2 (see p. 97): Only 15 cadences with a chord played by a deviant instrument were employed, since this condition initially only served to direct the participants' attention away from the harmonic dimension of the stimulation.

9.3.5 Summary

ERP-waveforms of in-key chords elicited a negative deflection around 550 ms, which declined towards the end of the cadence. Neapolitan chords at the fifth position of a chord-sequence elicited an early negativity with an onset around 150 ms which was right-anteriorly predominant, and a late bilateral frontal negativity peaking around 500-550 ms. Neapolitan chords at the third position tended to show similar effects, though distinctly smaller than when elicited by Neapolitans at the fifth position. Secondary dominants tended to elicit a small early negativity, a late effect was slightly observable at some electrodes, but statistically not significant.

9.4 Discussion

9.4.1 Building up a musical context

In-key chords in a cadence elicited an ERP-effect which varied systematically as a function of the position in the cadence: ERP-waves of in-key chords showed a negative frontal de-

flection with a latency of about 550 ms, which decreased in amplitude towards the end of the cadence (Fig. 9.5). It is suggested that this negativity reflects a musical integration of in-key chords into the preceding harmonic context, and that the amplitude-reduction of this negativity reflects the build-up of musical context.

Cadences were composed in a way that from a music-theoretical point of view a musical context was built up, and a key was specified with progressing in-key chords towards the end of each cadence. Whereas the first two chords of a chord-sequence did not clearly establish a key (e.g. a C major chord followed by an a minor chord may establish C major, G major, F major, a minor, e minor, and d minor), a key was unequivocally established after four chords.

It has already been shown that this music-theoretically derived establishment of a tonal key is cognitively represented in listeners (e.g. Krumhansl & Kessler, 1982). While listening to a chord-sequence, listeners specify a hierarchy of harmonic stability and perceive the increasing stability of the musical context. Therefore, each chord has to be integrated into the musical context (suggested to be reflected in the present data as the negative frontal deflection peaking around 550 ms). Since all progressing in-key chords of a cadence built up a musical context (and were compatible with one single key), the developing sense of key (and thereby the specificity of the hierarchy of harmonic stability) was represented in the brains of listeners, and supported with progressing chords of a chord-sequence. Thus, the further the position of an in-key chord in the cadence, the easier it could be integrated into the musical context established by the preceding chords (suggested to be reflected in the amplitude-decline of the negative frontal deflection).

It is interesting to note that such a similar amplitude reduction of a negativity is also present in ERPs elicited by words across the course of a sentence. Commonly, this N400- (or just 'N4') reduction is interpreted as the reflection of semantic context build-up during sentence comprehension (Van Petten & Kutas, 1990). As a working term, we label the negative frontal deflection elicited by music (being maximal around 500-550 ms) the N5.

Importantly, the amplitude of the N5 was dependent rather on the position in a cadence than on the amount of different chord functions presented at each position of the cadences: The N5 is larger at the fourth compared to the fifth position (though only one chord function occurred at the fourth position), and the N5 is larger at the first compared to the fourth

position (though at both positions only one chord function occurred). Thus, the position-effect of the N5 cannot be due to regularities of the experiment itself.

9.4.2 Processing unexpected chords

Neapolitan chords at the fifth position of the chord-sequences elicited a distinct early negative deflection in the ERP which had an onset of around 150 ms (Fig. 9.7). This deflection was fronto-temporally predominant and right larger in amplitude than left. As a working label for this effect, this deflection will be termed here the early right anterior negativity, or ERAN. The ERAN is suggested to reflect the brain's response to the violation of sound expectancy: In respect to the preceding harmonic context, Neapolitan chords contained two out-of-key notes (in C-major: a flat and d flat) and therefore modulated the sound of chords in a way which was not expected in the established tonal environment. Moreover, the remaining in-key note of the Neapolitan chords (in C-major: f) was also unexpected, since it did not match with the expected tonic (in C-major: c - e - g). Neapolitan chords at the fifth position thus contained three unexpected notes.

As described in Chapter 3, the perceived distances between chords (and keys, respectively) within a tonal context follow the principles of music theory. A musical context induces expectations for related chords to follow by activating representations of distance and relatedness (e.g. Krumhansl & Kessler, 1982; Bharucha & Krumhansl, 1983; Bharucha & Stoeckig, 1986, 1987; Krumhansl et al., 1982a,b; Berent & Perfetti, 1993). Moreover, the more distant a chord in respect of a preceding harmonic context, the less expected it is. Such expectancies were clearly violated in this experiment by the Neapolitan chords, since a Neapolitan can (at least from a music-theoretical perspective) also be interpreted as the sixth-chord of the flattened 2nd degree, i.e. as a chord which is at least 5 fifths (in the sense of the circle of fifths) distant.

The principles, or rules, of music theory which are reflected in the harmonic expectancies of listeners, may be termed syntax. Interestingly, syntactic violations in auditory language experiments have been found to be reflected in the ERP as an early left anterior negativity, or ELAN (Friederici et al., 1993, ; for review see Friederici, 1998). Besides, an ERP-effect similar to the ERAN has recently been reported in a music experiment performed by Patel et al. (1998), in which unexpected chords elicited a right antero-temporal

negativity (RATN), taken to reflect the application of music-specific syntactic rules. Thus the electrical reflections of the cognitive processing of syntactic aspects of music seem to be more right distributed, while analogous reflections of the processing of syntactic aspects of language seems to be more lateralized to the left. The term ERAN can be connected to both the ELAN and the RATN. Whereas the ERAN differs from the RATN in respect of time-course and distribution (the ERAN is also clearly visible over the left hemisphere), it differs mainly from the ELAN in respect of its distribution (the ERAN looks like a mirrored ELAN).

Neapolitan chords at the fifth position also evoked a distinct late bilateral negativity which was predominant at frontal electrode sites (Fig. 9.7, right of Fig. A.4). This component peaked around 500-550 ms and has a surprisingly similar distribution over the scalp compared to the effect of musical context build-up (cf. Fig. 9.6 and right of Fig. A.4). Because the musical context build-up was reflected in an amplitude-reduction of the N5, the N5 was taken to reflect musical integration processes. Compared to the tonic at the fifth position, Neapolitan chords were harder to integrate into the preceding harmonic context. Neapolitans contained notes which were not compatible with the established tonal schema, and a strong expectancy for the tonic chord (and not for a Neapolitan) was induced by the preceding dominant seventh chord. It is thus suggested that the larger late bilateral negativity elicited by Neapolitans compared to in-key chords reflects the higher effort needed to integrate the Neapolitan chords. Interestingly, analogous processes are known from language perception, where semantically unexpected words in a sentence elicit an N400, which is taken to reflect semantic integration (see e.g. Brown & Hagoort, 1993; Holcomb & Neville, 1991).

It is further suggested that the integration of Neapolitan chords is connected to a modulation of the hierarchy of the established tonal stability, since a Neapolitan chord might for example introduce a shift to a new key. This process has already been evidenced in behavioral studies (Krumhansl & Kessler, 1982, p.360), thus this process may also be reflected in the ERPs. Besides, a modulation of the hierarchy of harmonic stability (entailing a temporary decrease of stability) is connected to an increase in demand of resolution (Bharucha & Krumhansl, 1983; Bharucha, 1984).⁶ The resulting increased expectation of further musical

⁶Neapolitan chords contain out-of-key notes which clash with the stable tonal fabric established by the

events is an effect that Krumhansl & Kessler (1982) termed the ‘strong dynamic aspect of music in time’.

The late bilateral negativity elicited by Neapolitan chords is also termed here the N5. An N5 was thus not only elicited by in-key chords, but also by Neapolitans (with an enhanced amplitude compared to in-key chords). Notably, the processing of both, a progressing in-key chord and a Neapolitan chord involves integration (entailing either specification or modulation of the hierarchy of stability), and is reflected electrophysiologically with a similar time-course and scalp distribution.

9.4.3 Effects of position

Neapolitan chords at the third position of a chord-sequence also elicited an ERAN and an N5 (Fig. 9.8, left of Fig. A.4). These two effects were distinctly smaller for the Neapolitan chords at the third position than for the Neapolitans at the fifth position. That is, the same Neapolitan chords elicited ERP-effects that differed significantly in amplitude due to the position in the chord-sequence. It is hypothesized that Neapolitan chords violated the sound expectancy of listeners to a higher degree when presented at the fifth position (compared to the third position), and that Neapolitans required a larger amount of integration when presented at the fifth position. The effect of position on both ERAN and N5 would then indicate that the ERAN is sensitive to the degree of sound-expectancy-violation, and that the N5 is sensitive to the degree of required musical integration.

Three arguments strengthening these hypotheses can be derived from both music-theory and music psychology: (1) a tonal schema was established by progressing in-key chords, each chord strengthening the hierarchy of harmonic stability and specifying the sound-expectancy for related subsequent chords.⁷ Thus the sound expectancy was violated to a higher degree by a Neapolitan chord at the end of a chord- sequence (resulting in a larger ERAN) compared to a Neapolitan presented in the middle of a sequence. Correspondingly, Neapolitan chords required a larger amount of integration with progressing build-up of the previous chords and can be resolved, for example by leading via a subsequent dominant-seventh chord into the tonic.

⁷The build up of the hierarchy of stability was suggested to be reflected in the amplitude-decline of the N5 elicited by in-key chords

harmonic hierarchy, resulting in an enlargement of the N5. (2) As stated before, Neapolitans at the fifth position contained three unexpected notes. In contrast, Neapolitans at the third position contained only two unexpected notes: the out-of-key notes a flat and d flat. The remaining in-key note f is also the root of the subdominant, a chord which was from a music-theoretical perspective to be expected at the third position. Thus, the total amount of unexpected notes (and of notes that had to be integrated) was higher at the fifth compared to the third position. Correspondingly, Neapolitans at the third position function as a subdominant variation and thereby as a pre-dominant chord. They thus were less unexpected and could be integrated more easily into the tonal context compared to Neapolitans at the fifth position. (3) Chords at the fifth position were preceded by a dominant seventh chord which induces strong expectations for the tonic chord. No such specific expectation was induced for chords at the third position.

Results demonstrate that the musical context determined the processing of both in-key and Neapolitan chords. The amplitude-difference of effects elicited in the brains of listeners can be derived from the principles of music theory. Considering that participants were ‘non-musicians’, this finding is taken here as evidence for an implicit musical ability of the human brain. That is, whether due to an inherent representation of the major/minor tonal system in the human brain, or to long-term exposure to tonal music, the brain responses of the participants of the present study can be considered as musical.

9.4.4 Late positivity and P3-effects

A late positivity (present between 400-800 ms) was elicited by Neapolitan chords at the third position, whereas Neapolitans at the fifth position did not reveal such positivity (possibly due to a compensation of the positive parietal potentials by the negative potentials of the N5 in the same latency-window). Late positivities have already been found to correspond with the processing of harmonic incongruities in music (e.g. Besson & Faita, 1995; Patel et al., 1998). However, the functional significance of this component will not be further examined in the present study, especially because it cannot be excluded that this positivity overlaps in the following experiments with a P3.

Neapolitan chords at both the third and fifth position also elicited a frontally predominant positivity (maximal around 280 ms), which is taken here as a P3a. This component

is usually elicited by salient deviant sounds in classic oddball paradigms. The presence of a P3a supports the hypothesis that the Neapolitan chords were perceived by the listeners as unexpected. The P3a is commonly representing attentional processes (e.g. Ritter & Ruchkin, 1992; Näätänen, 1992). Since the ERAN preceded the P3a, the ERAN probably correlates with subsequent allocation of attention.

9.4.5 Secondary dominants

Compared to Neapolitan chords, secondary dominants elicited only small effects. Around 190 – 290 ms, a slight early negativity was present. A late negativity (around 550 – 610 ms) was statistically not significant, though tendentially present (see right of Fig. A.5). Whereas Neapolitan chords contained two out-of-key notes, secondary dominants contained on average only 1.25 out-of-key note (see Methods). Additionally, secondary dominants were presented at the second position of a chord-sequence, that is at a position where the musical context build-up was just to begin. It is thus not yet to clarify whether the differences of effects elicited by secondary dominants compared to Neapolitans are due to the amount of out-of-key notes, or due to the position in the chord-sequence.

However, Bharucha & Stoeckig (1986, 1987) have shown that a chord primes the expectation for tonally related chords to follow. From a music-theoretical perspective, secondary dominants were tonally less closely related to the first chord compared to in-key chords. The harmonic expectations induced by the tonic at the first position of a chord-sequence were thus confirmed to a slightly higher degree by following in-key chords (compared to when followed by a secondary dominant). Thus, the early negativity elicited by secondary dominants might reflect the difference (with respect of the degree of expectancy) between in-key chords and secondary dominants (this interpretation is also compatible with the interpretations of early effects elicited by Neapolitan chords).

Besides, an N5 tended to be slightly larger in amplitude when elicited by secondary dominants (compared to in-key chords). This effect is plausible, since it was suggested that integration processes are reflected in the N5, and more integration was required for secondary dominants compared to in-key chords: Because of the ‘tonicization’, the first chord of a chord-sequence was perceived as tonic, that is as tonal center (see Schenker, 1956, and Chapter 3). The seventh of a secondary dominant is perceived as characteristic

dissonance of a dominant. Thus, secondary dominants introduced a harmonic shift towards a new tonal center, that is a tonal center *different* from that established by the previously heard tonic. Psychologically, a shift to a new tonal center requires a different hierarchy of stability (Krumhansl & Kessler, 1982; Bharucha & Krumhansl, 1983). Besides, because secondary dominants were dominants to in-key chords of the first heard tonic (that is in-key chords in respect of the first chord of a sequence), secondary dominants could easily be integrated into the larger tonal context.

Since secondary dominants elicited, like the Neapolitan chords, early and late negativities, results suggest that both chord types are processed very similar. Further investigations (with higher signal-to-noise ratios) are needed to clarify this issue.

Chapter 10

Experiment 2

Degree of violation

10.1 Introduction

The second experiment was conducted in order to test the hypothesis that both ERAN and N5 are sensitive to the degree of sound-expectancy violation (see discussion of Experiment 1). Therefore, stimulation of Experiment 2 was identical to the stimulation of Experiment 1, except that Neapolitan chords were replaced by dissonant tone-clusters (Fig. 10.1). These clusters consisted of the same amount of unexpected notes as the Neapolitan chords at corresponding positions. Contrary to Neapolitan chords (which are harmonic triads and consonant), clusters are not triads (and are thus referred to here as non-harmonic), hence sound expectancy was violated not only in respect to the occurrence of unexpected notes, but additionally in respect to harmony. For the same reasons, clusters are harder to integrate into a harmonic context compared to Neapolitan chords. As in Experiment 1, stimuli were presented under the instruction to ignore the harmonies and to count the chords played by deviant instruments.



Figure 10.1: Examples of chord-sequences containing tone-clusters (clusters are indicated by the arrows). Clusters only occurred at the third or at the fifth position of a chord-sequence.

10.2 Methods

Subjects. Participants were 18 ‘non-musicians’¹ (aged 21 to 30 years, mean 23.2, 9 females; none of them participated in Experiment 1, all were right-handed and reported to have normal hearing).

Stimuli. Stimuli were the same as in Experiment 1, except that Neapolitan chords were replaced by half-tone clusters. These clusters consisted (in respect to the tonic) either of minor sixth, major sixth, and minor seventh, or of minor second, major second, and minor third. Thus clusters contained the same amount of unexpected notes as Neapolitan chords, and were physically on average virtually identical to Neapolitan chords.

Procedure, EEG measurements and Data-Analyses were the same as in Experiment 1.

10.3 Results

10.3.1 Clusters

Clusters at the fifth position of the chord-sequences elicited compared to in-key chords an early anterior negativity (with an onset around 150 ms) which was clearly lateralized to the right (Figure 10.2, right of Fig. A.6). Clusters at the fifth position also elicited both a P3a

¹See p. 72

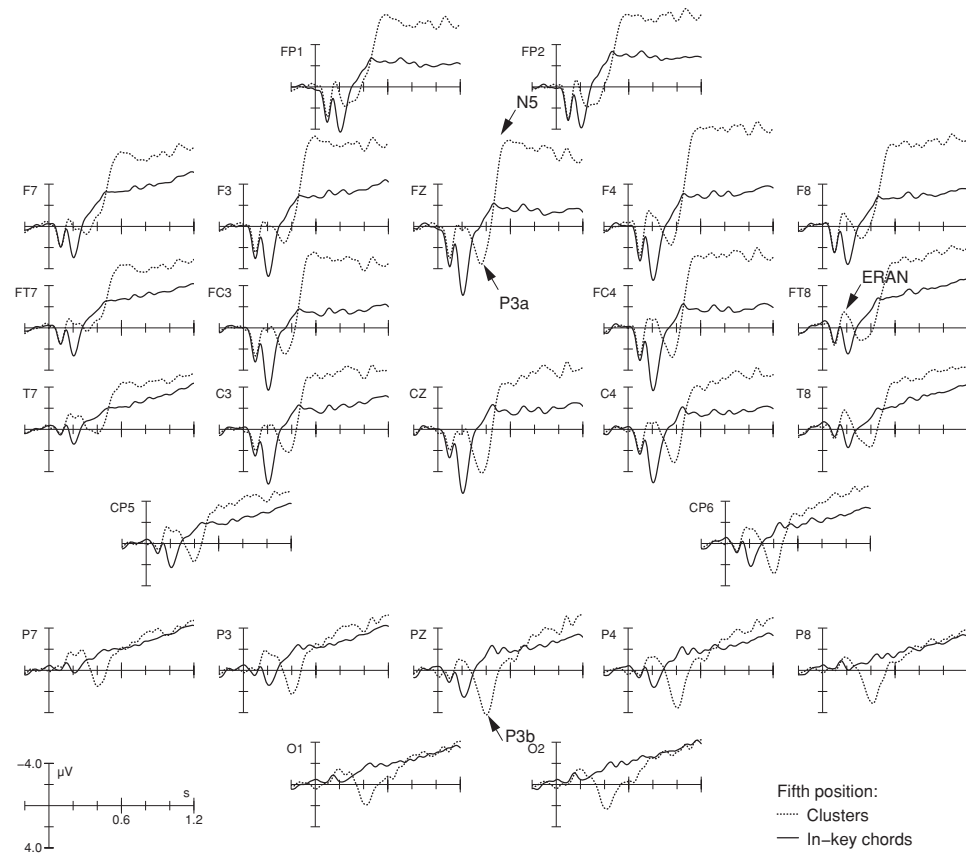


Figure 10.2: 5th position, grand-average ERPs. Clusters elicited an ERAN, a P3a, a P3b, and a late bilateral negativity (N5).

and a P3b, the latter presumably preceded by an N2b. A late frontal bilateral negativity was evoked with an onset around 500 – 550 ms.

ANOVAs with factors chord-type (in-key chords at the fifth position vs. clusters at the fifth position) and anterior-posterior distribution (frontal vs. parietal electrodes, see Methods) revealed effects of chord-type, and interactions between the two factors for both time intervals (interaction: $F(1, 16) = 14.51$, $p < 0.005$ in the 150 – 210 ms interval and $F(1, 16) = 103.36$, $p < 0.0001$ in the 550 – 610 ms interval). The analogous ANOVAs with factors chord-type (in-key chord vs. cluster) and lateralization (left frontal vs. right frontal) yielded effects of chord-type for both the early and the late interval ($F(1, 16) > 32$, p for both ANOVAs < 0.0001), as well as an interaction between the two factors for the early (150 – 210 ms) interval ($F(1, 16) = 16.03$, $p < 0.001$).

Clusters at the third position of the chord-sequences also elicited compared to in-key chords an early anterior negativity (with an onset around 150 ms), which was lateralized to the right (especially in respect of fronto-temporal electrode sites). Both P3a and P3b are also slightly visible in the ERPs of clusters, followed by a distinct late frontal bilateral negativity (onset around 500 – 550 ms, Fig. 10.3, left of Fig. A.6).

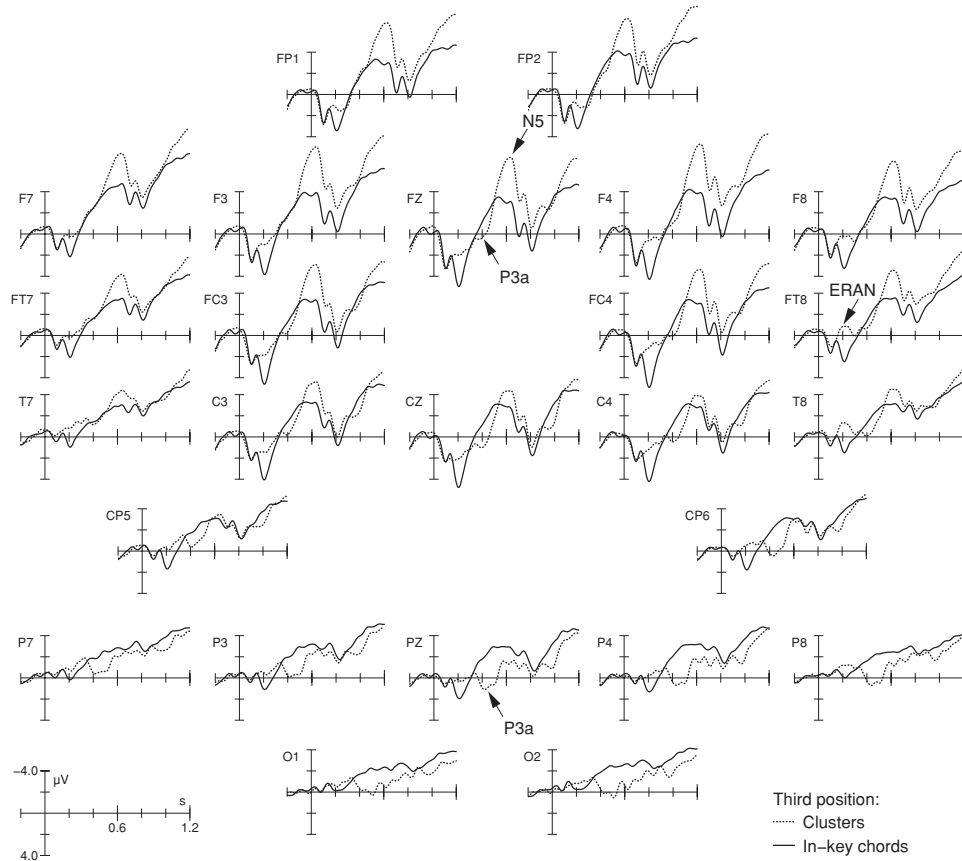


Figure 10.3: 3rd position, grand-average ERPs. Compared to in-key chords, clusters elicited distinct ERAN and N5.

ANOVAs with factors chord-type (in-key chords at the third position vs. clusters at the third position) and anterior-posterior distribution (frontal vs. parietal electrodes) revealed effects of chord-type, and interactions between the two factors for both time intervals (interaction: $F(1, 16) = 35.76$, $p < 0.0001$ in the 150 – 210 ms interval and $F(1, 16) = 54.7$, $p < 0.0001$ in the 550 – 610 ms interval). Although the right preponderance of the

early negativity is clearly visible in the ERPs (cf. FT7 vs. FT8 in Fig. 10.3, see also left of Fig. A.6), ANOVAs for the 150 – 210 ms interval with factors chord-type (in-key chords vs. clusters) and lateralization yielded an effect of chord-type ($F(1, 16) = 20$, $p < 0.0005$), but no interaction between the two factors. ANOVAs with factors chord-type and lateralization conducted for the late time interval (550 – 610 ms) revealed an effect of condition ($F(1, 16) = 28.22$, $p < 0.0001$; no interaction), analogous ANOVAs with factors chord-type and anterior-posterior distribution revealed an effect of condition ($F(1, 16) = 6.05$, $p < 0.05$) as well as an interaction between the two factors ($F(1, 16) = 54.7$, $p < 0.0001$).

10.3.2 Effects of position

As in Experiment 1, ERP-effects had larger amplitudes when elicited at the fifth position compared to when elicited at the third position of the cadence (Fig. A.6). Two-factor ANOVAs, employing chord-type (in-key chords vs. clusters) and position of clusters and chords in the cadence (3rd vs. 5th) as factors revealed an effect of chord-type and an interaction between the two factors in both early and late intervals (interaction in the 150 – 210 ms interval: $F(1, 16) = 17.77$, $p < 0.001$; interaction in the 550 – 610 ms interval: $F(1, 16) = 17.32$, $p < 0.001$).

10.3.3 Degree of violation: Clusters vs. Neapolitans

The amplitudes of both the early and the late negativities were larger when elicited by clusters at the third position (Experiment 2) compared to Neapolitan chords at the third position (Experiment 1) of a chord-sequence (Figure 10.4). Whereas Neapolitan chords at the third position in Experiment 1 elicited merely marginally significant effects, distinct early and late negativities were elicited by clusters at the same position.

In a between-subjects analysis of variance, comparing data from Experiment 1 and 2, ANOVAs were conducted separately for an early (150 – 250 ms) and the late (550 – 610 ms) time interval. Two factors were employed: stimulus type (in-key chords vs. out-of-key stimuli [i.e. clusters and Neapolitan chords]) and experiment (stimuli from Experiment 1 vs. stimuli from Experiment 2). An interaction between the two factors was

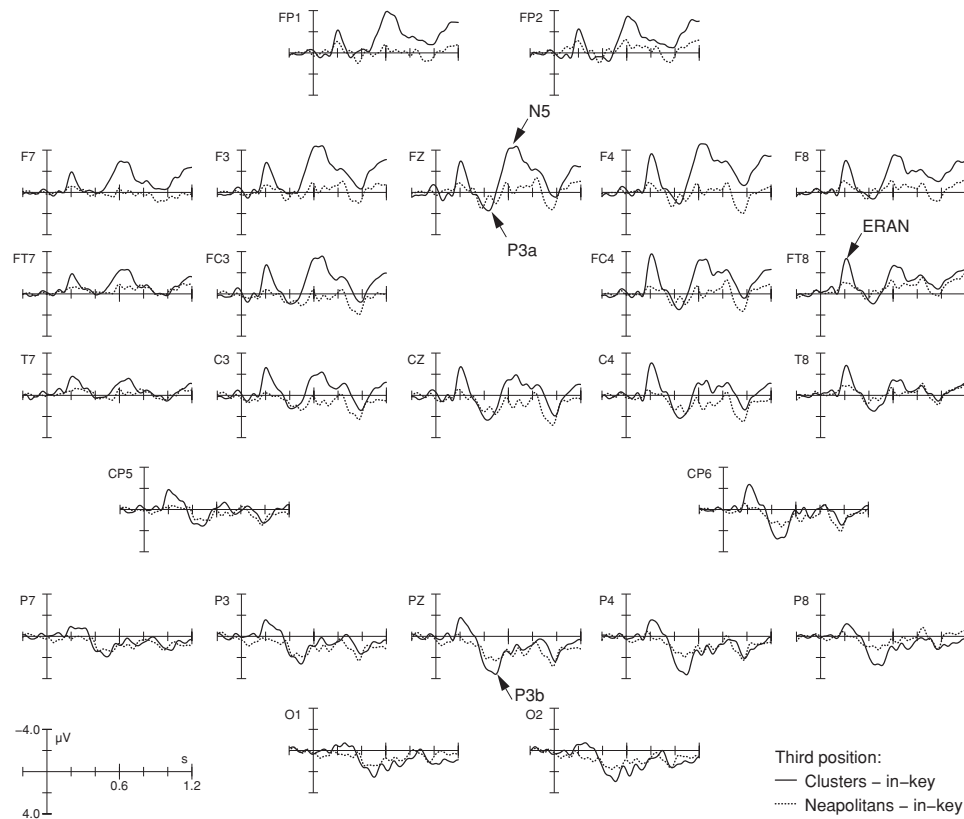


Figure 10.4: Experiments 2 vs. 1, 3rd position, effects elicited by Neapolitans and clusters (grand-average ERPs, difference-waves). Red line: effects of clusters (in-key chords subtracted from clusters), blue line: effects of Neapolitans (in-key chords subtracted from clusters).

revealed for both time intervals (150 – 250 ms: $F(1, 34) = 7.85$, $p < 0.01$; 550 – 610 ms: $F(1, 34) = 14.73$, $p < 0.0005$), indicating that both early and late negativities elicited by Neapolitans at the third position differed in amplitude from when elicited by clusters at the same position.

When elicited by clusters at the fifth position, the amplitude of the early negativity was only slightly larger compared to when elicited by Neapolitan chords at the same position (Figure 10.4). However, this difference was statistically not significant. In contrast, the amplitude of the late negativity elicited at the fifth position was distinctly larger for clusters compared to Neapolitan chords. An ANOVA (between-subjects analysis of variance, comparing data from Experiment 1 and 2) for stimuli at the fifth position with factors stimulus

type (in-key chords vs. out-of-key stimuli [i.e. clusters and Neapolitan chords]) and experiment (stimuli from Experiment 1 vs. stimuli from Experiment 2) for the 550 – 610 ms interval yielded an interaction between the two factors ($F(1, 34) = 13.15$, $p < 0.001$).

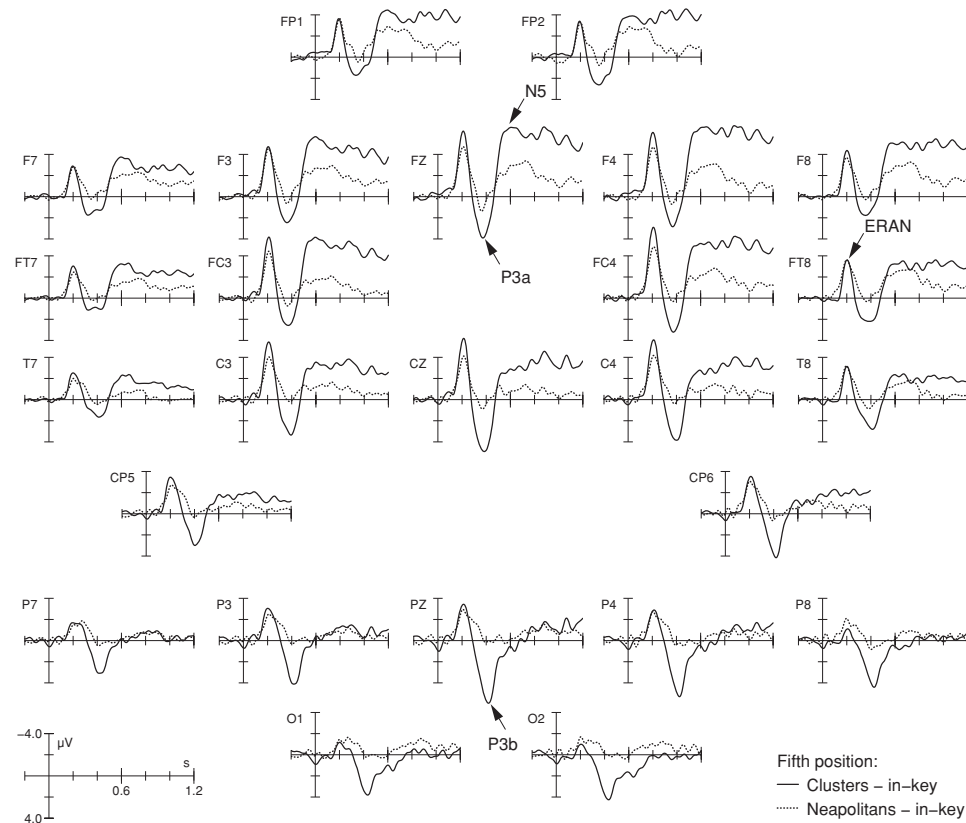


Figure 10.5: Experiments 2 vs. 1, 5th position, effects elicited by Neapolitans and clusters (grand-average ERPs, difference-waves). Red line: effects of clusters (Experiment 2, in-key chords subtracted from clusters), blue line: effects of Neapolitans (Experiment 1, in-key chords subtracted from clusters).

10.3.4 Secondary dominants

Secondary dominants opposed to in-key chords elicited both early and late effects (Fig. 10.6, Fig. A.7). From around 190 ms on, secondary dominants elicited a small, widely distributed negativity. A late bilateral frontal negativity (being maximal around 550 – 610 ms) was

larger in amplitude when elicited by secondary dominants (compared to in-key chords at the same position).

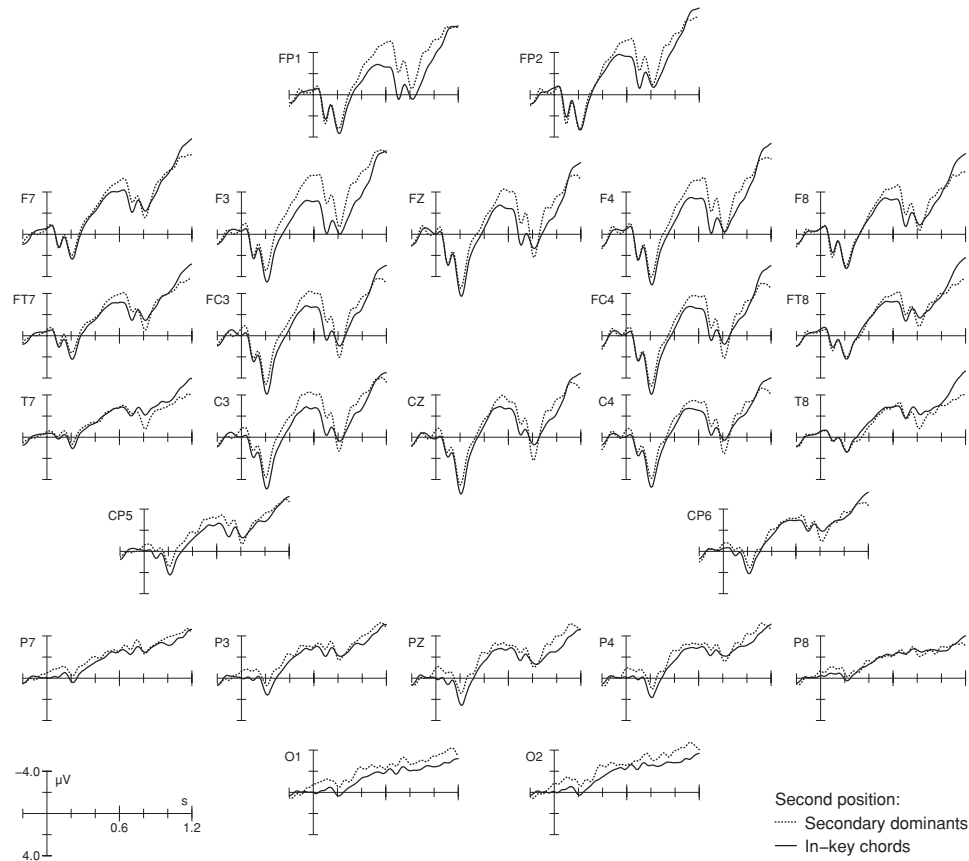


Figure 10.6: 2nd position, grand-average ERPs. secondary dominants elicited a small early negativity, and a late bilateral negativity (around 550 – 610 ms).

A 2-factor ANOVA conducted for a 190 – 250 ms interval, employing chord-type (two levels: in-key chords vs. Secondary dominants) and anterior-posterior distribution as factors, revealed an effect of chord-type ($F(1, 16) = 10.68$, $p < 0.005$), and no interaction between the two factors. An analogous ANOVA with factors chord-type and lateralization also yielded an effect of chord-type ($F(1, 16) = 6.53$, $p < 0.05$), and no interaction. An ANOVA with factors chord-type and anterior-posterior distribution for a 550 – 610 ms interval yielded an effect of chord-type ($F(1, 16) = 6.05$, $p < 0.05$), as well as an interaction between the two factors ($F(1, 16) = 4.59$, $p < 0.05$). The analogous ANOVA with factors

chord-type and lateralization revealed an effect of chord-type ($F(1, 16) = 5.29$, $p < 0.05$), and no interaction.

10.3.5 Deviant Instruments

ERPs elicited by the chords which were infrequently played on another instrument compared to chords played on a piano (averaged across all subjects from Experiments 1 and 2) are shown in Fig. 10.7. These chords elicited an early negative component developing from around 150 ms post-stimulus on. This component was larger, and wider distributed than when elicited by Neapolitan chords or clusters, and tended to be right preponderant. The early negativity was followed by an N2b-P3a-P3b complex (the N2b was centrally maximal and peaked around 220 ms, the P3a was frontally maximal and peaked around 380 ms, the P3b was parietally maximal and peaked around 400 ms). Following the P3a-P3b, a late frontal negativity developed peaking around 500 – 550 ms. When elicited by the deviant instruments, this late frontal negativity tended to be larger compared to when elicited by Neapolitan chords or clusters. Moreover, the late negativity was larger at right than left electrode sites.

An ANOVA with factors instrument (two levels: in-key chords played on a piano vs. chords played on deviant instruments) and lateralization conducted for the 150 – 210 ms interval revealed an effect of instrument ($F(1, 34) = 47.67$, $p < 0.0001$), and a marginal interaction between the two factors ($F(1, 34) = 2.95$, $p < 0.1$). The analogous ANOVA (factors instrument x lateralization), conducted for the 550 – 610 ms interval also revealed an effect of instrument ($F(1, 34) = 39.83$, $p < 0.0001$) and an interaction between the two factors ($F(1, 34) = 10.59$, $p < 0.005$).

10.3.6 Summary

Both clusters at the third and fifth position of the cadence elicited an early anterior negativity with an onset around 150 ms, and a late bilateral frontal negativity peaking around 500-550 ms. When elicited at the fifth position, effects were larger than when elicited at the third position. Compared to Neapolitan chords of Experiment 1, effects elicited by clusters at the third position were larger. Secondary dominants elicited an early negative effect, and

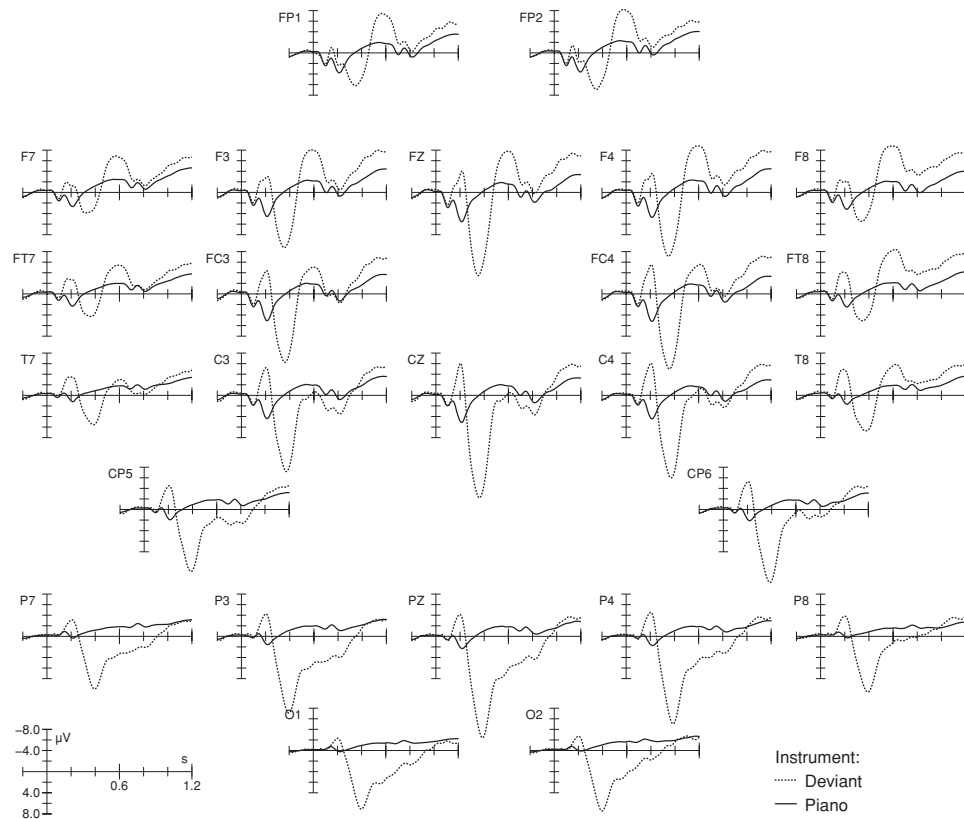


Figure 10.7: Deviant instruments (data from Experiments 1 and 2 pooled). Grand-average ERPs from chords infrequently played by deviant instruments compared to chords played on a piano (note the different amplitude scaling compared to previous figures). Deviant instruments elicited from around 150 ms post-stimulus on an early anterior negativity (followed by a P3a), and a late negativity which was lateralized to the right (preceded by N2b and P3b).

a late frontal bilateral negativity. Deviant instruments also elicited an early negativity which tended to be right preponderant, and a late frontal negativity which was larger at right than left electrode sites.

10.4 Discussion

10.4.1 Processing strong musical violations

Clusters at the third and fifth position of the chord-sequences elicited an ERAN. Though the lateralization of the ERAN elicited by clusters at the third position was clearly visible in the ERPs (especially at FT7 vs. FT8), it was statistically not significant. However, taking into account the results of all four experiments of the present study, the early negativity elicited by clusters at the third position is regarded here as an ERAN. Clusters contained out-of-key notes and were not harmonic, the chords preceding clusters were all harmonic, in-key, and built up a harmonic context. Clusters thus violated the sound expectancy of listeners, which is (as in the discussion of Experiment 1) suggested to be reflected in the ERAN. Clusters at both the third and the fifth position also elicited a late bilateral negativity (the N5). The N5 was hypothesized to reflect musical integration processes. Though clusters can only hardly be integrated into a harmonic context, the presence of the N5 elicited by clusters is suggested to reflect that nevertheless effort of integration was invested. Notably, this is compatible with results found in N400-experiments, where an N4 was elicited by legal non-words (e.g. Doyle et al., 1996).

10.4.2 Effects of position

As in Experiment 1, the amplitudes of both ERAN and N5 were larger when elicited at the fifth than when elicited at the third position of a chord-sequence (Fig. A.6). It was suggested that the effect of position in the cadence on both ERAN and N5 is due to the preceding musical context (see discussion of Experiment 1).²

Results of the present experiment also indicate that the smaller amplitudes of ERAN and N5 elicited in Experiment 1 by Neapolitans at the third compared to the fifth position were not merely due to the fact that Neapolitans at the third position are culturally more accepted (due to the cultural convention that Neapolitans function as a substitute of the subdominant

²Notably, the present data moreover indicate that the effects reflected in both ERAN and N5 are not mainly induced by a dominant seventh chord (which induced an strong expectancy for the tonic), since both effects were clearly elicited by clusters at the third position (which were never preceded by a dominant seventh chord).

and thereby as a pre- dominant chord): Clusters also elicited smaller effects at the third compared to the fifth position.

Besides ERAN and N5, clusters elicited also a P3a, an N2b and a P3b. These components were larger when elicited at the fifth position. Especially in respect of the P3a, this finding supports the interpretation of the ERAN as reflecting sound-expectancy violation: it is plausible to assume that sounds allocate more attention when they are more unexpected (cf. also Näätänen, 1992). The P3b was most presumably elicited by the decisional processes of the listeners (e.g. Pritchard, 1981; Näätänen, 1992): Participants reported that they were tempted to count clusters as deviant instruments, especially when clusters occurred at the fifth position.

10.4.3 Effects of degree of violation

Clusters at the third position elicited both distinct early and late negativities whereas Neapolitan chords at the third position (Experiment 1) showed only marginally significant effects (Fig. 10.4). It was hypothesized that the amplitude of the ERAN (and, consequently, of the N5) is a function of the degree of expectancy induced by the preceding musical context. ERPs elicited by clusters confirm this assumption: clusters violated the sound expectancy in respect to both tonality and harmony. That is, besides out-of-key notes, clusters introduced additionally a frank dissonance. Thus, the ERAN evoked by clusters at the third position was larger in amplitude than when elicited by Neapolitans.

When elicited at the fifth position of a chord-sequence, the amplitude of the ERAN did virtually not differ between clusters and Neapolitans (Fig. 10.5). Given the difference in amplitude observed for the third position, it is proposed that the almost non-difference in the amplitude of the ERAN elicited by a harmonic deviancy at the fifth position is due to the circumstance that it was already maximal in Experiment 1 (and therefore did not increase in Experiment 2). However, both clusters at the third and fifth position also elicited a larger N5 than the Neapolitan chords at the corresponding positions (suggested to reflect that more effort had to be invested in the integration of clusters compared to the integration of Neapolitans).

Scalp-distribution of both ERAN and N5 did virtually not differ when elicited by Neapolitans compared to clusters (see Fig. A.4 vs. Fig. A.6). Thus, the present data do not yield that the neural processes elicited by a dissonant sound differ essentially from effects elicited by harmonically unrelated but consonant sounds (processes different merely in respect of amplitudes of the electric potentials). Importantly, since both clusters and Neapolitans contained the same amount of unexpected notes, the effects of dissonance (inherent in the data of clusters) could be investigated without confounding with the factor of harmonic expectancy (analyzed with data of Neapolitan chords in Experiment 1).

10.4.4 Secondary dominants

Secondary dominants elicited around 190 – 290 ms a small early negativity. Besides, the N5 (maximal around 550 – 610 ms) elicited by secondary dominants was larger compared to in-key chords (Fig. 10.6, Fig. A.7).

As in the discussion of Experiment 1, the early negativity is suggested to reflect the difference (with respect of the degree of expectancy) between in-key chords and secondary dominants. Correspondingly, the larger N5 of secondary dominants is suggested to reflect the integration of secondary dominants into the larger tonal context, and the modulation of the hierarchy of stability connected to a shift toward a new tonal center.

In both Experiments 1 and 2, the early negativity was not lateralized to the right. This might be due to the fact that (contrary to Neapolitan chords or clusters) secondary dominants did not clearly violate a sound expectancy. Though secondary dominants were less closely related to the first chord of the chord-sequence (compared to in-key chords at the second position), secondary dominants contained (compared to Neapolitans or clusters) on average only one out-of-key note, and were presented at the beginning of a chord-sequence, where the harmonic expectancies of listeners were rather unspecified.

10.4.5 Deviant instruments

Deviant instruments elicited a P3a-N2b-P3b complex, reflecting the attentional and decisional processes of listeners following the occurrence of a deviant sound. Besides, deviant

instruments also elicited compared to piano-chords early and late negativities (Fig. 10.7). The lateralization of the early negativity was less distinct than when elicited by clusters or Neapolitans. In contrast, the late negativity was lateralized to the right.

The early negativity is presumably at least partly due to N1 refractoriness and mismatch negativity (since the spectral information of deviant instruments differed from that of the piano; see e.g. Schröger, 1998). However, due to the huge effect of the early negativity (over 10 microvolts), an additional effect is regarded here as most probable. Since the sound of a piano was expected, and this expectancy was violated by the occurrence of a deviant instrument, it is thus suggested that this sound-expectancy violation might also be reflected in the early negativity (similar to when the sound expectancy is violated in the harmonic dimension).

The late negativity is also taken to reflect mainly integration processes: chords played by deviant instruments were spectrally deviant, but harmonically correct. Thus these chords fitted in the harmonic context, though the earlier processing (reflected in the early negativity) reported a violation of sound-expectancy. The late negativity is therefore also termed N5. The abrupt ending of the N5 elicited by deviant instruments (compared to the N5 elicited by Neapolitan chords) might be due to a 're-orienting' towards the harmonic dimension of the cadence (Schröger & Wolff, 1998).

The lateralization of the N5 elicited by deviant instruments (compared to when elicited by a harmonic deviation) may be due to a different neural mechanism connected to the processing of timbre (as suggested e.g. by Platel et al. (1997); Gaschler-Markefski et al. (1998)). It might also be due to the low probability of the occurrence of deviant instruments (only 10% of the cadences contained a chord played on a deviant instrument, and each cadence contained 5 chords, thus only 1 out of 50 chords was played by a deviant instrument). However, the functional significance of the lateralization will not be further determined in this thesis.

Chapter 11

Experiment 3

Effects of task-relevance

11.1 Introduction

Notably, all formerly discussed ERP-effects were elicited under the instruction to ignore the harmonic context and to detect the deviant instruments. This suggests that both ERAN and N5 are elicited even when unexpected musical events are not task-relevant. In order to determine a possible influence of the task-relevancy of unexpected chords on ERAN and N5, the same stimuli as in Experiment 1 were presented under the condition of focusing the participants' attention onto the Neapolitan chords: Participants were informed about the presence of Neapolitan chords and their nature, and instructed to detect the Neapolitan chords. The deviant instruments were to be ignored.

11.2 Methods

Subjects and Stimuli. 18 'non-musicians'¹ participated in the experiment (aged 21 to 29 years, mean 23, 9 females; none of them participated in Experiment 1 or 2). All participants were right-handed and reported to have normal hearing. Stimuli were the same as in Experiment 1.

¹See p. 72

Procedure. Procedure was identical to Experiment 1, except that participants were informed about Neapolitan chords and their nature, and instructed to respond to the Neapolitan chords by immediately pressing a response button. As examples, two cadences exclusively consisting of in-key chords were presented, as well as two cadences containing a Neapolitan chord at the third, and two cadences with a Neapolitan chord at the fifth position. Subjects were also informed about the infrequent occurrence of deviant instruments and instructed to ignore these deviant instruments.

EEG measurements and Data-Analyses were analog to Experiments 1 and 2.

11.3 Results

11.3.1 Behavioral Data

Behavioral data are shown in Tab. 11.1. Participants detected more Neapolitan chords at the fifth position (on average 79%) than at the third position (58%; ($F(1, 17) = 57.77$, $p < 0.0001$)). Reaction times were on average 560 ms for Neapolitans at the fifth position, and 584 ms for Neapolitan chords at the third position (n.s.). The false-alarm rate was similar for both Neapolitans at the third and at the fifth position (below 4%).

Position	Reaction Times	Hits (in %)	False Alarms (in %)
3 rd	584 (74)	58 (21)	3.9 (3.6)
5 th	560 (158)	79 (21)	3.9 (2.9)

Table 11.1: Behavioral data (grand averages), separately for chords at the third and fifth position. Mean and standard deviation (in brackets) of reaction times, hit percentages (with respect to Neapolitan chords), and false alarm percentages (with respect to in-key chords). Means were first calculated for each subject, and then averaged across subjects.

11.3.2 ERP-effects

Chords at the fifth position: Figure 11.1 presents the brain responses of detected and undetected Neapolitan chords at the fifth position opposed to in-key chords from the same position. Especially at right anterior electrode sites, ERPs of Neapolitan chords were from

approximately 150 ms on consistently more negative than the ERPs of in-key chords. ERPs of detected compared to ERPs of undetected Neapolitan chords differed particularly at peripheral right anterior-temporal electrode sites (F8, FT8), where the ERP of detected Neapolitans is more negative compared to the ERP of undetected chords. The detected, but not the undetected Neapolitan chords, evoked a P3a (peaking around 380 ms) and a P3b (peaking around 400 ms), presumably preceded by an N2b. The P3b was followed by a late bilateral frontal negative component peaking around 500-550 ms. This late negativity is visible in the ERPs of both detected and undetected Neapolitan chords, but considerably more negative when elicited by undetected Neapolitans.

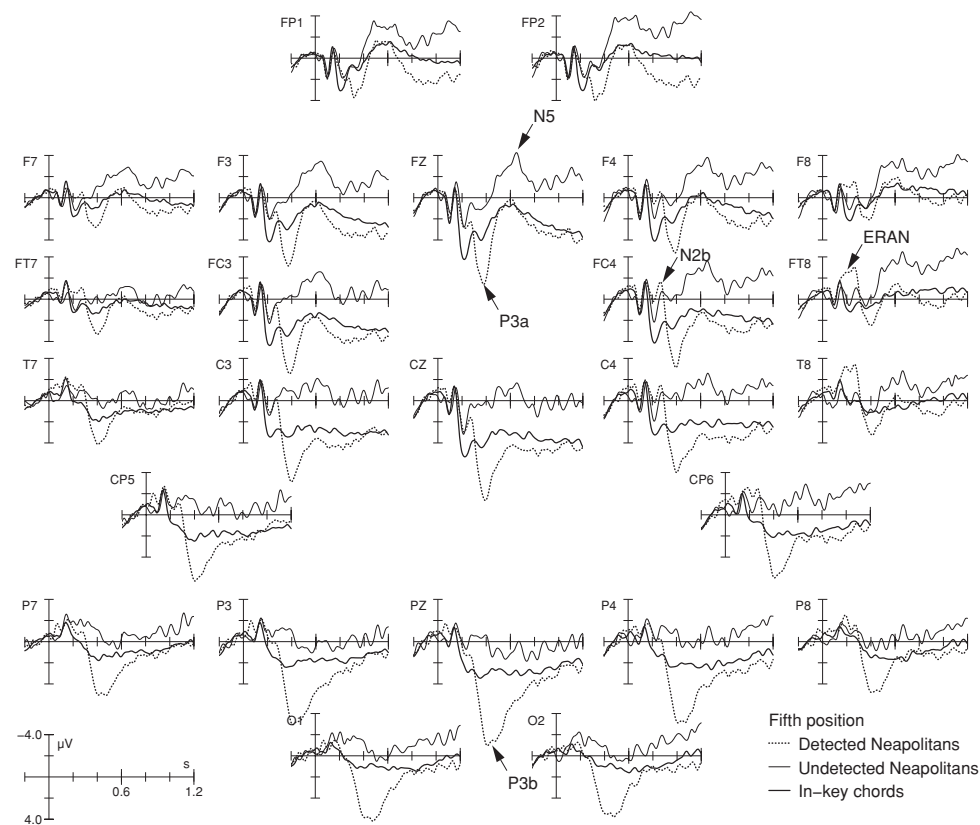


Figure 11.1: 5th position, grand-average ERPs of detected and undetected Neapolitan chords compared to in-key chords (unrejected trials cumulated over all participants). Especially at right fronto-temporal electrode sites, ERPs of detected Neapolitans are around 150-300 ms distinctly more negative than undetected Neapolitans and in-key chords. Detected, but not undetected Neapolitans elicited a large P3. Vice versa, undetected, but not detected Neapolitans elicited a large N5.

Since only 21% of the Neapolitans at the fifth position were undetected, no statistical analyses were carried out for detected and undetected Neapolitans separately. An ANOVA for the 150 – 210 ms time interval employing chord-type (in-key vs. all Neapolitan chords at the fifth position) and lateralization as factors revealed an effect of chord-type ($F(1, 16) = 54.78$, $p < 0.0001$), and an interaction between the two factors ($F(1, 16) = 9.92$, $p < 0.01$). An ANOVA conducted for the same time interval with factors chord-type and anterior-posterior distribution, yielded an effect of chord-type ($p < 0.0001$), as well as an interaction between the two factors ($F(1, 16) = 11.86$, $p < 0.005$). An ANOVA for the 550 – 610 ms time interval, employing chord-type and lateralization as factors, yielded merely a marginal effect of chord-type ($F(1, 16) = 3.9$, $p < 0.07$, no interaction between the two factors).

Chords at the third position: Figure 11.2 presents the ERP-waveforms of detected and undetected Neapolitan chords at the third position compared to in-key chords at the third position. Detected (but not undetected) Neapolitans at the third position elicited an early negative component which was right anteriorly predominant, had an onset around 190 ms, and peaked around 230 ms (i.e. the latency of this component was longer than when elicited by Neapolitans at the fifth position). Like Neapolitan chords at the fifth position, and contrary to the ERPs of undetected Neapolitans, a P3a (peaking around 380 ms) and a P3b (peaking around 400-450 ms) is present in the ERPs of detected Neapolitan chords. The P3a-P3b was preceded by a negative deflection, peaking around 290 ms, and being right-centrally maximal. This deflection is suggested to be an N2b.

The N2b-P3-complex was followed by a negative deflection which peaked around 500-550 ms. This negative deflection was more negative in the ERPs of undetected Neapolitan chords at the third position compared to the ERPs of in-key chords. In the ERP-waveform of detected Neapolitans compared to in-key chords, this deflection is more positive, especially at parietal sites. ANOVAs were conducted for a time interval ranging from 190 – 250 ms (this time window was chosen due to the longer latency of the early right anterior negativity for Neapolitans at the third position), employing factors chord-type (detected Neapolitans vs. in-key chords) and lateralization (left frontal vs. right frontal). An effect of chord-type ($F(1, 16) = 7.99$, $p < 0.05$) as well as an interaction between the two factors ($F(1, 16) = 4.88$, $p < 0.05$) was found. When levels of chord-type were undetected

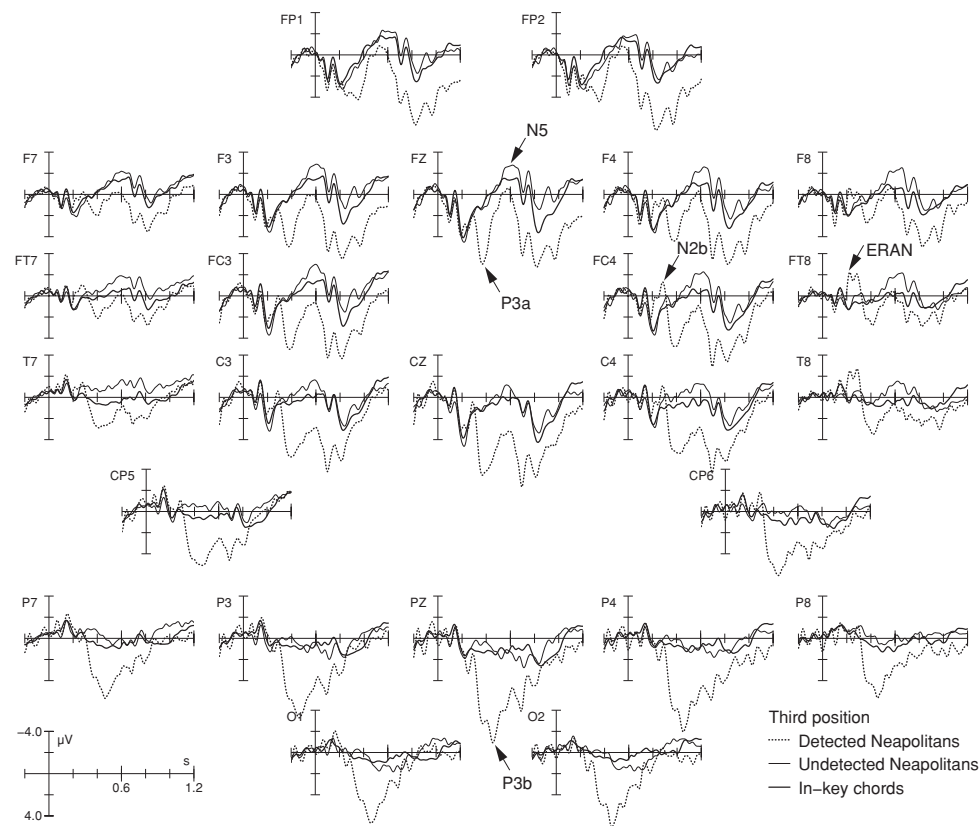


Figure 11.2: 3rd position, grand-average ERPs of detected and undetected Neapolitan chords. Essentially, compared to effects elicited at the fifth position, effects were similar but smaller when elicited at the third position.

Neapolitans vs. in-key chords, analogous ANOVAs revealed no effect of condition. In contrast, analogous ANOVAs for the 550 – 610 ms interval revealed an effect when levels of chord-type were undetected Neapolitans vs. in-key chords ($F(1, 16) = 12.8$, $p < 0.005$, no interaction between the two factors), but not when levels were detected Neapolitans vs. in-key chords. ANOVAs employing the factor detection (detected vs. undetected Neapolitans), carried out for the 190 – 250 ms interval, revealed an effect of detection ($F(1, 34) = 8.83$, $p < 0.01$).

11.3.3 ERPs: Effects of position

As in Experiment 1, the early right anterior negativity was larger when elicited by Neapolitans at the fifth position compared to Neapolitans at the third position. ANOVAs with factors position (chords at the third position in the time interval from 190 – 250 ms vs. chords at the fifth position in the time interval from 150 – 210 ms) and chord-type (Neapolitans vs. in-key chords) revealed an interaction between the two factors ($F(1, 16) = 22.19, p < 0.0005$). Due to the P3-effects, position-effects for the late negativities were not statistically evaluated.

11.3.4 Effects of task-relevance

Figure 11.3 shows the difference-waveforms from the chords of the fifth position of Experiment 3 (detected and undetected Neapolitan chords subtracted from in-key chords at the same position), opposed to the analogous (but task-irrelevant) stimuli of Experiment 1. The waveforms are highly similar up to 300 ms, statistical analyses did not reveal any difference: between-subjects analyses of variances comparing data for the chords at the fifth position from Experiment 1 and 3, conducted for the 150 – 210 ms interval with factors chord-type (in-key vs. Neapolitan chords at the fifth position) and experiment (1st vs. 3rd), revealed no interaction between the two factors. A distinct P3b is visible in the ERPs of Experiment 3, but not in those of Experiment 1. The late negativity (from around 500 ms on) is also larger in the waveforms of Experiment 1 compared to Experiment 3. Whereas the late negativity was clearly significant in Experiment 1 ($p < 0.001$), it was only marginally significant in the present experiment ($p < 0.07$).

Correspondingly, the early right anterior negativity elicited by all Neapolitan chords at the third position did virtually not differ between Experiment 1 and 3. For a between-subjects analyses of variances, comparing data from Experiment 1 and 3, ANOVAs were conducted for an interval from 190-250 ms employing 3 factors: chord-type (Neapolitans vs. in-key chords at the third position), experiment (1st vs. 3rd), and lateralization (left frontal vs. right frontal). Effects were revealed for chord-type ($F(1, 34) = 4.62, p < 0.05$), an interaction was yielded between factors chord-type x lateralization ($F(1, 34) = 8.44, p < 0.01$), and no interaction was yielded between factors chord-type x experiment. The analo-

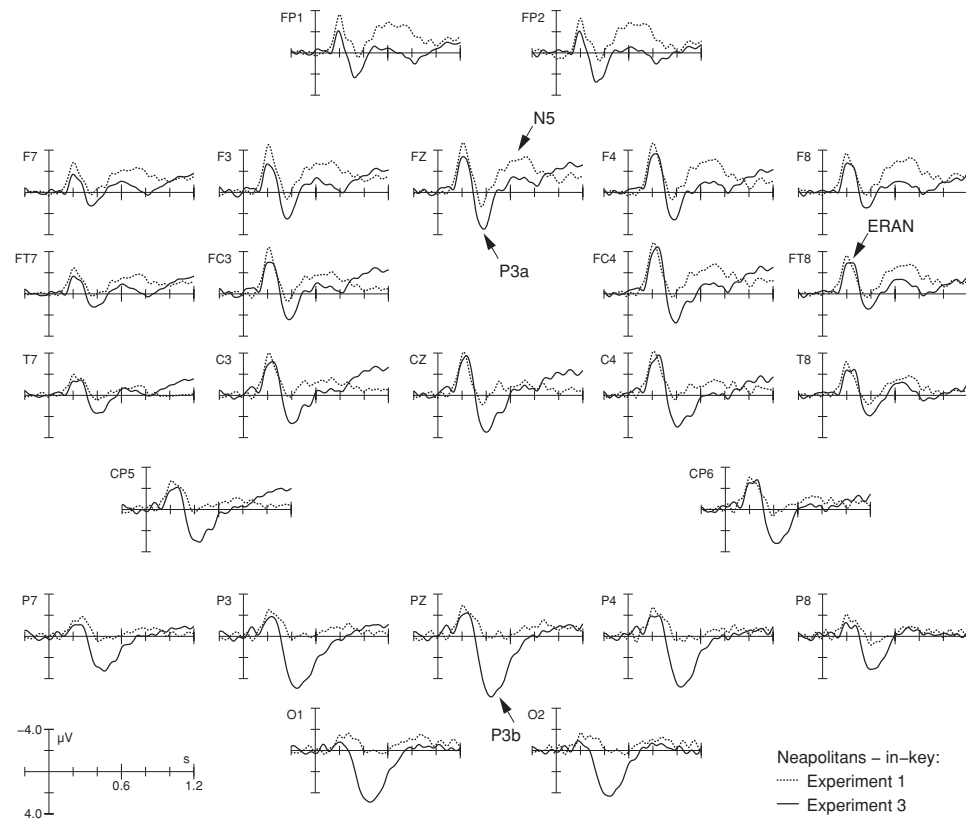


Figure 11.3: Experiments 3 vs. 1, 5th position, grand-average difference-waves (in-key chords subtracted from Neapolitan chords). Both ERPs do virtually not differ with respect of the ERAN, whereas the N5 elicited in Experiment 1 (task-irrelevant Neapolitans) was larger than in Experiment 3 (where Neapolitans were to be detected).

gous ANOVAs for the 550 – 610 ms window revealed an effect of chord-type ($F(1, 34) = 4.25$, $p < 0.05$), no interaction between factors chord-type x lateralization, and no interaction between factors chord-type x experiment.

11.3.5 Secondary dominants

Figure 11.4 shows the brain responses to the secondary dominants opposed to in-key chords. From around 190 ms poststimulus on, the ERP-waves of secondary dominants are at all electrode sites more negative compared to the ERP-waves of in-key chords (left of Fig. A.9). Secondary dominants also elicited a late bilateral negativity, peaking around 550-600 ms, and being frontally predominant (right of Fig. A.9).

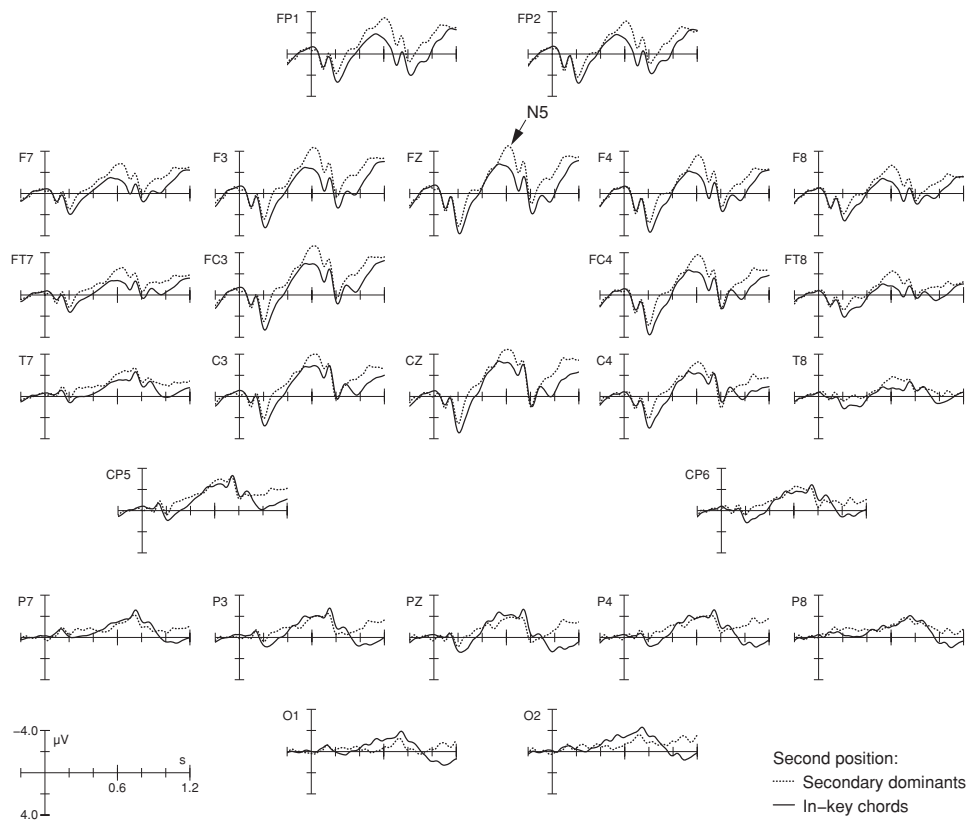


Figure 11.4: 2nd position, grand-average ERPs. secondary dominants opposed to in-key chords elicited a widely distributed early negativity, and an N5.

A 2-factor ANOVA conducted for a 190 – 250 ms interval employing chord-type (two levels: in-key chords vs. Secondary dominants) and anterior-posterior distribution as factors, revealed an effect of chord-type ($F(1, 16) = 22.23$, $p < 0.0005$), no interaction was yielded between the two factors. Similarly, ANOVAs with factors chord-type x lateraliza-

tion revealed an effect of chord-type ($F(1, 16) = 24.23$, $p < 0.0005$), and no interaction between the two factors. A two-factor ANOVA with factors chord-type and anterior-posterior distribution for the 550 – 610 ms time-interval yielded an effect of chord-type ($F(1, 16) = 9.71$, $p < 0.01$) and an interaction between the two factors ($F(1, 16) = 22.21$, $p < 0.0005$). An analogous ANOVA with factors chord-type and lateralization yielded an effect of chord-type ($F(1, 16) = 30.72$, $p < 0.0001$), and no interaction between the two factors.

11.3.6 Deviant Instruments

For the same reason as in Experiment 1 and 2, effects of chords which were infrequently played by another instrument compared to chords played on a piano will not be evaluated yet, but together with data of Experiment 4.

11.3.7 Summary

More Neapolitans were detected at the fifth than at the third position of the chord-sequences. Early right antero-temporal negativities elicited by Neapolitan chords at the fifth position were larger for detected than undetected Neapolitans. Compared to Experiment 1, the early negativity elicited by all Neapolitan chords (detected and undetected averaged) did virtually not differ between the experiments, independent on the position in the cadence. The late negativity was smaller in amplitude when elicited by Neapolitans at the fifth position compared to Experiment 1. When data of chords at the third position from Experiments 1 and 3 were pooled, the lateralization of the early effect elicited by Neapolitan chords was significant. While detected Neapolitans at the third position elicited an ERAN, this component was not present in the ERPs of undetected Neapolitans. Detected Neapolitans at both the third and fifth position elicited a P3b. Undetected Neapolitans at the third position elicited a distinct late bilateral negativity. Secondary dominants elicited a widely distributed early negativity, and a late bilateral frontal negativity.

11.4 Discussion

11.4.1 Effects of position

Participants detected more Neapolitan chords at the fifth compared to the third position. This could only be due to a greater saliency of Neapolitan chords when presented at the fifth position of the cadence. Reaction times for both Neapolitans at the fifth and third position were on average below 600 ms, thus the higher hit rate at the fifth position could not be due to the longer duration of Neapolitan chords at the fifth position, or to any other physical difference between the chords. The greater saliency of Neapolitan chords at the fifth position is also reflected in the ERPs: as in Experiment 1, the amplitudes of both ERAN and N5 were larger when elicited by Neapolitan chords at the fifth position (Fig. A.8). As ERPs of Experiment 1 already outlined, the saliency of a Neapolitan also seems to affect the latency of the ERAN, which was prolonged when elicited by Neapolitans at the third position.

It is unlikely that the higher detection rate of Neapolitans at the fifth position (i.e. the greater saliency) was just due to the experimental paradigm, in which only two different chord-functions occurred at the fifth position (tonic and Neapolitan), compared to several chord-functions at the third position (leading to an easy tonic/non-tonic discrimination at the fifth position). The greater saliency is reflected in the larger amplitudes of effects elicited by unexpected sounds occurring at the fifth vs. third position, and is consistent over Experiments 1-3. Importantly, these amplitude-differences were even present in Experiment 2, where stimuli at both the third and fifth position could easily be discerned into harmonic chords vs. non-harmonic clusters. As in the discussions of Experiments 1 and 2, it is rather proposed that the foregoing musical context determined the processing of unexpected chords in respect of amplitudes and latencies of effects.

11.4.2 Effects of task-relevance

The statistical analyses did not indicate any difference in amplitude of the ERAN between Experiments 1 and 3 (independently of whether elicited at the third or at the fifth position). Thus, for the time being, this supports the hypothesis that the task-relevance of Neapolitan

chords has virtually no influence on the ERAN elicited by all Neapolitans. As the ERAN elicited by detected Neapolitans was larger in amplitude compared to undetected Neapolitans, the ERAN seems to reflect processes which determine the conscious saliency (and thus detectability) of acoustic events. ERPs also demonstrate that the ERAN is not a frontally distributed N2b: The ERAN was found to be present already around 190 ms, thus the N2b is presumably the peak in the ERPs of detected Neapolitans around 290 ms (being maximal at right-central electrode sites).

The N5 elicited by all (detected and undetected) Neapolitan chords at the fifth position is still visible in Experiment 3, where Neapolitans were task-relevant. The N5 was only marginally significant in Experiment 3, but distinctly significant in Experiment 1 (where Neapolitan chords were task-irrelevant; see Fig. 11.3). The reduced N5 in Experiment 3 is most presumably due to positive potentials with an onset around 300 ms (P3b) elicited by detected Neapolitans which compensated negative potentials in the same latency window (the P3-component is still visible around 600 ms after the onset of detected Neapolitan chords).

11.4.3 Effects of (non-) detection

Interestingly, deviant chords were differently processed compared to in-key chords, even when subjects did not consciously realize (i.e. detect) the occurrence of these deviant chords: undetected Neapolitan chords at the third position of the cadence elicited a distinct N5, though no ERAN was present (Fig. 11.2). This suggests that the processes reflected in the ERAN and the N5 (see discussion of Experiment 1) are independent from each other. An explanation of this independence refers to the discussion of Experiment 1, where the ERAN was proposed to reflect a violation of musical rules, or musical syntax: Neapolitan chords at the third position might not have been perceived as violating a rule (the two out-of-key notes of the Neapolitan chords still fitted well into the harmonic context established by the previous two chords, especially since a Neapolitan might have been perceived as subdominant substitute). Nevertheless, the out-of-key notes of Neapolitan chords were perceived by the listeners (the N5 elicited by Neapolitan chords differs from the N5 elicited by in-key chords). It is thus suggested that the out-of-key notes have nonetheless been integrated into the musical context, including an effect on the build-up of the representation of

the hierarchy of harmonic stability (both processes previously suggested to be reflected by the N5). In other words, out-of-key notes were integrated into the harmonic context though they were not perceived as violating, therefore a larger N5 compared to in-key chords occurred without an ERAN. Notably, results suggest that paying attention to the harmonies did not minimize processes reflected in the N5.

11.4.4 Secondary dominants

As in Experiments 1 and 2, secondary dominants elicited compared to in-key chords a widely distributed early negativity, and a late frontal bilateral negativity. That is, taking into account the results of all three experiments, secondary dominants presented at the second position of the chord-sequences are differently processed compared to in-key chords. As suggested in the discussions of Experiments 1 and 2, the early negativity is taken to reflect that secondary dominants were tonally less closely related to the preceding tonic (compared to in-key chords), and thus less expected than in-key chords. The N5 is taken to reflect that secondary dominants were integrated into the tonal context, entailing a modulation of the hierarchy of stability (connected to the shift toward a new tonal center, see discussions of Experiments 1 and 2).

The early negativity elicited by secondary dominants was not lateralized (contrary to the ERAN elicited by Neapolitans and clusters). This might be due to the fact that secondary dominants did not clearly *violate* the sound expectancy, they were just *less expected* than in-key chords. This is in line with the hypothesis about the musical context build-up towards the end of a chord-sequence: at the beginning of a cadence, the tonal schema (and thus the hierarchy of harmonic stability) is just about to be established. Therefore, the sound expectancy is rather unspecified.

11.5 Supplementary behavioral study

Neapolitan chords at the third position of Experiments 1 and 3 elicited both an ERAN and an N5.² This finding is surprising, since the behavioral data of the present experiment revealed that Neapolitan chords at the third position are rather unsalient: only 58% of the Neapolitan chords at the third position were on average detected. That is, though participants realized merely about half of the Neapolitans, their brain responses differed significantly between Neapolitans and in-key chords.

It is even more surprising that secondary dominants also elicited both early and late effects, since they have to be assumed to be even more unsalient compared to Neapolitans at the third position: secondary dominants contain less out-of-key notes (on average 1.25 out-of-key notes, Neapolitans contained two out-of-key notes), and secondary dominants were presented at the second position, where the harmonic expectancies were (due to the harmonic context-build-up) less specific compared to the third or fifth position.

In order to test the hypothesis that secondary dominants at the second position are less salient than Neapolitan chords presented at the third position, a behavioral study was conducted. Stimulation was identical to Experiments 1 and 3, but participants were instructed to detect the secondary dominants

11.5.1 Methods

Subjects and Stimuli. Participants were 18 right-handed and normal hearing ‘non-musicians’³ (aged 20 to 27 years, mean 23.9, 9 females). No subject participated in Experiment 3. Stimuli were the same as in Experiment 3.

Procedure. Participants were informed about secondary dominants and their nature, and instructed to respond to the secondary dominants by immediately pressing a response button. As examples, three cadences exclusively consisting of in-key chords were presented, as well as three chord-sequences containing a secondary dominant. The duration of an experimental session was approximately 12 minutes.

²When data of the chords at the third position from Experiments 1 and 3 were pooled, both the early and the late negativities were statistically significant.

³See p. 72

Data-Analysis. Hit-percentages, false-alarm rates, and reaction times of two groups were compared: group 1 consisted of participants of the behavioral study (instructed to detect secondary dominants), group 2 comprised the participants of the ERP-study (instructed to detect Neapolitans). Two-tailed t -tests were conducted to test the differences between the two groups

11.5.2 Results

Behavioral results are shown in Tab. 11.2. Most of the secondary dominants remained undetected: participants detected on average only 36% of all secondary dominants.

The hit-percentage of secondary dominants is distinctly lower than compared to behavioral data obtained for Neapolitan chords in the ERP-study (58% of the Neapolitan chords at the third position were detected, and 79% of the Neapolitans at the fifth position). Correspondingly, the false-alarm rate of in-key chords was rather high (9%), and reaction times (on average 642 ms) tended to be longer for secondary dominants than for Neapolitan chords. Two-tailed t -tests (see *Data-Analysis*) yielded a difference of hit-percentages ($F(1, 34) = 8.76$, $p < 0.01$) between group 1 (detecting secondary dominants) and group 2 (detecting Neapolitans), as well as a difference of false-alarm rates ($F(1, 34) = 9.86$, $p < 0.005$). A marginal difference was revealed for reaction times ($F(1, 34) = 3.96$, $p < 0.06$).

Variable	Mean	Std. Dev.	Min	Max
Reaction Time	641.83	142.65	302.00	940.00
Hits (in %)	35.83	31.76	2.00	87.00
False alarms (in %)	9.17	6.21	1.00	21.00

Table 11.2: Behavioral data (grand averages) for chords at the second position. Mean, standard deviation, minimum and maximum of reaction times, hit percentages (with respect to secondary dominants), and false alarm percentages (with respect to in-key chords). Means of reaction times, hit percentages, and false alarm percentages were first calculated for each subject, and then averaged across subjects.

11.5.3 Discussion

Only one third of the secondary dominants was detected. This indicates that secondary dominants presented at the second position are rather unsalient, even less salient than Neapolitan chords at the third position. Notably, secondary dominants did nevertheless evoke distinct brain responses in Experiments 1-3. This is an interesting finding, since it suggests that non-musicians process unexpected musical events according to music-theory, even when most of these events are consciously not detectable.

Chapter 12

Experiment 4

Effects of probability

12.1 Introduction

In Experiments 1-3 of the present study, the probability of experimental manipulations was 25%. That is, Neapolitan chords at the third and at the fifth position, and secondary dominants at the second position of a chord-sequence occurred with a probability of 25% each (see *Methods* of Experiment 1). This contrasts ERP-experiments found in the literature (see Introduction), where this probability was 50% (e.g. Besson & Faita, 1995). It is therefore interesting to determine an influence of probability on ERAN and N5.

In the present experiment, Neapolitan chords were presented at the fifth position only (i.e. no Neapolitans occurred at the third position). The chord-sequences contained Neapolitans and secondary dominants occurring with a probability of 50%. A reduced amplitude of the ERAN was expected, since within a few trials subjects should be able to anticipate (at least to a certain extent) a Neapolitan chord at the fifth position, thus the sound of the Neapolitans was less unexpected. The amplitude of the N5 was also expected to be reduced, because after a few trials, when the Neapolitans are (at least by some subjects) recognized as sounding like a subdominant leading downwards to the tonic, the integration of Neapolitans becomes easier or even unnecessary. As in Experiment 3, participants were instructed to detect the Neapolitan chords and to ignore the deviant instruments.

12.2 Methods

Subjects and Stimuli. Participants were 18 right-handed and normal hearing ‘non-musicians’¹ (aged 20 to 29 years, mean 23.7, 9 females). None of the subjects participated in one of the previous experiments. Stimuli were the same as in Experiment 1 and 3, except that Neapolitan chords occurred at the fifth position only with a probability of 50%, and except that secondary dominants also occurred with a probability of 50%. Since Neapolitans were not presented at the third position of a chord-sequence, the pool of sequences consisted of 96 chord-sequences. From this pool, 172 chord-sequences were randomly chosen.

Procedure. Procedure was the same as in Experiment 3, except that the examples (presented before starting the measurement) were two cadences of in-key chords, and two with a Neapolitan sixth chord at the fifth position of the chord-sequence (since Neapolitans were not employed at the third position). As in Experiment 3, participants were instructed to respond to the Neapolitan chords by immediately pressing a response button. Subjects were also informed about the infrequently occurring deviant instruments and instructed to ignore these deviant instruments. The duration of an experimental session was approximately 12 minutes.

EEG measurements and Data-Analyses were analog to the previous experiments.

12.3 Results

12.3.1 Neapolitan chords

ERP-waveforms of the chords at the fifth position are shown in Fig. 12.1. Neapolitan chords elicited an early anterior negativity (onset around 130 ms) which tended to be lateralized to the right. Neapolitan chords also elicited a P3a (frontally peaking around 350 ms), and a P3b (parietally maximal, peak latency around 390 ms). The P3b was presumably preceded by an N2b which is possibly present in the negative peak around 260 ms. The late bilateral negative frontal component, which was elicited by Neapolitan chords in the previous experiments, is merely visible at frontal electrode sites (peaking around 550 ms).

¹See p. 72

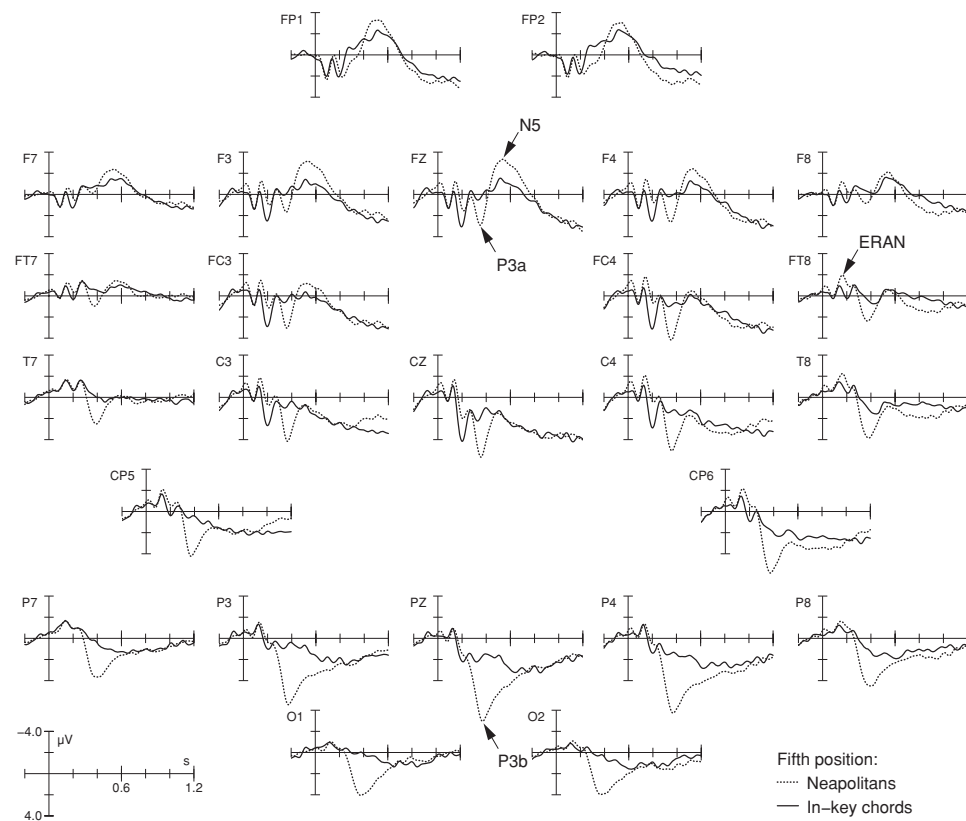


Figure 12.1: 5th position, grand-average ERPs of Neapolitans ($p = 0.5$) and in-key chords.

ANOVAs with factors chord-type and anterior-posterior distribution (frontal vs. parietal electrodes, see Methods for further description) revealed for the 150 – 210 ms time interval an effect of chord-type ($F(1, 16) = 11.67$, $p < 0.005$), and an interaction between the two factors ($F(1, 16) = 5.83$, $p < 0.05$). The analogous ANOVAs with factors chord-type and lateralization (left vs. right frontal electrodes) revealed an effect of chord-type ($p < 0.005$), but no interaction between the two factors. ANOVAs for the 550 – 610 ms interval employing factors chord-type and lateralization (left vs. right frontal electrodes) revealed no effect of chord-type.

12.3.2 Effects of probability

Figure 12.2 shows the difference waves (Neapolitans - in-key chords at the fifth position) from Experiments 3 and 4. Early right anterior and late frontal negativities are reduced in the ERP of Experiment 4 (50% probability for Neapolitan chords), compared to Experiment 3 (25% probability). Between-subjects ANOVAs comparing data from Experiment 3 and 4, conducted for the 150 – 210 ms interval (factors chord-type x experiment), revealed a significant effect of experiment ($F(1, 34) = 4.25, p < 0.05$). Whereas the late negativity elicited by Neapolitan chords was marginally significant in Experiment 3, no late effect was yielded for Neapolitan chords in the present experiment.

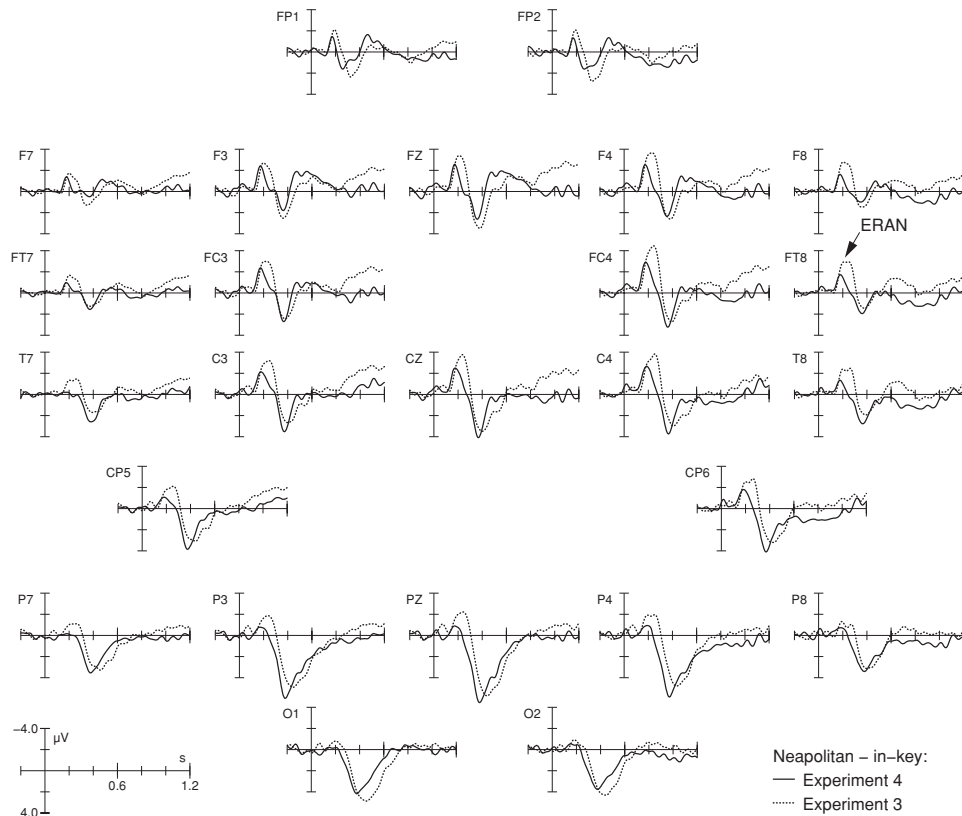


Figure 12.2: Experiments 4 vs. 3, 5th position, grand-average difference waves (in-key chords subtracted from Neapolitans). The ERAN elicited by Neapolitan chords in Experiment 4 was smaller in amplitude compared to Experiment 3 (where Neapolitans occurred with a probability of 25%). The N5 almost disappeared in Experiment 4.

12.3.3 Secondary dominants

ERPs of the chords at the second position are shown in Fig. 12.3 and Fig. A.11. secondary dominants tended to elicit a small early negativity (being maximal around 200 ms) which was widely distributed, but frontally predominant. From around 450 ms poststimulus on, the late negativity elicited by secondary dominants tended to be larger compared to in-key chords. This effect tended to be frontally predominant.

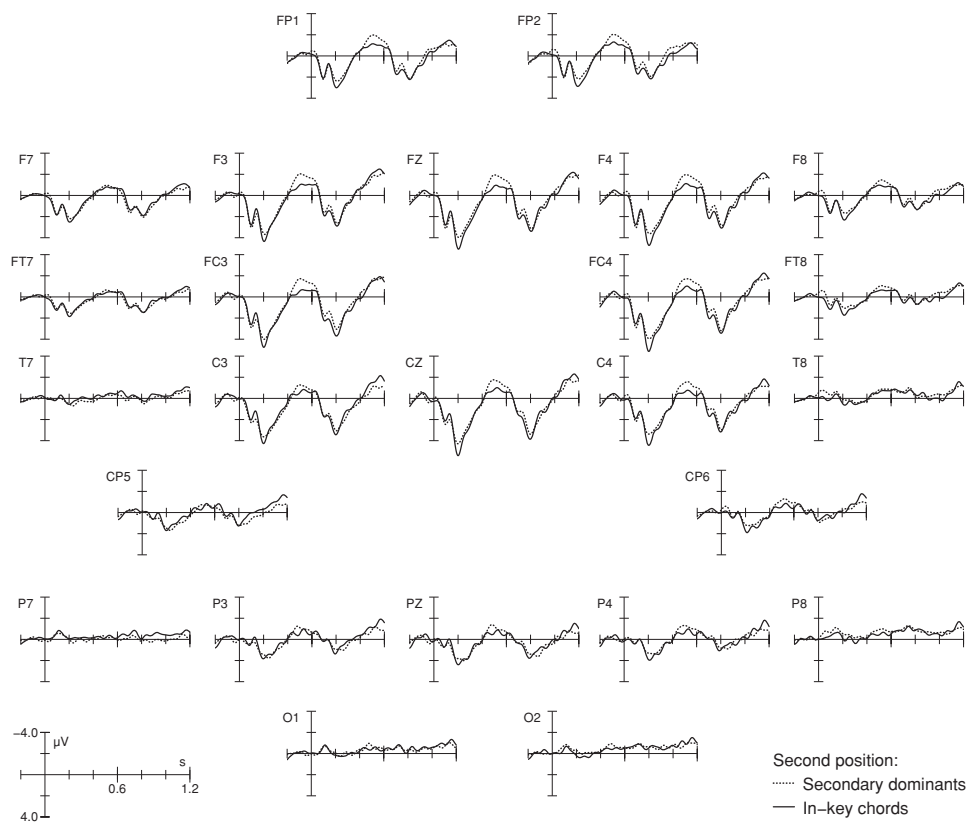


Figure 12.3: 2nd position, grand-average ERPs from the second position.

A two-factor ANOVA with factors chord-type and lateralization for a 190 – 250 ms time-interval yielded a marginal effect of chord-type ($F(1, 16) = 4.22$, $p < 0.06$) and no interaction between the two factors. Similarly, an analogous ANOVA with factors chord-type and anterior-posterior distribution yielded a marginal effect of chord-type ($F(1, 16) =$

3.37, $p < 0.1$) and no interaction between the two factors. An ANOVA with factors chord-type and lateralization for the 550 – 610 ms interval yielded no effect of chord-type. However, an analogous ANOVA for a longer time-interval (450 – 600 ms) yielded a marginal effect of chord-type ($F(1, 16) = 3.08$, $p < 0.1$, no interaction between the two factors).

Figure 12.4 shows the data from chords presented at the second position, obtained in Experiments 3 (where the probability of secondary dominants was 25%) and 4 (where the probability was 50%). When data of both experiments were pooled, both early and late effects were significant. It is clearly visible in the ERPs that both early and late effects elicited by secondary dominants differed in amplitude between Experiments 3 and 4 (see also the potential maps in Fig. A.9 and Fig. A.11). However, the statistical analyses revealed an amplitude-difference between the experiments only for the late, but not for the early negativity.

A between-subjects ANOVA comparing data from Experiment 3 and 4, conducted for the 190 – 250 ms interval with factors chord-type, lateralization, and experiment, yielded an effect of chord-type ($F(1, 34) = 20.96$, $p < 0.0001$), but no interaction, neither between factors chord-type x experiment, nor between factors chord-type x lateralization. The analogous ANOVA conducted for a late time-interval (550 – 610 ms) revealed an effect of chord-type ($F(1, 34) = 23.45$, $p < 0.0001$), and an interaction between factors chord-type and experiment ($F(1, 34) = 5.29$, $p < 0.05$).

12.3.4 Deviant instruments

Figure 12.5 shows the ERPs elicited by the chords which were infrequently played on another instrument compared to chords played on a piano (averaged across all subjects from Experiments 3 and 4). Similarly to Experiments 1 and 2, these chords elicited an early negative component from around 150 ms post-stimulus on, which was only slightly right-anteriorly preponderant. Following a P3, a late bilateral frontal negativity also developed peaking around 500-550 ms. Both P3 and late negativity were smaller in amplitude than when compared to Experiments 1 and 2 (Fig. 12.6). However, as in Experiments 1 and 2, the late frontal negativity was larger at right than left electrode sites.

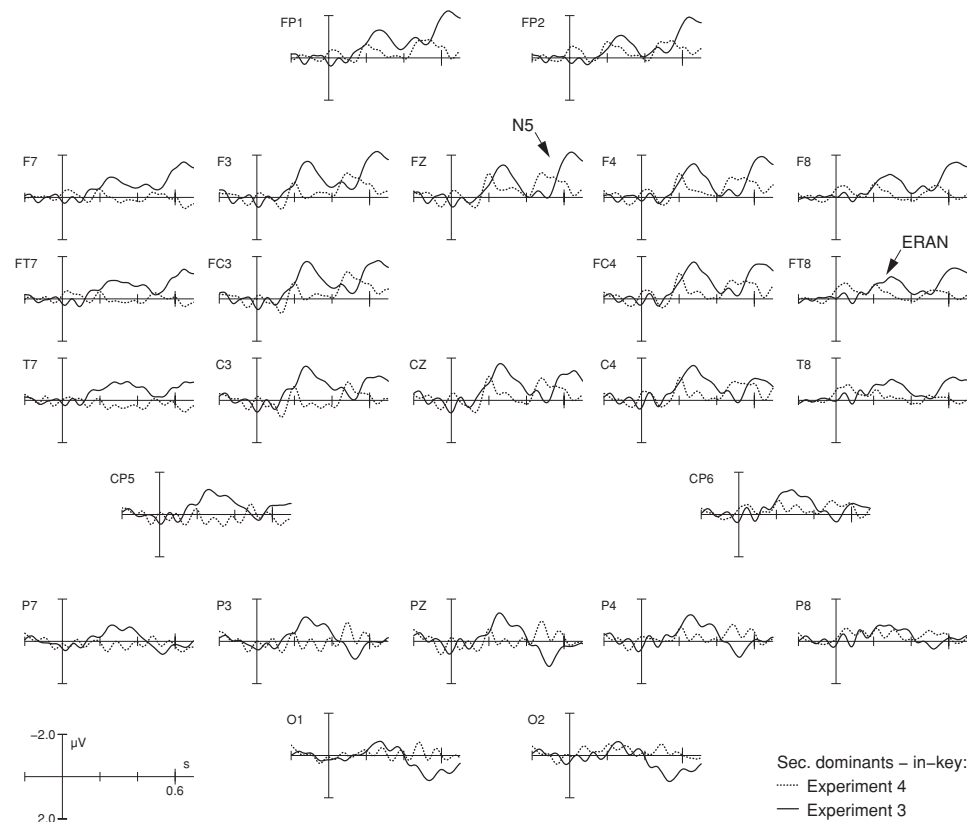


Figure 12.4: Experiments 4 vs. 3, 2nd position, grand-average ERPs (difference waves: in-key chords subtracted from secondary dominants, note the different scaling compared to previous figures). Statistical analyses yielded an amplitude-difference between experiments for the late, but not the early, negativity.

An ANOVA with factors instrument (two levels: chords played on a piano vs. chords played on deviant instruments) x lateralization conducted for an early interval (150-250 ms) revealed an effect of instrument ($F(1, 34) = 90.37, p < 0.0001$), but no interaction between the two factors. The analogous ANOVA, done for a late interval (550-650 ms) revealed an effect of instrument ($F(1, 34) = 5.77, p < 0.05$) and an interaction between the two factors ($F(1, 34) = 14.63, p < 0.0005$). A Between-subjects ANOVA with factors instrument x experiments (1 and 2 vs. 3 and 4) revealed an interaction between the two factors for the late (550 – 610 ms) interval ($F(1, 34) = 6.79, p < 0.05$). An analogous ANOVA for the early time interval (150 – 210 ms) revealed no interaction.

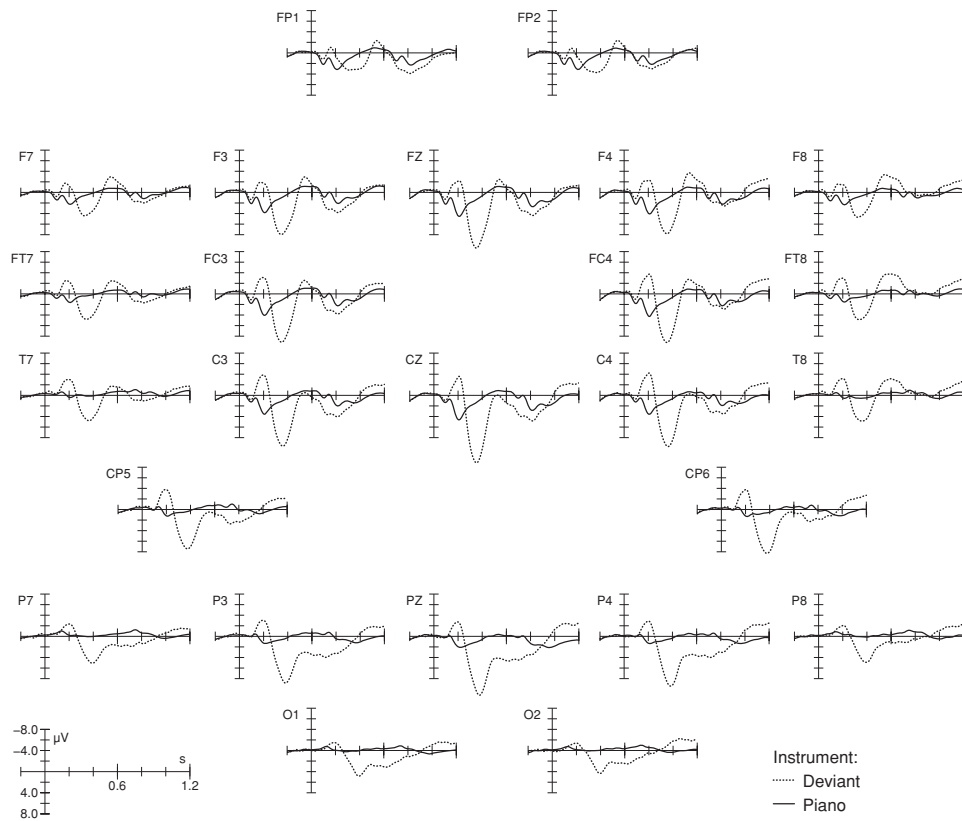


Figure 12.5: Deviant instruments (data from Experiments 3 and 4 pooled). Grand-average ERPs from chords infrequently played by deviant instruments compared to chords played on a piano (note the different amplitude scaling compared to previous figures). Deviant instruments elicited from around 150 ms post-stimulus on an early anterior negativity, followed by a P3, and a late negativity which was lateralized to the right.

12.3.5 Summary

Neapolitan chords presented with a probability of 50% elicited early anterior and late frontal negativities which were both smaller than in Experiment 3 (where the probability was 25%). Secondary dominants tended to elicit small early and late negativities. When data of Experiments 3 and 4 were pooled, both early and late effects of secondary dominants were significant. Both early and late effects elicited by secondary dominants seem to differ in amplitude between Experiments 3 and 4. Deviant instruments elicited again an early negativity which tended to be larger at right than left electrode sites, and a late frontal negativity which was right predominant.

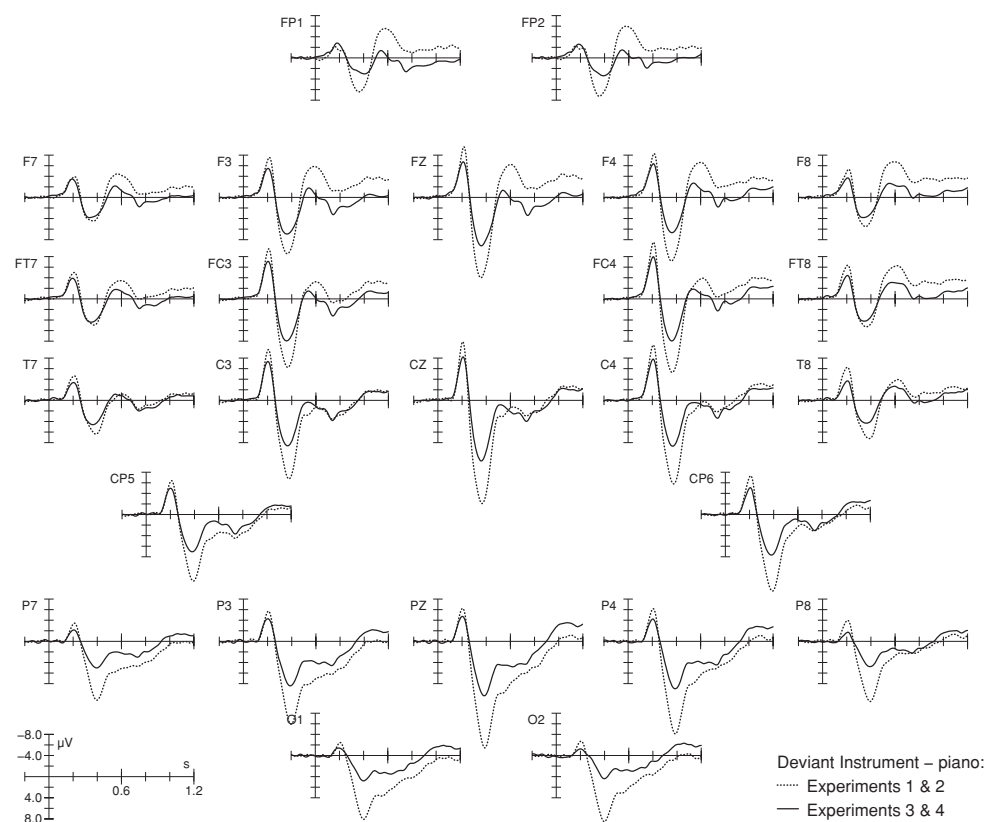


Figure 12.6: Deviant instruments, Experiments 1 and 2 vs. 3 and 4 (grand-average difference waves: chords played on a piano subtracted from chords played on deviant instruments).

12.4 Discussion

12.4.1 Effects of probability

Neapolitan chords elicited an early anterior negativity, which diminished in amplitude compared to the Neapolitans at the fifth position from the previous experiment (where the probability was 25%; Fig. 12.2). A lateralization of the early anterior negativity to the right was consistently observable at lateral frontal and fronto-temporal electrode sites (Fig. 12.1 and Fig. A.10). Thus, though statistically not significant, the early negativity is taken here as an ERAN. The results indicate that probability influences the amplitude of the ERAN. An amplitude-reduction of the ERAN in the present experiment is plausible, since subjects got familiar with the Neapolitan chords and became therefore able to anticipate them (at

least to a certain extent). That is, participants became able to expect the Neapolitan chords. The ERAN was suggested to reflect the violation of sound expectancy, the amplitude of the ERAN thus decreased in Experiment 4 because the sound of the Neapolitans was less unexpected.

The late bilateral frontal negativity (N5), which was elicited by Neapolitan chords in the previous experiments, almost disappeared. While in Experiment 3 the N5 elicited by Neapolitans at the fifth position was still marginally significant, it was not significant in the present experiment. This suggests that the probability of a culturally deviant sound influences the amplitude of the N5. This is plausible, since due to the frequent occurrence of Neapolitans, subjects became soon able to recognize the notes of a Neapolitan chords as sounding like a subdominant. This makes the processes of integration easier (if not unnecessary), and prevents from loosening from the hierarchy of the established tonal stability, because Neapolitan chords are now perceived as function within the key, and not as introducing a shift to a new key. Processes of integration, entailing a loosening from the harmonic stability, were hypothesized to be reflected in the N5.

In respect of Experiments 1 and 3, the present results demonstrate that the larger negativities elicited by Neapolitans at the fifth position (compared to the third position) were not due to a memory-based template (being most specific for the tonic chord at the fifth position, which occurred in 75% of all cadences): in the present experiment, no tonic-specific template for the fifth chord could be established, since 50% of the chords at the fifth position were Neapolitans, and 50% tonic chords. Brain responses of participants thus actually reflected the principles of distance and relatedness inherent in the major/minor tonal system.

Secondary dominants: The effects of probability on both early and late negativities were also clearly present when elicited by secondary dominants (Fig. 12.4, see also Fig. A.9 and Fig. A.11), though statistically not significant for the early effect. However, the amplitude-differences of ERP-effects elicited by secondary dominants between Experiments 3 and 4 are taken here to support the hypothesis that the probability of an unexpected musical event results in the reduction of both early and late negative brain potentials.

12.4.2 Deviant instruments

Similarly to Experiments 1 and 2 (where deviant instruments were to be detected), in Experiment 3 and 4 (where the instrument was to be ignored) chords played by deviant instruments compared to piano-chords elicited early and late negativities (Fig. 12.5). The early negativity had an onset around 150 ms, the late negativity (peaking around 500-550 ms) was lateralized to the right.

As in the discussion of Experiment 2, it is proposed that (besides N1-refractoriness and mismatch negativity) a sound-expectancy violation is reflected in the early negativity. The early negativity was followed by a P3 which is hardly to discern into P3a and P3b. The P3 indicates that participants paid attention to the deviant instruments - whether due to the novel sound, or whether they were tempted to respond also to the deviant instruments. The P3 was smaller when elicited in Experiments 3 and 4 compared to Experiments 1 and 2 (Fig. 12.6), presumably due to the fact that participants were instructed to ignore the deviant instruments in Experiments 3 and 4 (and thus responded less to them compared to Experiments 1 and 2; e.g. Näätänen, 1992).

The P3 was succeeded by a late negativity, taken here as N5, which was lateralized to the right. This lateralization replicates results of Experiments 1 and 2. The N5 is again taken to reflect integration processes (see discussion of Experiment 2), since the chords played by deviant instruments could be integrated as deviant sound which is nevertheless harmonically correct. As the P3, the N5 was also diminished when elicited by deviant instruments in Experiments 3 and 4 compared to Experiments 1 and 2. In Experiments 3 and 4 participants were instructed to detect the Neapolitans, but notably they also paid attention to the deviant instruments (as reflected in the P3). Hence after paying attention to a deviant instrument in Experiments 3 and 4, participants had to orient their attentional focus back to the task-relevant harmonic dimension of the stimulation. This process might have suppressed further integration of the chords played by a deviant instrument (e.g. recognizing the deviant sound as harmonically correct), resulting in a reduced N5 compared to Experiments 1 and 2.

Chapter 13

Experiment 5

Processing changes in key

13.1 Introduction

The present experiment investigates how a change of key is electrophysiologically reflected in the brains of ‘non-musicians’. Most of the melodies in western tonal music (from classic, pop, rock, etc.) normally consist out of tones (or chords) which refer to one single key. However, music becomes more interesting for listeners, when the key sometimes changes, e.g. between two songs, or two melodies, or even within one melody. Whether in a jazz-, pop-, rock-, or classical concert, different songs often belong to different keys, and in every first movement of a classical sonata or symphony a key-change takes place between the first and the second theme. In music theory, a change of key within a progression of harmonies is termed ‘modulation’.

Modulations have a strong dynamic aspect in time, because they induce the expectancy for a completion of the modulation¹ (or even the expectation for a return to the initial key). During the last centuries, composers have found numerous ways to modulate from one key to another. Modulations are generally hardly detectable for a ‘non-musician’, and even musicians often have difficulties detecting modulations, especially for modulations between

¹Usually at least with a V-I (dominant - tonic) progression.

closely related keys, and when performed smoothly and elegantly by the composer. Thus, modulations are musically highly relevant though subjectively quite unsalient.

As described in Chapters 1 and 2, a musical key always refers to a tonal center which is ideally represented by the tonic chord. However, there are several other chords which have a function in a key (e.g. subdominant, or dominant). Importantly, the function of each chord with respect to one key can be interpreted as a different function with respect to another key: e.g. in a *C* major context, a *G* major chord functions as the dominant (of *C* major), but a *G* major chord may also function as the subdominant of *D* major (Fig. 13.1), or function as the tonic in the key of *G* major.

Once a key is established (usually within the first few notes or chords), listeners tend to interpret following chords as belonging to this initial key (e.g. Krumhansl & Kessler, 1982, ; see also Chapter 3). Nevertheless, due to the fact that each chord may also belong to another key, there always remains a residual ambiguity for every chord. The way of modulating from one key to another by interpreting an in-key chord of the first key as different in-key chord-function of another key (as done in the present study) is termed *diatonic modulation*. The chord which functions in two ways (namely as function of the old, and as function of the new key) is termed *pivot chord* (Fig. 13.1).'

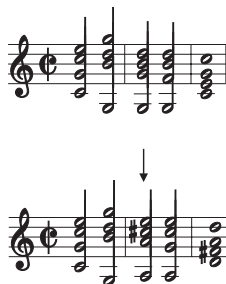


Figure 13.1: Examples of chord-sequences employed in the present Experiment. Top: *C* major chord-sequence exclusively consisting of in-key chords. Bottom: chord-sequence modulating from *C* major to *D* major. The second chord is the pivot chord, functioning as dominant in *C* major, and also as subdominant in *D* major. The third chord of the modulating sequence (indicated by the arrow) is the dominant chord of *D* major, introducing an out-of-key note with respect to *C* major.

The only possible way for an individual to detect a change of key is to come to realize that certain notes do not belong to the former key. This requires an exact representation of

the major-minor tonal system, especially during the modulation between two closely related keys. In such a case, only few notes (or even only one single note) belong to only one of the two keys (see Chapter 2). Within a modulation, at least one chord occurs which does not belong to the old, but to the new key. Generally, this chord directly follows the pivot chord. That fact that a chord belongs to a new key is indicated by notes which are not compatible with the preceding key (but with another key). Only after this moment, listeners know that a modulation might take place.²

As described in Chapter 3, during a sequence of harmonies belonging to one single key, listeners generally tend to expect that subsequent chords are also within this key (instead of expecting the huge number of possible out-of-key chords, or representing several possible ambiguities). Since in the present experiment modulations introduce out-of-key notes, it was hypothesized that a chord containing out-of-key notes will be perceived as unexpected (see also discussion of Experiment 1), and that this violation of expectancy will be reflected in the ERPs. Such a violation of expectancy was in the previous experiments reflected in the ERPs as an early right anterior negativity (ERAN).

Moreover, it has been described in Chapter 3 (and investigated in Experiment 1), that during a musical context build-up within a sequence of harmonies, progressing chords are integrated into this context, each chord specifying the tonal schema established by the preceding chords. With increasing degree of context build-up, less integration is necessary for in-key chords. For the present experiment, it was hypothesized that modulations, since they contain out-of-key notes, need more integration compared to in-key chords. This difference in amount of integration was also expected to be reflected in the ERPs.

As described before, modulations have a strong dynamic aspect in time. From both a music-theoretical and a music-psychological perspective, it is thus interesting to investigate whether this aspect is also reflected in the brains of non-musicians.

²It might also be the case that merely a 'harmonic sidestep' without a modulation was performed, instantly returning to the initial key (e.g. like Neapolitan chords at the third position of Experiments 1-3).

13.2 Methods

13.2.1 Subjects and Stimuli

22 subjects (aged 20 to 30 years, mean 23.3, 11 females) participated in the experiment. As in Experiments 1-4, subjects were 'non-musicians', right-handed and normal hearing.

Similarly to Experiments 1-4, stimuli were sequences of chords, each consisting of five chords. The first chord was always a tonic chord. Chords at the second position were dominant or mediant. In non-modulating cadences, chords at the third position were dominant chords, at the fourth position dominant seventh chords, and at the fifth position tonic. In modulating sequences, dominant chords at the second position were subdominant of the new key (mediants were the supertonic of the new key, respectively), followed by a dominant chord of the new key at the third position, a dominant seventh chord of the new key at the fourth position, and the new tonic at the fifth position. Modulations thus stepped two fifths upwards and had a duration of three chords.³ Presentation time of chords 1 – 4 was 600 ms, of the fifth chord 1200 ms.

Chords were presented in different variations (with the third, the fifth or the octave in the top voice), resulting in a pool of 18 chord-sequences. From this pool, 172 sequences were randomly chosen in a way that modulations occurred with a probability of 25%.

As in the previous experiments, all chords had the same decay and were played under computerized control via MIDI on a synthesizer. In 10% of the cadences an in-key chord at the second, third, fourth or fifth position was played by another instrument than piano. Chord-sequences were played immediately one after the other.

13.2.2 Procedure

Participants were only informed about the deviant instruments, not about the modulations or their nature. An example of a cadence played on a piano and of a cadence in which one

³According to music-theory, the last chord of a modulation (i.e. the new tonic) is not a modulating chord. However, for the reason of simplicity, the last chord of a modulating sequence will be referred to in the present study as 'modulating chord'.

chord was played by a deviant instrument (organ) was presented to each participant before starting the EEG-measurement. Participants were instructed to ignore the harmonies and to count the deviant instruments. They were informed that they would be asked approximately every 2 minutes about the number of deviant instruments, and report their answer by pressing a response button. The duration of the experimental session was approximately 12 minutes.

13.2.3 EEG measurements and data-Analysis

Measurements were analogous to measurement of Experiments 1 – 4.

To test lateralization of effects, EEG-data were referenced off-line to the algebraically mean of both mastoid electrodes. Then, ANOVAs were conducted with factors chord-type (in-key chords vs. modulating chords) and lateralization (left [mean of F3, FC3, F7, FT7] vs. right [mean of F4, FC4, F8, FT8] frontal electrodes). Variances of ERPs were analyzed by repeated measures as univariate tests of hypotheses for within subjects effects.

To discern fast and slow potentials, raw-EEGs were filtered off-line with 0.5 Hz low-pass, and 0.5-10 Hz bandpass filters (1001 point, FIR).

13.3 Results

13.3.1 Modulations

Brain responses to modulating opposed to in-key chords from the third position are shown in Fig. 13.2. The ERPs elicited by modulating chords distinctly differed from the ERPs elicited by in-key chords. Modulating chords elicited an early right anterior negativity (ERAN) which was present around 180 – 280 ms. This ERP-effect was followed by a late frontal negativity which had an onset around 400 ms and peaked approximately at 500 ms (the N5). The late negativity was lateralized to the right.

An ANOVA with factors chord-type (modulating vs. in-key chords, both from the third position of the chord-sequences) and lateralization (left vs. right frontal) for a 180 – 280 ms

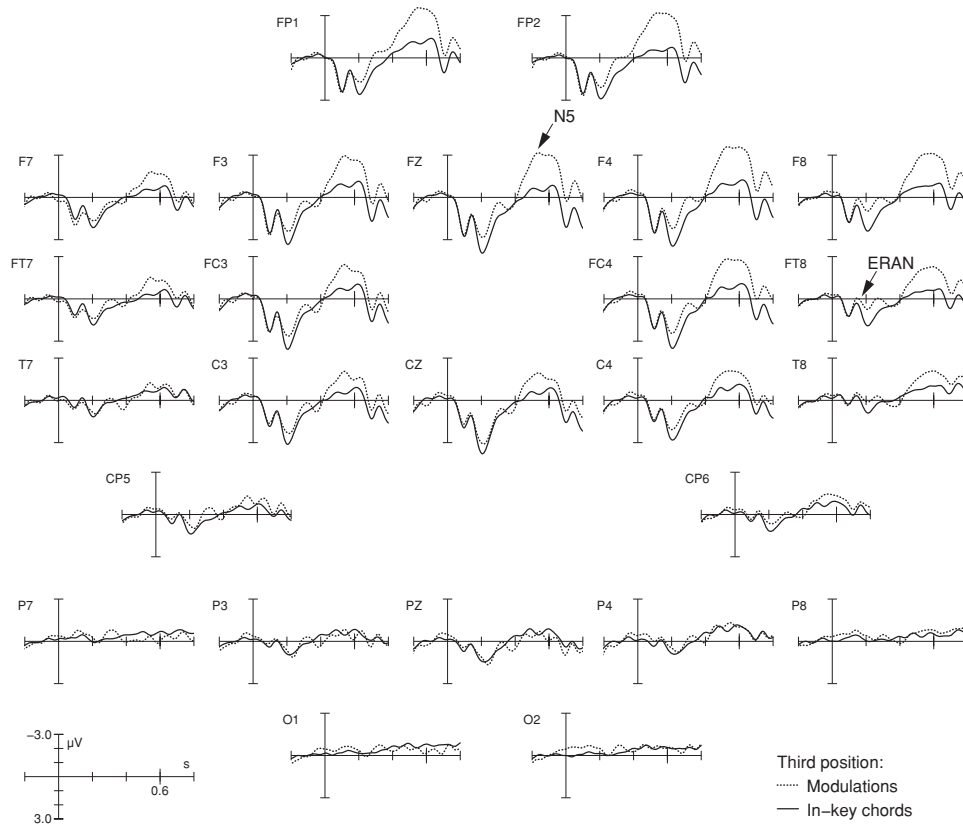


Figure 13.2: 3rd position, grand-average ERPs of modulating and in-key chords. Modulating chords elicited an ERAN and an N5.

time-interval revealed an effect of chord-type ($F(1, 20) = 11.1$, $p < 0.005$) and an interaction between the two factors ($F(1, 20) = 12.48$, $p < 0.005$). The analogous ANOVA (factors chord-type x lateralization) for a late time interval (500 – 600 ms) showed an effect of chord-type ($F(1, 20) = 24.93$, $p < 0.0001$) and an interaction between the two factors ($F(1, 20) = 6.38$, $p < 0.05$).

ERPs of the last three chords of the chord-sequences, plotted separately for in-key and modulating sequences are shown in Fig. 13.3. Strong ERP-effects were elicited by all modulating chords, i.e. by chords at the third, fourth, and fifth position of the modulating chord-sequences. These effects were predominant at frontal electrode sites, and larger over the right compared to the left hemisphere.

As can best be seen in the difference-waves of Fig. 13.3, the late negative ERP-effect elicited by chords at the third position of the modulating sequences seems to be rather tonic (contrary to the early negativity which is more phasic). Thus, the slow negative potential elicited by the modulating chords at the third position might overlap in time with both phasic and tonic ERP-effects elicited by the modulating chords at the fourth position. Similarly, potentials elicited by modulating chords at the fifth position overlap with potentials elicited by previous chords (especially at right anterior leads).

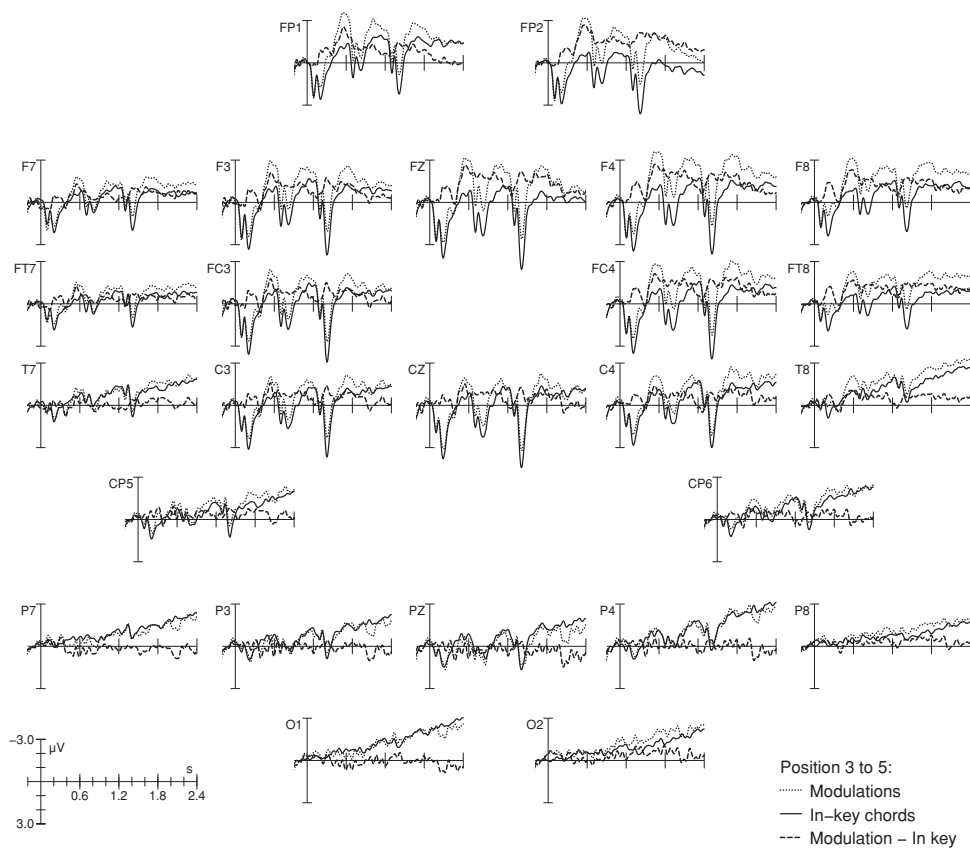


Figure 13.3: 3rd to 5th position, grand-average ERPs of modulating and in-key chords. Red line: Difference waves (in-key subtracted from modulating chords). The onset of the fourth chord was at 600 ms, the onset of the fifth chord at 1200 ms. Compared to in-key chords, modulations elicited overlapping fast and slow potentials.

In order to tease apart more phasic processes from those with a more prolonged (or cumulative) time course, EEGs were 0.5 Hz low-pass filtered before averaging the ERPs (for

a similar procedure employed for the analysis of ERPs elicited in language experiments see e.g. Kutas & King, 1996). ERPs of both non-modulating and modulating sequences reveal a slow-going negative potential towards the end of the chord-sequences (Fig. 13.4). Notably, compared to non-modulating sequences, modulating sequences elicited a tonic negative potential which was maximal around 500 – 1500 ms (best to be seen in the difference-wave of Fig. 13.4). This effect was frontally predominant and stronger over the right compared to the left hemisphere (cf. Fig. A.12). Only at C3, this effect was larger compared to the homologous electrode over the right hemisphere (C4). However, statistical analysis did not reveal any significant amplitude difference of this effect between the two electrodes C3 and C4. Hence, the larger amplitude of the effect at C3 compared to C4 is regarded here as artifact. Data of C3 were thus excluded from map-interpolation in Fig. A.12.

For statistical analysis of the 0.5 Hz low-pass filtered ERP-data, an ANOVA was conducted for the time interval from 500 – 1500 ms. Two factors were employed: sequence-type (non-modulating vs. modulating chord-sequences) and lateralization (left vs. right frontal). An effect of sequence-type ($F(1,20) = 10.73$, $p < 0.005$), and an interaction between the two factors ($F(1,16) = 5.46$, $p < 0.05$) was found.

ERPs of band-pass filtered (0.5 – 10 Hz) raw-data are shown in Fig. 13.5. Each modulating chord (i.e. chords at the third, fourth, and fifth position) elicited an early negativity with a right-anterior predominance, regarded here as ERAN. The ERAN was present around 180 – 280 ms after the onset of each chord, and consistently predominant over the right hemisphere (see also Fig. A.13). Generally, the ERAN declined towards the end of the chord-sequence (best to be seen at FT8 in Fig. 13.5). At Fz and Cz, the ERAN elicited by the fifth chord was larger in amplitude compared to the ERAN elicited by the third chord.

Besides the ERAN, a distinct late frontal negativity was elicited by the modulating chords at the third position, and a small late frontal negativity by modulating chords at the fifth position of a chord-sequence.

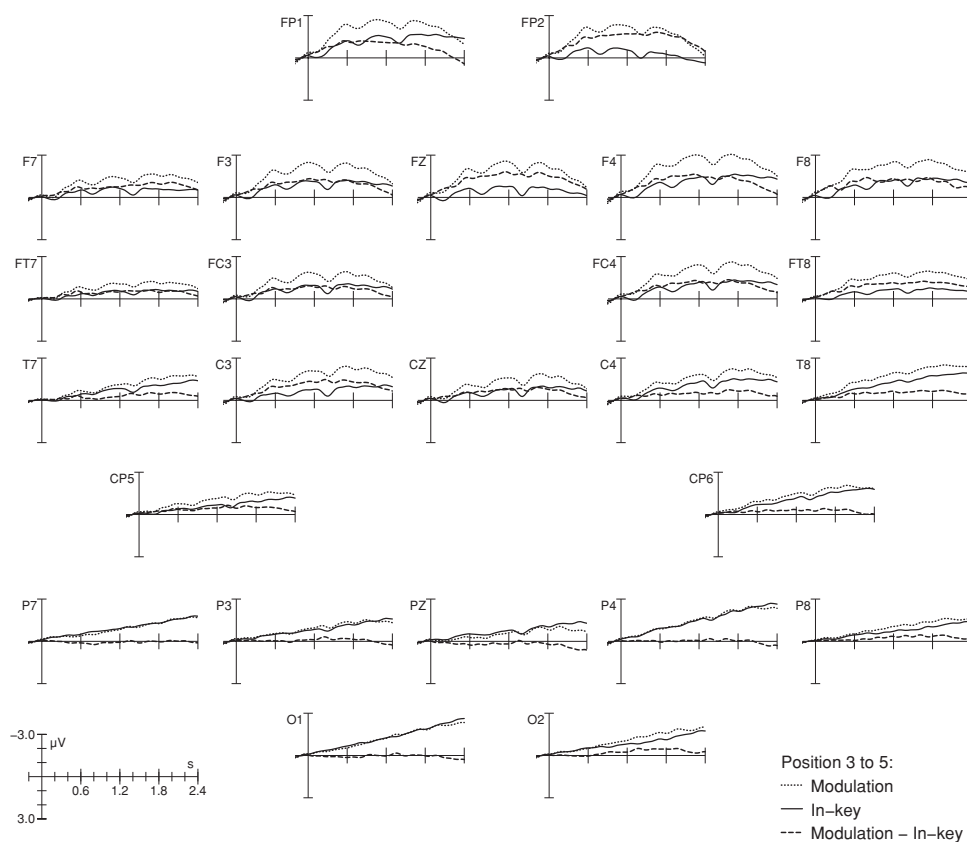


Figure 13.4: 3rd to 5th position, 0.5 Hz low-pass filtered data. Grand-average ERPs of modulating and in-key chord-sequences. Red line: Difference waves (in-key subtracted from modulating sequences). The onset of the fourth chord was at 600 ms, the onset of the fifth chord at 1200 ms. Modulations elicited a distinct right-frontal tonic negativity which was maximal around 500-1500 ms.

13.3.2 Chord-Inversions

In the present experiment, chords at the third position were presented equiprobably in root position, as sixth chords⁴, and as six-four-chords⁵. The ERPs elicited by these chord-types are shown in Fig. 13.6. All chords elicited very similar ERPs. Only at FP1, FP2, Fz, and F4, the ERPs of six-four chords were slightly more negative compared to in-key chords. However, this effect failed to reach statistical significance.⁶

⁴I.e. with the third as base-tone; for further explanation see p. 19

⁵I.e. with the fifth as base-tone; for further explanation see p. 20

⁶ $p < 0.15$ for the mean of the four electrodes [FP1, FP2, Fz, F4] in an 450 – 650 ms interval.

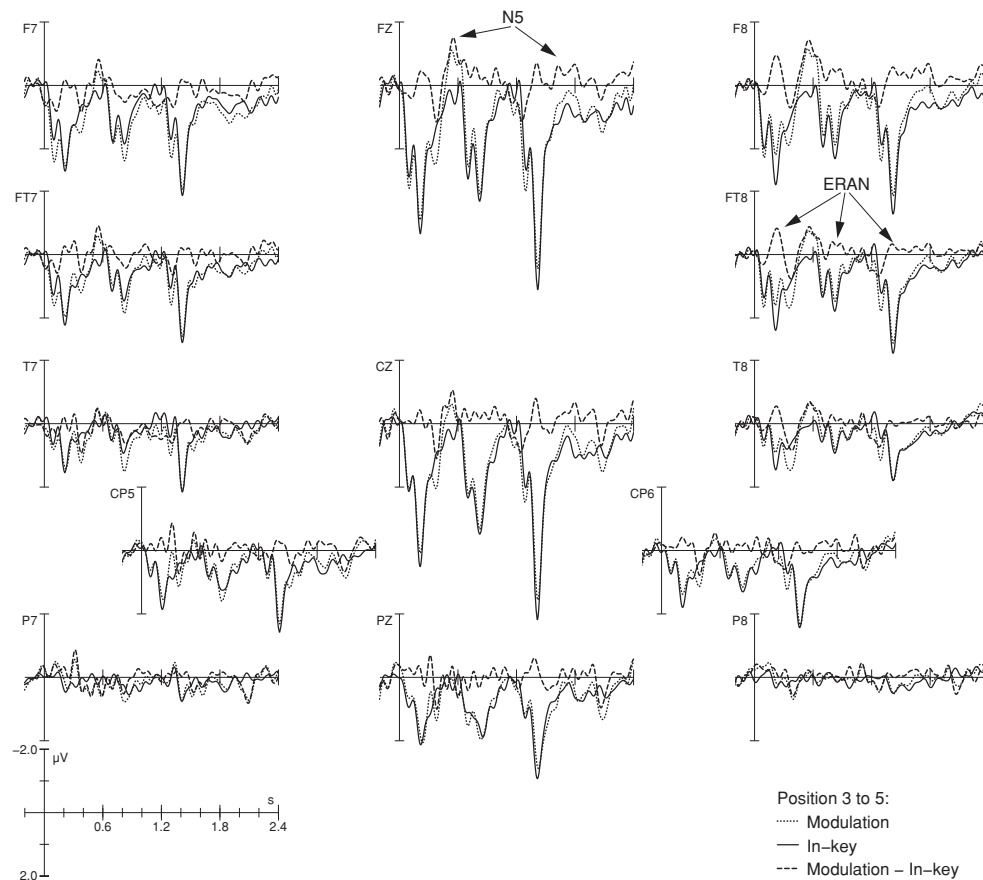


Figure 13.5: 3rd to 5th position, 0.5 – 10 Hz band-pass filtered data. Grand-average ERPs of modulating and in-key chord-sequences. Red line: Difference waves (in-key subtracted from modulating sequences). The onset of the fourth chord was at 600 ms, the onset of the fifth chord at 1200 ms.

13.3.3 Deviant Instruments

ERPs elicited by chords which were infrequently played on another instrument compared to chords played on a piano are shown in Fig. 13.7. As in Experiments 1 – 4, these chords elicited an early negative component developing from around 150 ms post-stimulus on. This component was larger, wider distributed, and not lateralized - contrary to when elicited by modulating chords (and Neapolitan chords or clusters, respectively). The early negativity was followed by an N2b-P3a-P3b complex (the N2b was centrally maximal and peaked around 220 ms, the P3a was frontally maximal and peaked around 350 ms, the P3b was

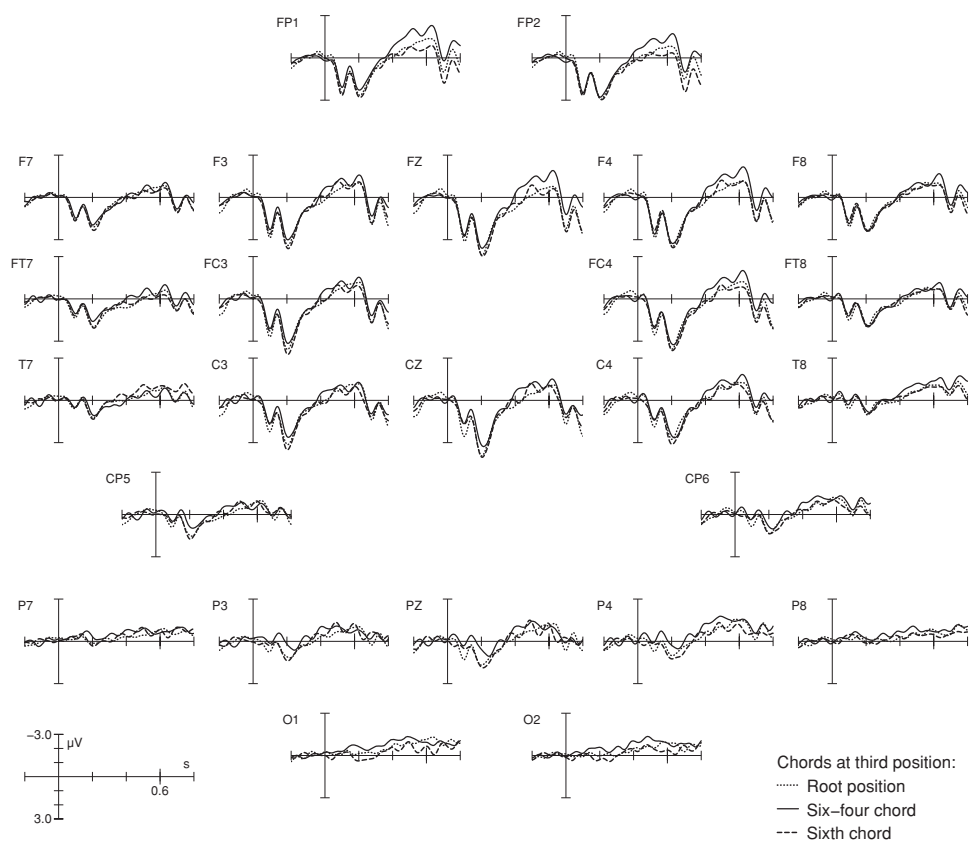


Figure 13.6: Chord-inversions, grand-average ERPs. Chords presented in root position, as sixth chords, or as six-four chords elicited similar ERPs.

parietally maximal and peaked around 400 ms). Following the P3a-P3b, a late frontal negativity developed peaking around 550 – 600 ms which was larger at right than left electrode sites.

An ANOVA with factors instrument (two levels: in-key chords played on a piano vs. chords played on deviant instruments) and lateralization conducted for the 150 – 210 ms interval revealed an effect of instrument ($F(1, 34) = 33.14$, $p < 0.0001$), and no interaction between the two factors. The analogous ANOVA (factors instrument x lateralization), conducted for the 550 – 610 ms interval also revealed an effect of instrument ($F(1, 34) = 13.93$, $p < 0.005$) and an interaction between the two factors ($F(1, 34) = 6.51$, $p < 0.05$).

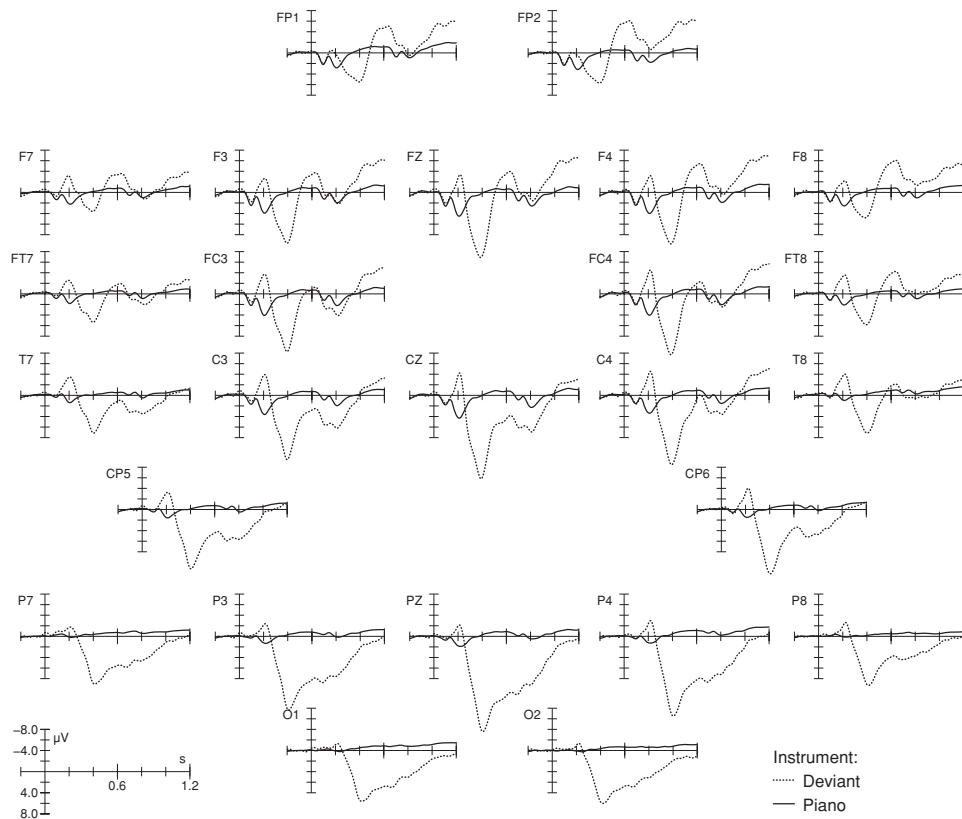


Figure 13.7: Deviant instruments, grand-average ERPs from chords infrequently played by deviant instruments compared to chords played on a piano (note the different amplitude scaling compared to previous figures). Deviant instruments elicited from around 150 ms post-stimulus on an early anterior negativity (followed by a P3a), and a late negativity which was lateralized to the right (preceded by N2b and P3b).

13.3.4 Summary

Modulating chords at the third position elicited an ERAN and a right-preponderant N5. Modulating sequences elicited a tonic negative potential which was maximal around 500 – 1500 ms. This effect was frontally predominant and stronger over the right compared to the left hemisphere. Besides, each modulating chord elicited an early negativity with a right-anterior predominance; late frontal negativities were elicited by the modulating chords at the third and at the fifth position of a chord-sequence. Chords presented in root position, as sixth chords, or as six-four chords elicited similar ERPs. Chords which were infrequently

played on another instrument elicited a large early negative component which was widely distributed and not lateralized, and a late frontal negativity which had a right preponderance.

13.4 Discussion

13.4.1 Modulations vs. in-key chords

The brain responses elicited by modulating chord-sequences distinctly differed from those elicited by in-key chord-sequences. Modulating chords at the third position of a chord-sequence elicited an ERAN (present around 180 – 280 ms) which was followed by an N5 (peaking around 500 ms). The finding of early and late negativities elicited by chords containing out-of-key notes replicates the findings of Experiments 1 – 4. As in the discussions of the previous experiments, the ERAN is taken to reflect the violation of sound expectancy, since modulations introduced out-of-key notes which are perceived as unexpected (cf. p. 83). Correspondingly, the N5 is taken to reflect harmonic integration, since modulating chords contained out-of-key notes (with respect to the old key), and had to be integrated into the new key (cf. p. 85).

Compared to when elicited by Neapolitans at the third position in Experiments 1 and 3, both ERAN and N5 were considerably larger in amplitude when elicited by modulating chords at the third position. This amplitude-difference could neither be due to the amount of unexpected notes (which was identical for Neapolitans and modulating chords), nor could it be due to the total amount of chords containing out-of-key notes (which was also identical in Experiments 1, 3, and 5).

The amplitude-difference is suggested to indicate that during the experimental session, participants soon realized that unexpected chords occurring at the third position introduced a shift to a new key. That is, participants realized that the modulating chords at the third position contained relevant information with respect to the following modulation (unlike Neapolitan chords at the third position which could be assimilated into the larger tonal context as subdominant-substitute, and thereby as pre-dominant chord). It is suggested that the awareness of this particular function of a modulating chord at the third position led

to a different processing compared to the processing of Neapolitan chords. This different processing might account for the larger amplitudes of both ERAN and N5.⁷

The N5 elicited by modulating chords at the third position was lateralized to the right. This contrasts the N5 elicited by Neapolitan chords at the third (and fifth, respectively) position in the previous experiments (which was distributed bilaterally). It is regarded here as unlikely that the lateralization of the N5 in the present experiment is a characteristic feature for the processing of modulations, since the N5 elicited by deviant instruments (and by Neapolitan chords in the following experiment) was also lateralized to the right.⁸

The lateralization might be due to a habituation of the participants to the processing of modulations. In the present experiment, only one type of ‘violation’ was employed: Modulations which occurred always at the third to fifth position. In the previous experiments, Neapolitan chords occurred at the third as well as the fifth position, and secondary dominants occurred at the second position. The stimulation of the previous experiments was thus more diversified. In the present experiment, participants might have realized that they were confronted with only one type of violation. For the reason of efficiency, the brain-system which is processing the modulations might have reduced its activity in the left hemisphere.⁹

Both non-modulating and modulating chord-sequences elicited a sustained negativity. This negativity was widely distributed over the scalp and increased in amplitude towards the end of the sequences.¹⁰ Such a similar effect has first been described by Walter et al. (1964) as the ‘contingent negative variation’ (CNV, see also Rohrbaugh & Gaillard, 1983), which was maximal over fronto-central regions and originally taken as an ‘expectancy’ wave. Interestingly, sustained and increasing negativities associated with the CNV have also been found to be elicited during the processing of sentences (e.g. Kutas & Hillyard,

⁷It would be interesting to confirm this hypotheses by conducting an experiment with an analogous design as in the present experiment, except that Neapolitan chords at the third position of the chord sequences are used to modulate. It would then to be expected that Neapolitans elicit both larger ERAN and N5 compared to Experiments 1 and 3.

⁸It is thus also unlikely that the right lateralization is connected to a modulation-specific operation of (working) memory.

⁹Further description of this brain system remain matter of investigation. For further discussion see p. 158 and p. 162.

¹⁰This effect was also present in the previous experiments, cf. Appendix A. For ERPs of entire non-modulating chord-sequences (i.e. from chords 1 – 5) see Fig. B.5 in Appendix A.

1980, see also Fig. 7.1).¹¹ The sustained and increasing activity elicited by chord-sequences is suggested here to reflect the increasing expectancy (i.e. anticipation) for tonally related chords to follow. The increasing expectancy correlates with the build up of musical context which is connected to the specification of the hierarchy of harmonic stability (Bharucha & Krumhansl, 1983; Krumhansl & Kessler, 1982; Bharucha & Stoeckig, 1986, 1987, see also discussion of Experiment 1).

Notably, compared to non-modulating sequences, modulations elicited an additional effect, namely a slow-going negativity which was maximal around 500 – 1500 ms. This negativity was right-frontally predominant. No such slow negativity could be found for the chord-sequences of the previous experiments, i.e. neither for chord-sequences containing Neapolitan chords, nor for sequences containing clusters. The slow negativity elicited by modulations is therefore suggested to reflect cognitive operations characteristic for the processing of tonal modulations.

These cognitive operations presumably reflect more global integration with respect to the change of key, namely the restructuring of the hierarchy of harmonic stability. From a music-psychological point of view, the hierarchy of stability established by the chord-sequences preceding a modulation had to be entirely restructured: A new tonal center had to be established, entailing the notion of key membership of other chords, of intrakey and contextual distances, of intrakey and contextual asymmetries, and of contextual identity (see pp. 30-33, and Bharucha & Krumhansl, 1983).¹²

The amplitude of the slow negative potential (that is the duration of the processes of integration connected to the change of key) correlates with the time-course of the modulation: It declines with the establishment of the new tonic. The slow-going potential elicited by modulations returned to baseline after approximately three modulating chords, that is participants needed in the present experiment on average around 2.5 sec. to restructure their harmonic hierarchy two fifths upwards.

¹¹In the study from Kutas & Hillyard (1980), the CNV was interpreted as reflecting the anticipation of a significant stimulus.

¹²Given the present interpretation of N5 and the slow negativity elicited by modulations, modulating chords were thus in one dimension integrated with respect to the change of key (reflected in the slow negativity), and in another with respect to their function within the old and /or the new key (reflected in the N5).

Because time is involved in the restructuring of the tonal hierarchy, it is suggested here that working memory operations are highly involved in this process. Since frontal brain areas are theorized to be involved with central executive processes (Baddeley, 1995, 1999), it is plausible to assume that the frontal slow shift found to be elicited by modulations is related to working memory processes. This interpretation is supported by findings from Zatorre & Samson (1991) and Zatorre et al. (1994), who reported interactions between temporal and frontal cortices to be entailed in working memory for pitch. It is interesting to note that slow negative potential-shifts have also been observed during the processing of language and associated with working memory operations (e.g. King & Kutas, 1995; Vos, 1999, see the latter also for review).¹³

When looking at the band-pass filtered EEG-data (i.e. ERPs that do not contain the slow negative potential), the ERPs of each modulating chord (i.e. ERPs of chords at the third, the fourth, and the fifth position of the modulating sequences) were consistently more negative at right anterior leads in the time interval from 180 – 280 ms after the onset of the chord (cf. Fig. 13.5, especially F8 and FT8, and Fig. A.13). It is therefore suggested that each modulating chord elicited an ERAN. The ERAN declined towards the end of a modulation, reflecting that chords (containing out-of-key notes with respect to the old key) were perceived as less unexpected with the establishment of the new key. Correspondingly, the N5 elicited by the modulating chords at the third and fifth position declined with progressing modulating chords, reflecting the establishment of the new tonal center.¹⁴

Notably, participants of the present study were ‘non-musicians’ who extracted abstract musical information from the harmonies by distinguishing between ‘in-key’ and ‘out-of-key’ sounds (even though harmonies were task-irrelevant). Moreover, results of the present experiment revealed that the brain responses of participants correlated specifically with the time-course of a modulation.

¹³In the experiment from King & Kutas (1995), Object vs. Subject Relative sentences elicited a slow frontal negativity.

¹⁴Modulating chords at the fourth position did virtually not elicit an N5. This is suggested to be due to the very similar function of chords presented at the third and at the fourth position (at the third position: dominant, at the fourth position: dominant with characteristic dissonance, i.e. dominant seventh chord). Chords at the fourth position thus contained only little new information (with respect to chords at the third position), suggested here to result in a smaller N5.

13.4.2 ERAN vs. MMN

It is interesting to note that an ERAN was elicited by three (modulating) chords in a row.¹⁵ Comparing the ERAN with the MMN, such a phenomenon would not be expected for the MMN. The MMN is known to decrease clearly when elicited by two directly succeeding deviants (cf. Sams et al., 1984; Giese-Davis et al., 1993; Näätänen, 1992), a third deviant does virtually not elicit any MMN.¹⁶ The finding that the ERAN was elicited by three directly succeeding chords thus supports the hypothesis that the ERAN is not merely a MMN (elicited by the abstract feature ‘out-of-key’), but rather an ERP-component specifically connected to the processing of musical information.

13.4.3 Chord inversions

In the present experiment, chords at the third position of the chord-sequences (and at the fourth position, respectively) were equiprobably presented in root position, as sixth-chords, and as six-four chords (for explanation of chords see Chapter 2). The ERPs elicited by these chord-types were very similar to each other. Nevertheless, from around 450 – 650 ms, the ERPs of six-four chords were at frontopolar sites, and at Fz and F4, slightly more negative compared to chords presented in root-position. Though this effect was statistically not significant, it might become significant in an experiment employing more trials, resulting in an enhanced signal-to-noise ratio.

13.4.4 Deviant instruments

Deviant instruments (which were to be detected) elicited an early negativity, followed by N2b, P3a, and P3b, and a late frontal negativity which did not predominate. ERPs elicited

¹⁵Though the ERAN generally declined towards the end of a modulation, the amplitude of the ERAN elicited by the fifth chord was at Fz, Cz, and frontopolar electrodes even larger compared to the ERAN elicited at the third position of a modulating sequence.

¹⁶In the studies from Sams et al. (1984) and Giese-Davis et al. (1993), however, all deviants were physically identical. To my knowledge, no experiment has so far been conducted in which three abstract-feature deviants occurred directly succeeding in a row. Nevertheless, it should be noted that chords at the third and at the fourth position were both physically and functionally very similar.

by deviant instruments mainly replicate findings of Experiments 1-4 (see Experiment 2 and 4 for discussion).

Chapter 14

Experiment 6

Automaticity of musical processing

14.1 Introduction

Experiments 1 – 4 of the present study have shown that during listening to a musical piece, unexpected harmonies evoke brain responses which differ in intensity according to music-theory. The brain responses to unexpected harmonies were reflected electrically as ERAN and N5. Both ERAN and N5 were elicited even when Neapolitan chords were not task-relevant, that is when participants were instructed to ignore the harmonies, to attend to the sound of the stimulation, and to detect infrequently occurring deviant instruments (see Experiment 1).

However, due to the fact that the task of detecting deviant instruments was not demanding, it is not likely that participants actually ignored the harmonies. The present Experiment was conducted to investigate whether or not ERAN and N5 can be evoked pre-attentively, that is even when a musical stimulation is ignored. Therefore, a stimulation similar to that of Experiment 1 was employed (see *Methods*), but in a first experimental block, participants were reading a self-selected book. Such a procedure is commonly employed to investigate auditory processing in the absence of attention (cf. Näätänen, 1992; Schröger, 1998).

A second block was employed in order to investigate effects of attention on the processing of chord-sequences compared to the first block. Therefore, participants listened to the same stimuli under the instruction to detect the Neapolitan chords.

14.2 Methods

14.2.1 Subjects and Stimuli

Participants were 18 normal hearing ‘non-musicians’¹ (aged 18 to 27 years, mean 23.4 years, all right-handed, 9 females).²

The pool of stimuli was identical to Experiment 1, except that chord-sequences containing secondary dominants were excluded (resulting in a total set of 108 different chord-sequences). From this pool of cadences, chord-sequences were randomly chosen in a way that (1) Neapolitan chords occurred with a probability of 20% at each the third and the fifth position, and (2) cadences containing a Neapolitan chord were always preceded by at least one cadence exclusively consisting of in-key chords. As in the previous experiments, presentation time of chords 1-4 was 600 ms, of the fifth chord 1200 ms. All chords had the same decay, stimulation was presented via speakers and played under computerized control via MIDI on a synthesizer with approximately 60dB SPL. Contrary to Experiments 1 – 5, no deviant instruments were employed.

First block: 750 chord-sequences were presented in the first block (resulting in a duration of approximately 45 minutes). 150 Neapolitans occurred at the third position, and 150 Neapolitans at the fifth position of a chord-sequence.

Second block: 250 chord-sequences were presented in the second block (resulting in a duration of approximately 15 minutes). 50 Neapolitans occurred at the third position, and 50 Neapolitans at the fifth position of a chord-sequence.

¹See p. 72

²15 participants regarded themselves as ‘unmusical’

14.2.2 Procedure

Participants were seated in a comfortable chair. For the first block, they were instructed to read a self-selected book, and to ignore all acoustic stimuli.

After the first block, participants were informed about the presence of Neapolitan chords. Two cadences consisting of in-key chords, two chord-sequences containing a Neapolitan chord at the third position, and two sequences containing a Neapolitan at the fifth position were presented as examples. Participants were then asked to detect the Neapolitan chords, and indicate their detection by pressing a response button. Participants were instructed to look at a fixation-cross during the second block.

14.2.3 EEG measurements

Measurements were performed in an acoustically and electrically shielded room. The EEG was recorded with Ag-AgCl Electrodes using 32 electrodes: 29 scalp sites of the 10-20-system, both mastoids, and nose-tip. During the EEG-recording, the left mastoid electrode was used as reference. Sampling rate was 250 Hz (30 Hz low-pass). The EOG was recorded bipolarly between electrodes situated at the outer right and outer left canthus; the vertical EOG was recorded bipolarly between electrodes situated above and below the right eye.

14.2.4 Data-Analysis

For reduction of artifacts caused by drifts or body movements, EEG-data were rejected off-line from the raw EEG whenever the standard deviation within any 500 ms interval of all data exceeded $20\mu V$ at either of the following electrodes: T7, T8, FT7, FT8, P7, P8, O1, and O2.

In both blocks Epochs with vertical eye-movements were rejected whenever the standard deviation in each 200 ms interval of the vertical EOG exceeded $40\mu V$. In order to guarantee that the evaluated data of the first block were not attended by the participants, epochs from the first block with no (sic!) horizontal eye-movement (i.e. where participants were not reading) were rejected off-line from the raw-EEG. That is, only epochs of the first block with horizontal eye-movements (indicating the reading of participants) were included

in the data-analysis. For analysis of data obtained in the second block, epochs with horizontal eye-movements were rejected whenever the standard deviation in each 200 ms interval of the horizontal EOG exceeded $20\mu V$.

ERPs were analyzed by repeated measures analyses of variance as univariate tests of hypotheses for within subjects effects. To test lateralization of effects, EEG-data were referenced off-line to the algebraically mean of both mastoid electrodes. Then, ANOVAs were conducted with factors chord-type (in-key chord vs. Neapolitan) and lateralization (left [mean of F3, FC3, and C3] vs. right [mean of F4, FC4, and C4] frontal electrodes). ERPs presented in the figures were low-pass filtered for presentational purposes only (10 Hz, 41 point, FIR).

14.3 Block 1: Ignore condition

14.3.1 Results

Musical context build-up

ERP-waveforms of in-key chords are shown in Fig. 14.1. Similarly to Experiment 1, a negative ERP deflection was present at frontal electrode sites around 500 – 600 ms after the onset of a chord. Especially at frontopolar, frontal, and frontocentral sites, the amplitude of this negative deflection differed between chords from different positions in the cadence: though not as distinct as in Experiment 1 (where participants attended the musical stimulation) this deflection was larger in amplitude when elicited at the beginning compared to the end of a chord-sequence.³

This effect of position holds in particular for chords at the first, the second, and at the fifth position (left of Fig. 14.2). An ANOVA employing position in the cadence (first vs. second vs. fifth chord) as within-subjects factor in the time window from 540 to 600 ms revealed an effect of position ($F(2, 32) = 19.49$, $p < 0.0001$). Importantly, chords at the first and fifth position were both tonic chords, thus ERPs can be compared between two chords with identical harmonic function. Similarly to Experiment 1, the negative ERP-deflection around 550 ms differed distinctly in amplitude between the tonic chord presented

³For ERPs of entire in-key chord-sequences (i.e. chords 1 – 5 see Appendix A, Fig. B.6.

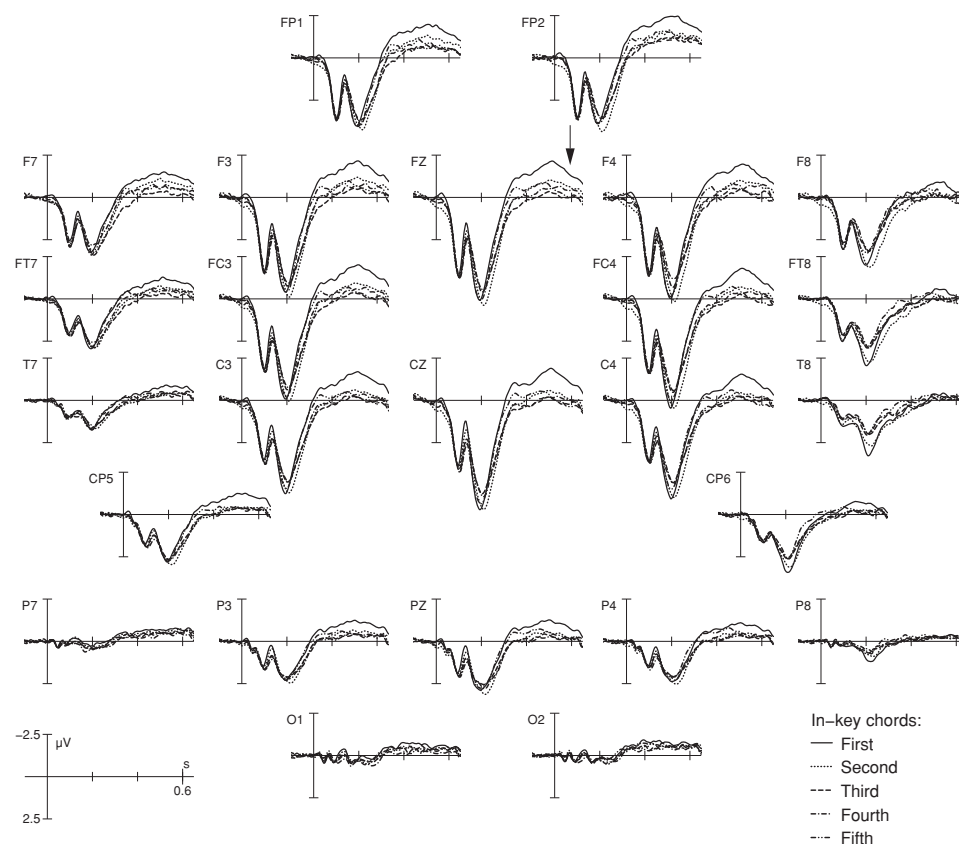


Figure 14.1: In-key chords, grand-average ERPs (first to fifth position). A late bilateral frontal negativity was larger when elicited at the beginning compared to the end of the chord-sequences (indicated for the Fz-electrode by the arrow).

at the beginning compared to the tonic chord presented at the end of a cadence. The fronto-central predominance of this negative effect is illustrated in the right of Fig. 14.2.

Neapolitan chords

Fifth position: Figure 14.3 shows the brain responses of Neapolitan opposed to in-key chords at the fifth position of the chord-sequences, referenced to the algebraically mean of left (A1) and right (A2) mastoid electrodes (see left of Fig. A.14 for potential maps). Neapolitan chords elicited a distinct ERAN (around 150-250 ms). The ERAN was directly succeeded by a right-frontally distributed negativity, which was maximal around 500-600 ms (the N5). Notably, no P3 (neither P3a, nor P3b), and no N2b was elicited (cf. also Fig.14.5),

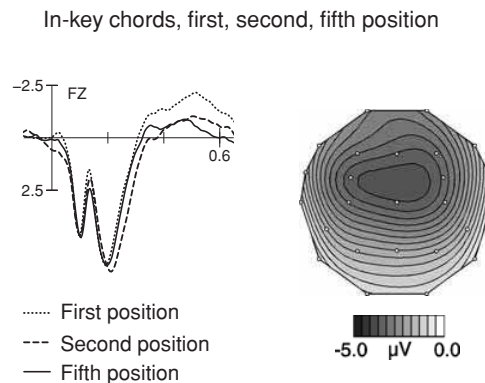


Figure 14.2: Grand-average ERPs of in-key chords from the 1st, 2nd, and 5th position (left). Right: Potential-map of the position-effect between chords at the 1st and 5th position (difference-ERPs: chords at the fifth subtracted from first position, view from top), interpolated over the time window from 540 – 600 ms.

indicating that the stimulation was actually ignored by the participants during the epochs included in the data-analyses.

When the ERP-data were referenced to the nose-electrode, the ERAN inverted polarity over left fronto-temporal and right centro-parietal electrode sites. The N5 also inverted polarity with nose-reference, namely over the left hemisphere at a line from left frontal over fronto-temporal to central electrodes, and over the right hemisphere at a line from central over fronto-central to temporal electrode sites (right of Fig.A.14).

A two-factor ANOVA for an early time interval (150 – 210 ms), employing chord-type (in-key chords vs. Neapolitan chords) and lateralization as factors, revealed an effect of chord-type ($F(1, 16) = 42.38$, $p < 0.0001$) and an interaction between the two factors ($F(1, 16) = 5.26$, $p < 0.05$). An analogous ANOVA (factors chord-type x lateralization) for a late time interval (540 – 600 ms) showed an effect of chord-type ($F(1, 16) = 47.27$, $p < 0.0001$) and an interaction between the factors ($F(1, 16) = 4.96$, $p < 0.05$).

Third position: An ERAN elicited by Neapolitans compared to in-key chords at the third position was very small in amplitude (n.s.), and only visible in the potential maps (Fig. A.15). A distinct late frontal negativity with a right preponderance is clearly visible in both the ERP-plot (Fig. 14.4) and the potential maps (Fig. A.15). However, this lateralization was statistically not significant. Neither ERAN, nor N5 inverted polarity when nose-reference was used (right of Fig.A.15).

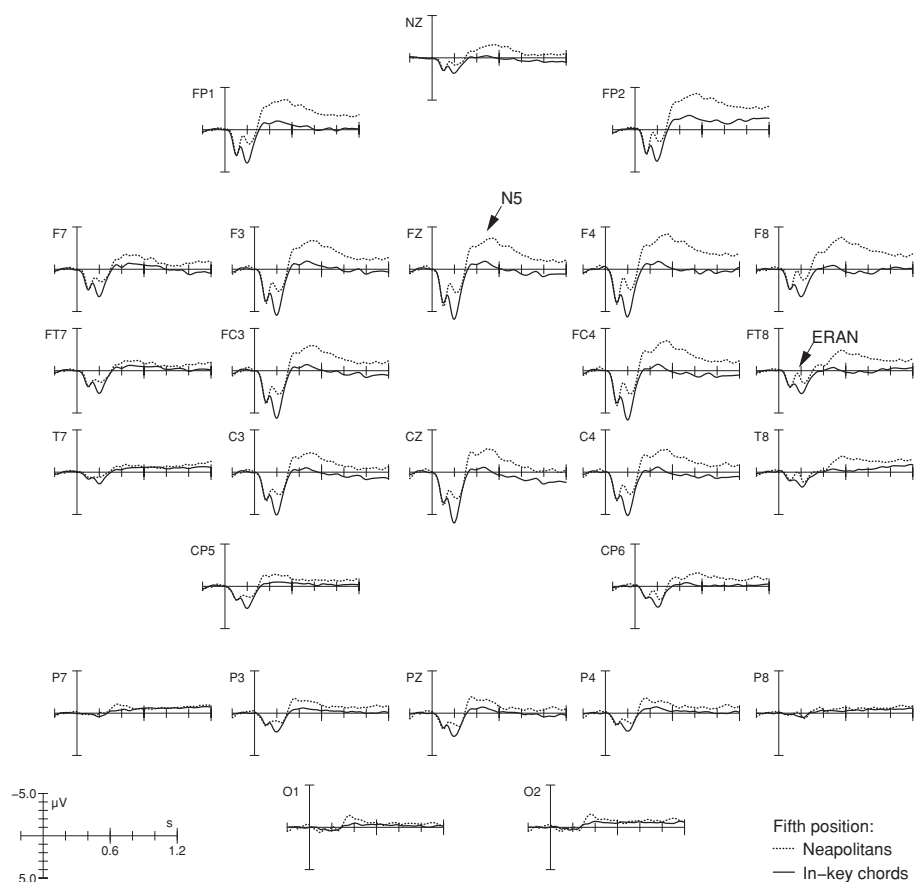


Figure 14.3: 5th position, grand-average ERPs of Neapolitans and in-key chords (reading condition). NZ: nose electrode, reference was the mean of A1 and A2.

An ANOVA with factors chord-type and lateralization, conducted for the early (150 – 210 ms) time-interval yielded a marginal effect of chord-type ($F(1, 16) = 3.67$, $p < 0.1$, no interaction between the two factors). The analogous ANOVA for a late time-interval (540 – 600 ms) revealed an effect of chord-type ($F(1, 16) = 16.93$, $p < 0.001$), and no interaction between the two factors.

Effects of position: The ERP-effects elicited by Neapolitans at the third opposed to the fifth position are shown in Fig. 14.5. Both early and late negativities were distinctly larger when elicited at the fifth compared to the third position. An ANOVA for the 150 – 210 ms time interval with factors chord-type (in-key vs. Neapolitan chords) and position of chords in the cadence (3rd vs. 5th) revealed an effect of chord-type ($F(1, 16) = 26.87$, $p < 0.0001$),

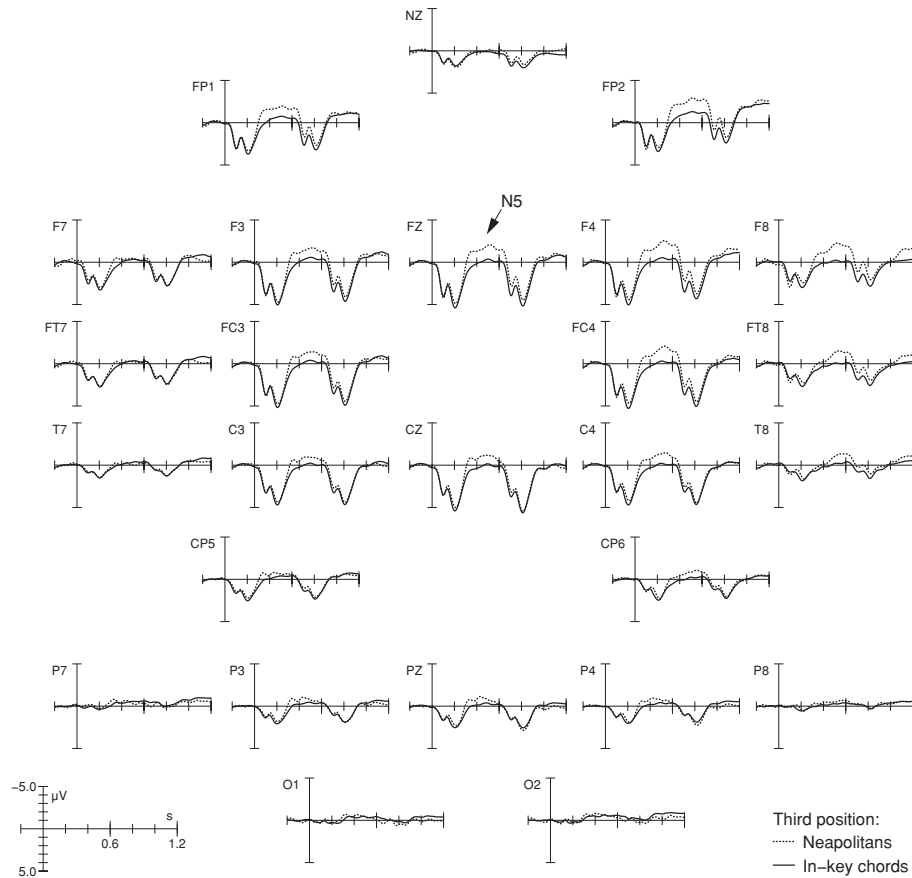


Figure 14.4: 3rd position, grand-average ERPs of Neapolitans and in-key chords (reading condition). Reference: mean of A1 and A2.

and an interaction between the two factors ($F(1, 16) = 26.43$, $p < 0.0001$). The analogous ANOVA for the 540 – 600 ms interval also revealed an effect of chord-type ($F(1, 16) = 41.96$, $p < 0.0001$), and an interaction between the two factors ($F(1, 16) = 16.54$, $p < 0.001$).

14.3.2 Discussion

Similarly to Experiment 1, progressing in-key chords elicited a negative ERP deflection which was maximal at frontal electrodes around 500 – 600 ms after the onset of a chord. This deflection is regarded here as N5, and (analogously to Experiment 1) suggested to reflect the musical integration of in-key chords into the preceding harmonic context. The

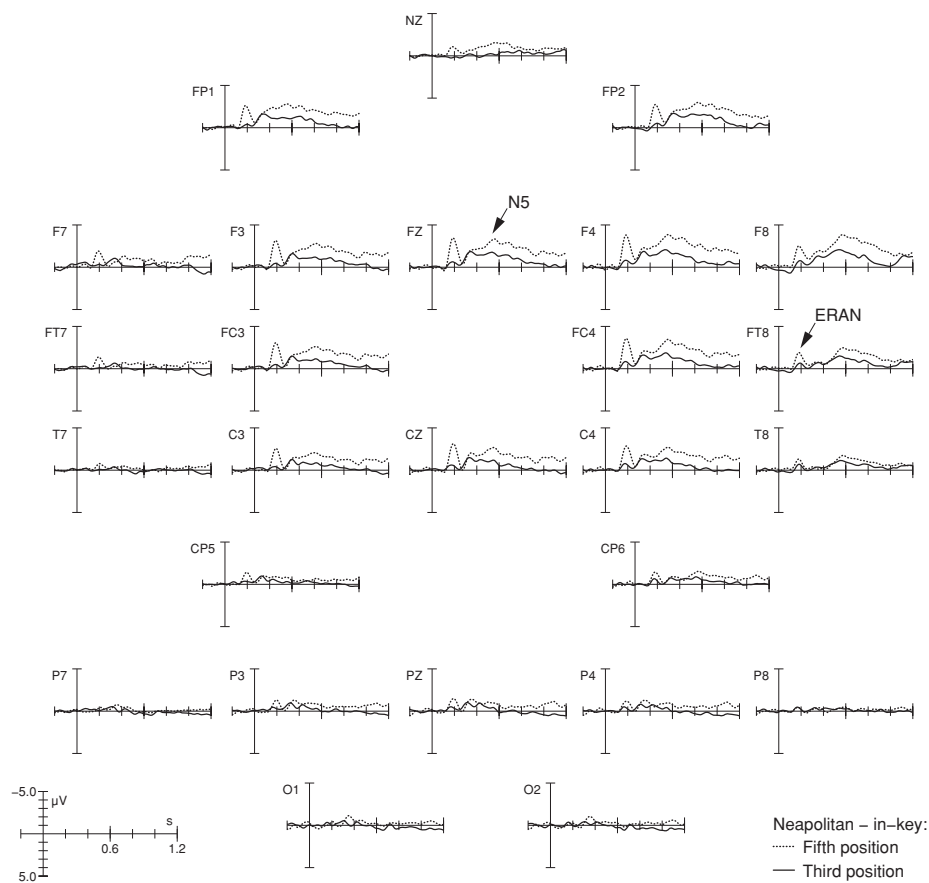


Figure 14.5: 5th vs. 3rd position, grand-average ERPs of effects elicited by Neapolitans (difference-waves: in-key chords subtracted from Neapolitans). Reference was the mean of A1 and A2.

amplitude of the N5 decreased when elicited at the end compared to the beginning of a chord-sequence. This amplitude reduction is (also analogously to Experiment 1) suggested to reflect the build-up of musical context (see p. 81 for further explanation). Importantly, as in Experiment 1 the amplitude of the N5 depended on the position in a cadence, rather than on the amount of different chord functions presented at each position of the cadences (cf. Fig. 14.2).

Notably, the decline of the N5 was present though participants were reading a book during the stimulation. This finding suggests (1) that a musical context was build up pre-attentively in the brains of participants (that is even though the musical stimuli were ignored), and (2) that participants processed both language and music simultaneously.⁴

Neapolitan chords elicited both ERAN and N5 (for the interpretation of ERAN and N5 see discussion of Experiment 1, pp. 81-88).⁵ Contrary to Experiments 1-4, but similarly to Experiment 5, the N5 was lateralized to the right. As in Experiment 5, the lateralization of the N5 is suggested to be due to a habituation of the participants to the processing of the Neapolitan chords. Compared to the previous experiments, the duration of the first block of the present experiment was about three times longer. Besides, the stimulation of the present experiment was less diversified compared to Experiments 1-4 (where the N5 was not lateralized), since no secondary dominants were employed. Similarly to Experiment 5, participants might have realized in the present experiment that they were confronted with only one type of violation (Neapolitan chords) that occurred infrequently at either the third or the fifth position. As in the previous experiment, the brain-system processing the Neapolitans might thus have reduced its activity in the left hemisphere for the reason of efficiency.

Importantly, both ERAN and N5 were elicited pre-attentively (since participants were reading). This finding indicates that ‘non-musicians’ automatically process chords with out-of-key notes in a different way from in-key chords.

As in Experiment 1, the amplitude-difference between effects elicited by Neapolitan chords at the third and at the fifth position could not be due to any physical difference between Neapolitan chords at the third and fifth position (whether presented at the third or fifth position, Neapolitan chords consisted on average of the same notes, and all chords had the same loudness-decay). The amplitude-difference could only be due to the harmonic expectancy of listeners, which was induced by the preceding harmonic context, and which was more specific at the fifth compared to the third position of the cadence. Thus Neapoli-

⁴Most of the subjects reported that they were not distracted by the musical stimuli, and that they were happy that they were paid for reading during the experiment. Therefore, it is assumed here that participants were actually reading during the experiment (and not just moving their eyes).

⁵The lateralization of the early negativity elicited at the third position was statistically not significant, but visible in the ERPs and thus regarded here as ERAN.

tans at the fifth position violated this harmonic expectancy to a higher degree compared to Neapolitan chords at the third position of a cadence.

The differing degree of harmonic expectancy violation is reflected in the brain responses, and corresponds with the logic of music theory (see p. 70 and pp. 83-86). Given that participants were ‘non-musicians’ who ignored the musical stimulation, the present results are thus taken to indicate a pre-attentive musicality of the human brain.

14.4 Block 2: Attend condition

14.4.1 Results

Behavioral Data

Behavioral data are shown in Tab. 14.1. Participants detected distinctly more Neapolitans at the fifth position (97%) compared to the third position (74%). Similarly, the false-alarm rates were higher for responses at the third (participants responded on average to 2% of all in-key chords) compared to the fifth position (0.45%). Reaction times were only slightly (n.s.) faster for Neapolitan chords at the fifth (567 ms) compared to the third position (596 ms). An ANOVA of hit percentages at the fifth vs. third position revealed an effect of position ($F(1, 17) = 28.7$, $p < 0.0001$). An ANOVA of false-alarm percentages at the fifth vs. third position also revealed an effect of position ($F(1, 17) = 7.77$, $p < 0.05$).

Position	Reaction Times	Hits (in %)	False Alarms (in %)
3 rd	596 (74)	74 (21)	2.0 (2.5)
5 th	566 (158)	97 (4)	0.4 (0.5)

Table 14.1: Behavioral data (grand averages), separately for chords at the third and fifth position. Mean and standard deviation (in brackets) of reaction times, hit percentages (with respect to Neapolitan chords), and false alarm percentages (with respect to in-key chords). Means were first calculated for each subject, and then averaged across subjects.

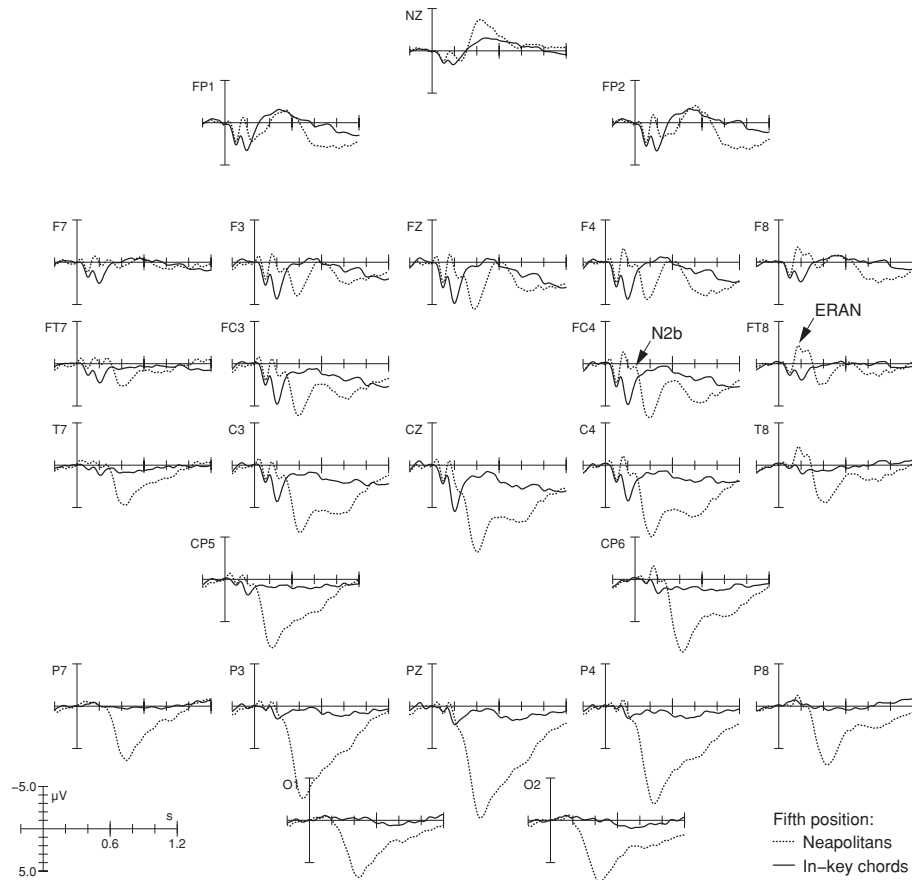


Figure 14.6: 5th position, grand-average ERPs of Neapolitans and in-key chords (attend condition). NZ: nose electrode, reference was the mean of A1 and A2.

ERP-effects

Fifth position: Brain responses to Neapolitans opposed to in-key chords are shown in Fig. 14.6. As in the first block, Neapolitan chords elicited an ERAN. The ERAN was followed by an N2b-P3-complex (reflecting the conscious detection of Neapolitan chords and the decisional processes related to the button-press-responses, cf. e.g. Näätänen, 1992, Schröger, 1998). Contrary to the first block, an N5 was virtually not observable. Similarly to Block 1, when nose-reference was used the ERAN inverted polarity at temporal and centroparietal sites (right of Fig. A.16).

A two-factor ANOVA for an early time interval (150 – 210 ms), employing chord-type (in-key chords vs. Neapolitan chords) and lateralization as factors, revealed an effect

of chord-type ($F(1, 16) = 55.54$, $p < 0.0001$) and an interaction between the two factors ($F(1, 16) = 8.13$, $p < 0.05$). Because of the overlap of N5 and P3, no ANOVA was conducted for the late (540 – 600 ms) time window.

Third position: An early right anterior negativity is observable in the ERPs of Neapolitan chords at the third position opposed to in-key chords (Fig. 14.7), as well as in the potential maps (Fig. A.17). However, this early negativity was statistically not significant. A P3 was maximal around 400 ms, an N5 is only tendentially visible at anterior leads.⁶ Similar to the first block, neither ERAN nor N5 inverted polarity when nose-reference was used (right of Fig.A.17).

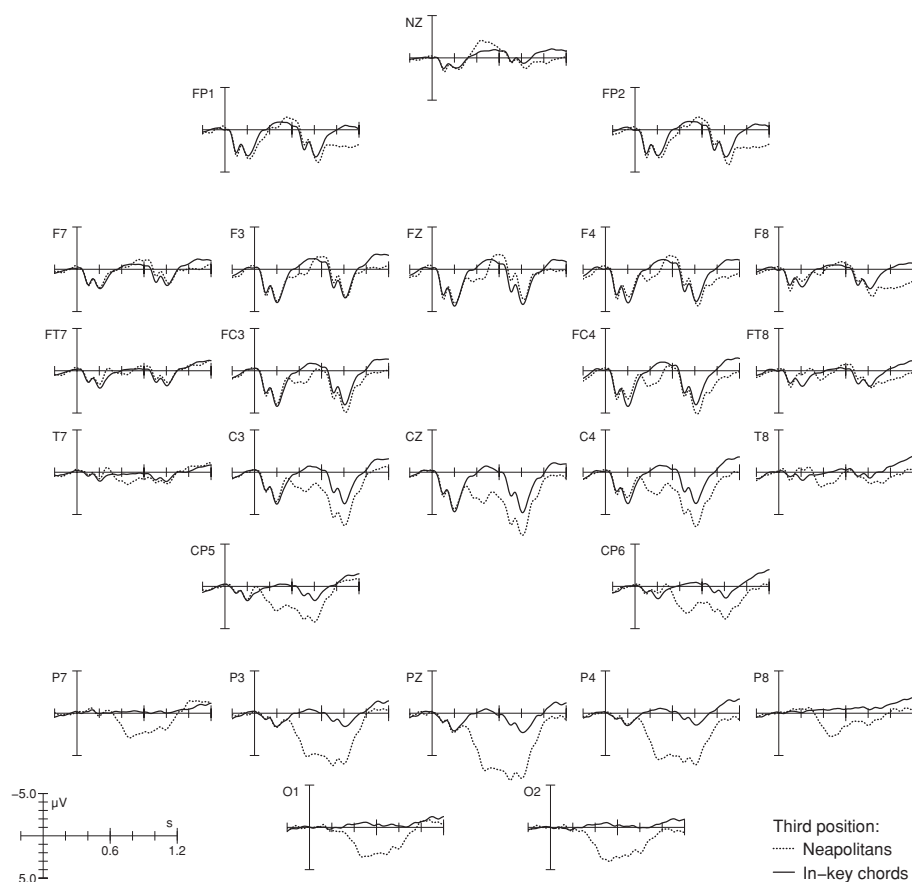


Figure 14.7: 3rd position, grand-average ERPs of Neapolitans and in-key chords (attend condition). Reference was the mean of A1 and A2.

⁶No ANOVA was conducted for the late (540 – 600 ms) time window because of the overlap of N5 and P3.

As in Block 1, the ERAN was larger in amplitude when evoked at the fifth position. An ANOVA with factors chord-type (in-key vs. Neapolitan chord) x position (3rd vs. 5th), 150 – 210 ms, revealed an effect of chord-type ($F(1, 16) = 27.96$, $p < 0.0001$), and an interaction between the two factors ($F(1, 16) = 28.12$, $p < 0.0001$).

Effects of attention and detection: Comparing ERP-effects of Neapolitan chords from the first and the second block, the amplitude of the ERAN elicited at the fifth position of the cadence shows at most of the electrodes only a little difference between both blocks (Fig. 14.8). However, especially right lateral leads (F8, FT8, T8), the ERP-effects elicited by Neapolitans from the second block tended to be more negative from around 180 ms on compared to early effects elicited in the first block. An ANOVA comparing data for the chords at the fifth position from block 1 and 2, conducted for the 150 – 210 ms interval with factors chord-type (in-key vs. Neapolitan chords at the fifth position), lateralization, and block (1st vs. 2nd), revealed an effect of chord-type ($F(1, 34) = 107.65$, $p < 0.0001$), an interaction between factors chord-type and lateralization ($F(1, 34) = 12.39$, $p < 0.005$), and a marginal interaction between factors chord-type and block ($F(1, 34) = 4.06$, $p < 0.06$).

When elicited at the third position, the amplitude of the ERAN did virtually not differ between block one and two.⁷ A statistical analysis for the 150 – 210 ms time interval did not reveal any difference between effects elicited in the first vs. second block.

14.4.2 Discussion

As in Experiment 3, participants detected distinctly more Neapolitans at the fifth compared to the third position of the chord-sequences, indicating that Neapolitan chords were more salient at the fifth than at the third position. Again, reaction times for both Neapolitans at the fifth and third position were on average below 600 ms, thus the higher hit rate at the fifth position is unlikely to be due to the longer duration of Neapolitan chords at the fifth position, or to any other physical difference between the chords.

⁷Though, similar to the fifth position, the ERPs of Neapolitans were compared to in-key chords slightly more negative at FT8 and T8.

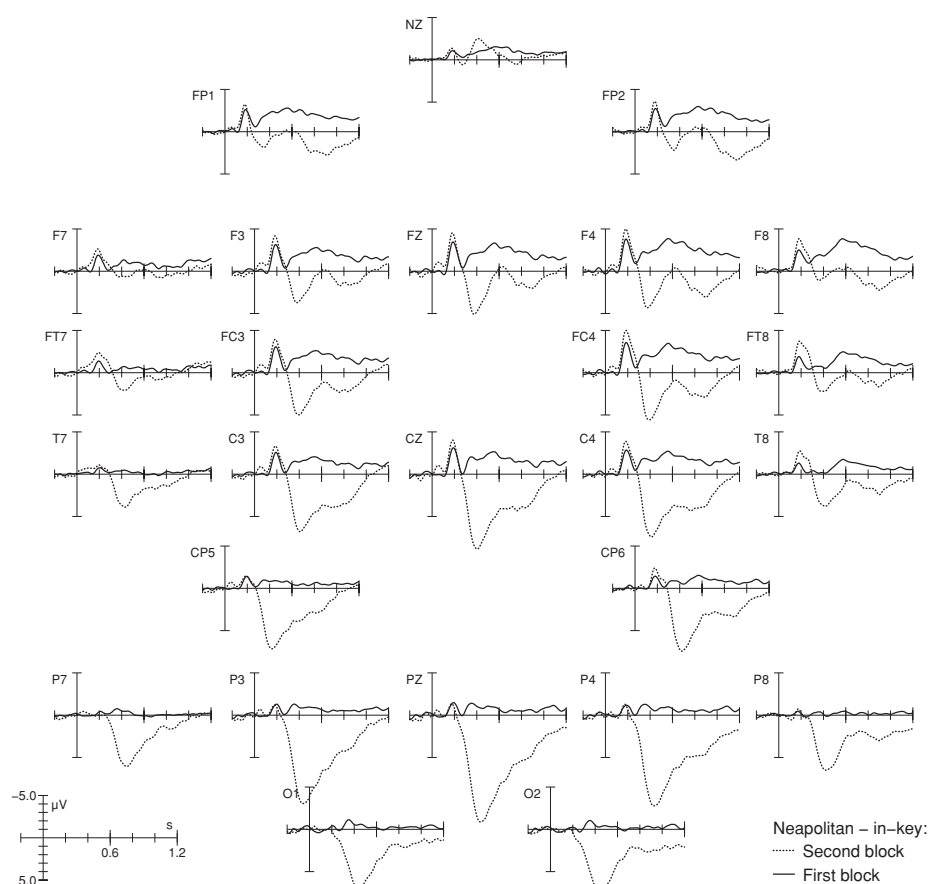


Figure 14.8: Block 1 vs. 2, grand-average ERPs of effects elicited by Neapolitans at the 5th position (difference-waves: in-key chords subtracted from Neapolitans). Reference was the mean of A1 and A2.

The greater saliency of Neapolitan chords at the fifth position of the chord-sequences was also reflected in the ERPs. In both Block 1 and 2 Neapolitan chords at the fifth position elicited an ERAN which was distinctly larger compared to when elicited at the third position. In the first block, the amplitude of the N5 also clearly differed between Neapolitans at the third and fifth position (in the present block, the N5 was almost entirely overlapped by the potentials of the P3, see also p. 113). As in the discussions of Experiments 1 – 3, it is suggested that the foregoing musical context determined the processing of unexpected chords with respect of amplitudes (and latencies) of effects.

Results of Block 1 have already shown that the ERAN can be elicited even pre-attentively. Interestingly, the ERAN did at most electrodes virtually not differ between

blocks. Only at peripheral right fronto-temporal electrodes, the ERAN was slightly more negative when elicited under attend conditions (i.e. compared to when elicited in Block 1). Statistically, the data of both blocks did only marginally differ. However, the difference in amplitude of the ERAN elicited in Block 1 vs. 2 might become significant in an Experiment employing more trials (resulting in a higher SNR). The ERAN is, for the time being, therefore taken here as only marginally influenced by attention.⁸

⁸This interpretation also corresponds to the effect of task-relevancy on the ERAN, see Experiment 3.

Chapter 15

Experiment 7

Localizing neural correlates of music perception

15.1 Introduction

The present experiment aimed on localizing the neural generators of the ERAN using MEG.¹ In order to compare data from EEG and MEG, the same experimental paradigm as in Experiment 1 was employed.

Up to now, only little is known about the brain structures involved in the processing of music, especially with respect to the processing of multi-part music (i.e. mainly consisting of chords; for a PET-study investigating emotional aspects of music processing see Blood et al., 1999). However, brain structures involved in the processing of one-part (i.e. melodic) stimuli have quite intensively investigated in patients with brain lesions.

In a classic paper, Milner (1962) described deficits following right temporal lobectomy for timbre, duration and tonal patterns, but not for simple pitch discrimination.² Concepts of strict hemispheric differences, however, did not hold properly. Generally, studies with

¹Due to its latency, it was not expected that the N5 could be explained with a two-dipole-solution (cf. Chapter 5). Given the constraints of signal-to-noise ratio and inverse problem for solutions employing more than two dipoles (see also Chapter 5), the investigation of the N5 with MEG data was not the primary subject of the present experiment.

²The contrast between these impairments and the linguistic deficits following left temporal-lobe damage was initially conceptualized as corresponding to a verbal/non-verbal dichotomy.

brain-damaged patients found deficits after right temporal lobe lesions in tasks demanding the processing of melodies with respect to contour and interval information (see e.g. Zatorre, 1985; Peretz, 1990), as well as with respect to timbral information (e.g. Milner, 1962; Samson & Zatorre, 1993). Damage to the left side appears to cause problems when familiar tunes are involved, especially if naming or identification is required, regardless of the presence or absence of aphasia. Damage to the right hemisphere also affects performance in such cases, but not usually to the extent that left-hemisphere lesions do (see e.g. Zatorre, 1984; Peretz, 1990; Peretz et al., 1994; Platel et al., 1997; Liegeois-Chauvel et al., 1998, for more detailed descriptions).

In addition to the important role of the (superior) temporal lobes in music processing, Shapiro et al. (1981) and Grossman et al. (1981) suggested that damage to the anterior portion of the right hemisphere, presumably including the right frontal lobe, can cause deficits in melodic perception, especially in the detection of pitch changes within melodic segments. This hypothesis was supported by functional imaging studies which also indicated that regions of auditory cortex within the right superior temporal gyrus are specifically involved in analysis of pitch (Zatorre et al., 1992), and that working memory for pitch entails interactions between temporal and frontal cortices (Zatorre & Samson, 1991; Zatorre et al., 1994).

15.1.1 Musical syntax as reflected in ERPs

In Experiments 1 – 6, the processing of musical syntax has been found to be reflected electrically as the ERAN. The ERAN was elicited when a harmonically unexpected chord occurred within in sequence of in-key chords.

As described before (p. 2, see also p. 69), it is commonly agreed that music has a syntax. However, which aspects of music may be described as ‘syntactic’ has remained a matter of debate (Swain, 1997; Raffmann, 1993; Paynter et al., 1997; Sloboda, 1985; Bernstein, 1976; Lerdahl & Jackendoff, 1999). In order to investigate the processing of a musical ‘syntax’ in Experiment 1, it was simply taken advantage of the psychological reality of musical syntax as demonstrated by the brain’s ability to expect musical events to a higher or lower degree (i.e. to identify ‘wrong’ notes, see e.g. Krumhansl & Kessler, 1982; Bharucha & Krumhansl, 1983; Bharucha & Stoeckig, 1986). That is, the principles

of harmonic relatedness (which are reflected in harmonic expectancies of listeners) were regarded as musical syntax.

Interestingly, violations of musical syntax were found to be reflected in the ERAN, which highly resembles the early *left* anterior negativity, which is thought to reflect syntactic processing of language (see p. 59 Friederici et al., 1993; Friederici, 1998; Hahne, 1999). Besides, an ERP-effect similar to the ERAN has recently been reported in a music experiment performed by Patel et al. (1998), in which unexpected chords elicited a right antero-temporal negativity (RATN), taken to reflect the application of music-specific syntactic rules (see p. 67). With this respect, the present experiment will also investigate if the ERAN is generated in brain areas which are also involved in the processing of syntax in language.

15.2 Methods

15.2.1 Subjects and stimuli

6 right-handed and normal hearing subjects ('non-musicians'³, aged 20 to 27 years, mean 22.5, 4 females) participated in the experiment.

Stimuli were the same as in Experiment 1. From the pool of 128 sequences, 1350 chord-sequences were randomly chosen, resulting in a total amount of 330 secondary dominants, 330 Neapolitans at the third, and 330 Neapolitans at the fifth position.

Criterion for an acceptable dipole-localization was for each subject a residual normalized variance of less than 10%. To reach this criterion, more stimuli as in Experiment 1 had to be employed in order to increase the signal-to-noise ratio (SNR) (see also p. 49).

15.2.2 Procedure

Participants performed 3 experimental sessions, each consisting of 3 blocks. No participant performed two sessions within less than two weeks. Each block consisted of 150

³See p. 72

chord-sequences, resulting in a total amount of 1350 chord-sequences per subject across all sessions. Each block was intermediated by a short pause. After such a pause, the following chord-sequences were from another key (resulting in 6 sub-blocks from different keys in every experimental session). Block-duration was approximately 10 min (the duration of an experimental session was approximately 35 minutes).⁴

Participants were seated in a comfortable chair and instructed to keep their eyes open and to look at a fixation-cross. They were only informed about the deviant instruments, not about the Neapolitan chords or their nature. An example of a cadence played on a piano and of a cadence in which one chord was played by a deviant instrument (organ) was presented to each participant before starting the MEG-measurement. Participants were instructed to ignore the harmonies and to detect the deviant instruments by pressing a response-button.

The position of the sensors with respect to the position of the head was recorded before each block and held as constant as possible across blocks and sessions. The dewar was positioned over the head in a way that the coverage of temporal as well as frontal areas was ensured. Besides, each subject's head shape was digitized with approximately 1300 points using a 'Polhemus 3space Fastrak' 3-d digitizer.

15.2.3 MEG recording

The continuous raw-MEG was recorded using a BTI Magnes WHS 2500 whole head system. 148 magnetometer channels, 11 magnetic reference channels and four EOG-channels were employed. MEG-signals were digitized with a bandwidth of 0.1 Hz to 50 Hz and a sampling rate of 254.31 Hz. The magnetometer signals were transformed into software gradiometer by the BTI online noise suppression method, which is a subtraction of a weighted sum of the reference channels from each of the 148 MEG channels (Robinson, 1989).

⁴Thus, in contrast to Experiment 1 subjects were confronted with distinctly more stimuli. The large amount of trials was needed in order to reach a signal-to-noise ratio of the data high enough for reasonable dipole fits (cf. p. 49). This strategy was justified by results of Experiment 6, where the ERAN (and the N5, respectively) turned out to be elicited automatically.

15.2.4 Postprocessing

In order to eliminate artifacts caused by eye-blinks, the standard-deviation was calculated for each 200 ms interval of each EOG-channel. Whenever the standard-deviation exceeded in any EOG-channel $30\mu V$ in such a 200 ms interval, all MEG-data within this interval were marked as rejected.

Artifacts produced by muscle-tensions and environmentally caused magnetic field variations were reduced by rejecting all MEG-data whenever the standard-deviation exceeded 1500 fT in any magnetometer-channel in any 200 ms interval, or 2500 fT in any 1000 ms interval. In case that a single channel was responsible for a rejection of more than 10% of the raw-data, this channel was excluded from further data-analysis, and the rejection-procedure was repeated without this channel.

In addition to the rejection procedure, channels not operating properly were detected by the following algorithm: For each epoch, the cross covariances of all channels were calculated. The elements S_{ij} of the resulting covariance-matrix were calculated according to:

$$S_{ij} = \sum_{k=1}^N S_{ik}S_{jk}; i, j = 1..L,$$

where N equals the number of samples in an epoch and L equals the number of channels.

The covariance-matrices were averaged across all epochs of one condition of one single block. The averaged covariance-matrices S were then transformed into correlation-matrices R :

$$R_{ij} = \frac{S_{ij}}{\sqrt{S_{ii}S_{jj}}}.$$

For each channel, the median of the magnitude of the correlation values of the spatially adjacent channels was calculated. The number of adjacent channels varied from 3-6, according to the position of a channel within the sensor-array (peripheral channels, e.g., have less neighbored channels compared to non-peripheral channels). A channel was excluded from further data-analysis of all data of the respective block when the value of the median did not exceed 0.78^5 . This value led to an exclusion of slightly more channels than sug-

⁵After trying some other values, this criterion was found to be reasonable for the present data.

gested by the rejection procedure or than yielded by visual inspection. On average, 2.8% of all channels were excluded.

The continuous MEG-data were then filtered with a 2-10 Hz bandpass filter (1001 points, FIR). Epochs were averaged separately for each condition for an interval of -400 – 600 ms relative to stimulus onset.

To guarantee that the head-position of one subject within the dewar differed only slightly between all blocks, sensor-positions measured before each block were compared with each other visually using *Advanced Source Analysis* (ASA, A.N.T.-software). The visual inspection with ASA also yielded which sensor-position was nearest to the mean of all measured sensor-positions from this subject. All averaged data from a subject were then transformed onto this sensor-position, resulting in a data-set virtually measured with a constant position of the head within the sensor across all blocks. Within this transformation procedure, channels excluded during the rejection procedure were interpolated. Subsequently, data of each condition were cumulated per subject across all blocks.

15.2.5 Modeling and Data-Analysis

For each participant, a realistically shaped volume conductor was constructed. The size of the volume conductor was according to the subject's real head size. This was achieved by adjusting the Curry-Warped brain in size to each subject's head shape (Maess & Oertel, 1999). This method results in individual scaling factors for all three spatial dimensions. The adjustment procedure thus enabled to a source localization with an accuracy close to that achieved with individual MR-based models. Besides, the scaling factors were also used for the back transformation of localization results into the Warped brain. Hence, the adjustment procedure additionally allowed a grand-average of the back transformed results of dipole-localizations. Back transformed dipole positions were subjected to statistical analysis.

In order to achieve a higher SNR, the event-related fields (ERFs) evoked by all in-key chords were cumulated (the magnetic field maps of the P1m, the N1m, and the P2m did virtually not differ between in-key chords presented at different positions within the chord-sequences). Data from in-key chords following a secondary dominant or a Neapolitan chord were discarded.

For source localization of the (early) effect elicited by Neapolitan chords at the fifth position, the event-related magnetic fields (ERFs) elicited by in-key chords at the fifth position were subtracted from the ERFs of Neapolitans.⁶

Dipoles were fitted as rotating dipoles (that is as regional sources, see Scherg, 1990; Scherg & Berg, 1996), using 3 to 9 sampling points preceding the maximal mean global field power (MGFP). Dipole localizations referred to the coordinate system defined by the pre-auricular (PA) points and nasion (x-axis from right to left PA, y-axis from nasion perpendicular through x-axis).⁷

ANOVAs were performed as repeated measures analysis of variance (univariate tests of hypotheses for within subject effects).

15.3 Results

In-key chords. Fig. 15.1 shows the brain responses of two subjects to in-key chords. At most sensors, the largest magnetic field strength was present around 200 ms (relative to stimulus onset). This magnetic effect will further be referred to as the P2m. The P2m revealed the largest mean global field power (MGFP) in four subjects, but was distinctly present in all subjects. Virtually no effects were present in the event-related magnetic fields (ERFs) after around 350 ms.

Neapolitan chords. Fig. 15.2 shows the brain responses to Neapolitan chords opposed to in-key chords elicited at the fifth position of the chord-sequences. The responses distinctly differed between Neapolitans and in-key chords. Neapolitan chords elicited a particular early magnetic field effect which was at any sensor nearly uni-modal over time⁸, and largest around 200 ms. This effect can best be seen in the difference waves of Fig. 15.2 and

⁶Both MEG-data (see *Results*) and data from EEG (see previous experiments) revealed that the ERAN has at any channel virtually the same latency and a unimodal time-course (between 100-300ms). We thus assume that the ERAN is elicited by a single activation in each hemisphere and can best be investigated using the difference-fields.

⁷For an illustration: The brain presented in (Nieuwenhuys et al., 1995, p. 12, see Appendix B) is approximately oriented according to this coordinate system.

⁸Due to the filtering, the uni-modality of the magnetic field effect was naturally best observable in the unfiltered data (not presented here).

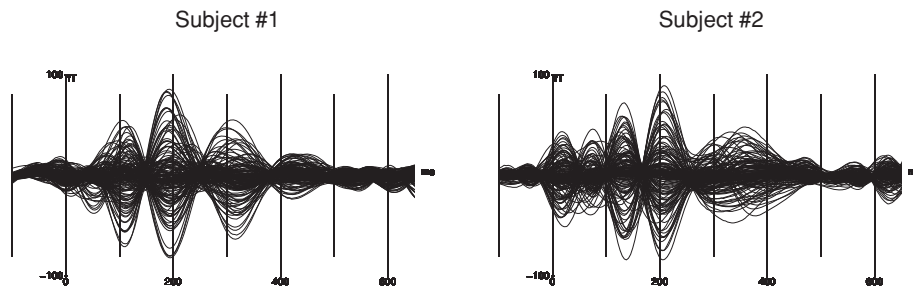


Figure 15.1: In-key chords: Time course of magnetic field strength of all sensors from two subjects. In-key chords were cumulated across all positions of the chord-sequences. The largest MGFP was present around 200 ms after the onset of the chords.

will further be referred to here as the ERANm. Virtually no magnetic effect was observable after around 350 ms, neither for Neapolitans, nor for in-key chords.

P2m vs. ERANm. Fig. A.18 shows the magnetic field maps of the ERANm (elicited at the fifth position) and the P2m (elicited in a similar time window by all in-key chords).⁹ The maps of the ERANm (right of Fig. A.18) were calculated by subtracting the event-related fields (ERFs) elicited by in-key chords at the fifth position from the ERFs of Neapolitans.

The field maps of both P2m and ERANm reveal a dipolar pattern over each hemisphere. As can be seen in the right of Fig. A.18, the steepest field gradients of the ERANm are located more anteriorly compared to those of the P2m (left of Fig. A.18). In all subjects the fields of the ERANm had virtually an inverted ‘polarity’ compared to the fields of the P2m.

Fifth vs. third position. Fig. 15.3 shows the time-course of magnetic field effects elicited by Neapolitans at the third position opposed to in-key chords (the corresponding magnetic field maps are shown in Fig. A.19). Compared to when elicited at the fifth position, effects elicited by Neapolitans at the third position were very similar in distribution and time-course, but distinctly smaller.

Dipole solutions. Means and standard errors of x-, y-, and z-coordinates, as well as of dipole moments and dipole normals are presented in Tab. 15.1.¹⁰ After obtaining dipole

⁹The magnetic field maps of the P2m did virtually not differ between in-key chords presented at positions 1 – 5 of the chord-sequences; see also *Methods*.

¹⁰See *Methods* for description of the coordinate-system

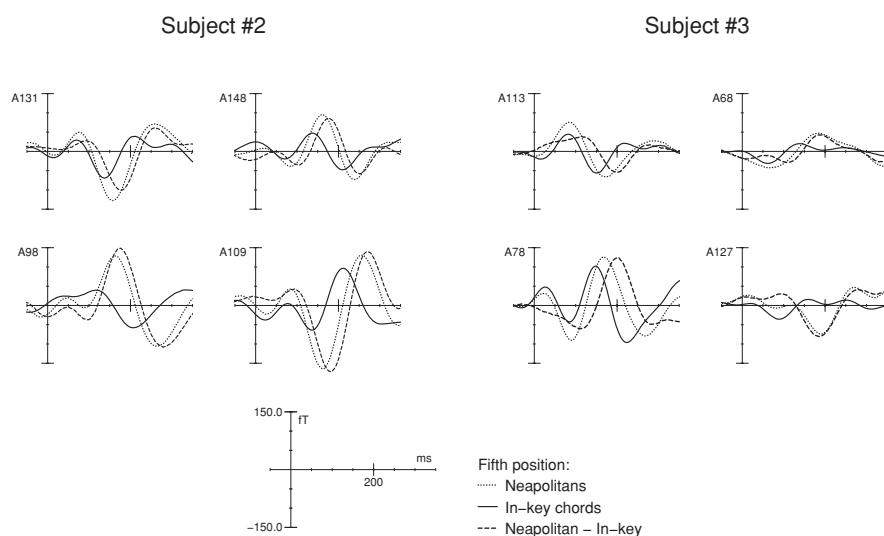


Figure 15.2: 5th position: Time course of magnetic field strength from two representative subjects, separately for Neapolitans and in-key chords (dotted line: difference-wave). Data were chosen from four sensors located in the magnetic field maxima. Neapolitan chords elicited an ERANm which was maximal around 200 ms.

solutions from each subject, locations of dipoles were back-transformed into the Curry-Warped brain, and then grand-averaged across subjects. Both dipole-solutions for the P2m (elicited by all in-key chords, left of Tab. 15.1) and the ERANm (elicited at the fifth position, right of Tab. 15.1) refer to two-dipole configurations (one dipole in each hemisphere). The residual normalized variance of dipole solutions was for all subjects on average 4.95% for the ERANm (original 9.78%), and 4.34% for the P2m of cumulated in-key chords (original 8.06%).

In both hemispheres, the generators of the ERANm had a different location compared to the P2m with respect to their y-coordinates (i.e. along the anterior-posterior dimension) and their z-coordinates (i.e. along the inferior-superior dimension). X-coordinates did only slightly differ between P2m and ERANm. In each hemisphere, the generators of the ERANm were located ca. 2.5 cm anteriorly, and 0.5 cm superiorly with respect to the generators of the P2m.

Besides, the generators of the P2m had a stronger dipole moment in the right than in the left hemisphere. Both generators of the ERANm had on average virtually the same strength. However, a clear right-predominance of the ERANm was present in four subjects.

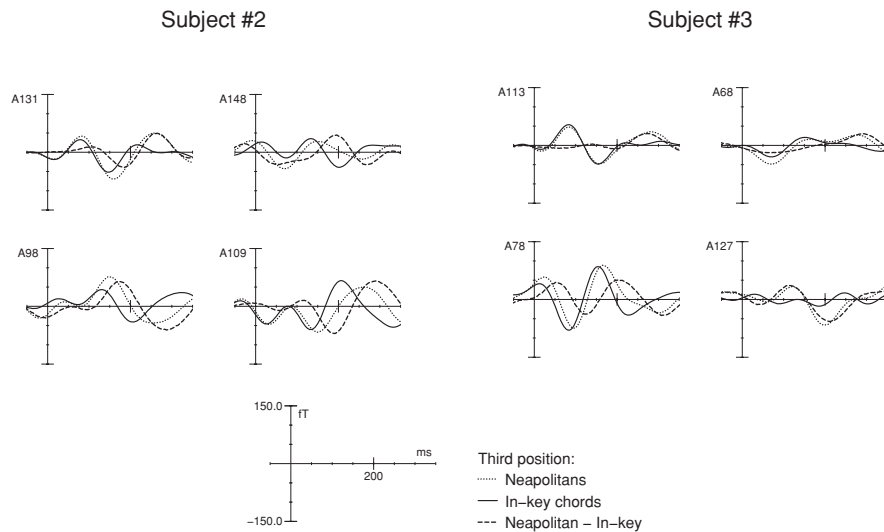


Figure 15.3: 3rd position, magnetic signals from two representative subjects (see Fig. A.19 for maps).

To proof the significance of the different dipole locations of ERANm and P2m, x-, y-, and z-coordinates were analyzed separately by conducting ANOVAs with factors condition (P2m vs. ERANm) and hemisphere (left vs. right dipoles). The ANOVA for the y-coordinates of dipoles yielded an effect of condition ($F(1, 5) = 37.23$, $p < 0.005$), and no interaction between the two factors. The analogous ANOVA for the z-coordinates also revealed an effect of condition ($F(1, 5) = 21.48$, $p < 0.01$) and no interaction. No effect was yielded for the corresponding ANOVA of the x-coordinates.

Fig. A.20 shows the grand-average of back-transformed dipole solutions for the P2m (axial slices parallel to AC-PC line¹¹). In each hemisphere, a dipole was located within the middle part of Heschl's gyrus (see Appendix B). Both dipoles were oriented towards fronto-central brain regions.

The dipole solution for the ERANm (grand-average of back-transformed dipole solutions) are shown in Fig. A.21. In each hemisphere, one dipole was located within the lower part of the pars opercularis (in the inferior frontal gyrus), i.e. in the lower part of Brodman's area (BA) 44 (see Appendix B). The dipole in the right hemisphere was oriented towards (right) frontal brain regions, the left dipole was directed towards right central regions.

¹¹AC: anterior commissure, PC: posterior commissure

Dipole-coordinates				
	P2m left	P2m right	ERANm left	ERANm right
x [mm]	44.8 (1.8)	-46.4 (1.8)	44.5 (4.8)	-49.9 (2.4)
y [mm]	-8.3 (4.1)	-11.6 (1.7)	-32.8 (3.4)	-35.9 (3.7)
z [mm]	48.2 (1.6)	48.3 (0.7)	53.9 (0.8)	55.9 (1.5)

Dipole-normals				
	P2m left	P2m right	ERANm left	ERANm right
x	-0.22 (0.23)	0.23 (0.24)	0.10 (0.29)	-0.10 (0.36)
y	-0.61 (0.14)	-0.57 (0.14)	-0.06 (0.26)	0.05 (0.22)
z	0.38 (0.08)	0.43 (0.08)	-0.05 (0.18)	-0.16 (0.08)

Dipole-moments [nAm]			
P2m left	P2m right	ERANm left	ERANm right
16.6	25.1	41.6	42.9

Table 15.1: Location, normals, and strength of P2m (left) and ERANm (right) dipoles, separately for left and right hemisphere. Coordinate system refers to pre-auricular points and nasion (see *Methods*); i.e. x-Dimension: right - left, y-Dimension: anterior - posterior.

Criterion for an acceptable dipole-solution was the explanation of at least 90% of normalized variance for each subject (see *Methods*). For the ERANm elicited at the third position, the data of only two subjects enabled to fulfill this criterion (most presumably due to the smaller signals which caused a decrease of the SNR). Thus, no grand-average analysis of dipole-solutions was carried out for the ERANm elicited at the third position.

15.4 Discussion

In-key chords elicited a distinct magnetic field effect which was maximal around 200 ms. This effect was consistent over all subjects and is referred to here as the P2m. The grand-average of back-transformed dipole-solutions yielded two generators of this effect, one lo-

cated in each hemisphere in the middle of Heschl's gyrus. That is, the generators of the P2m were located within, or in the close vicinity of the primary auditory cortex, near to the generators of the P1m (Liegeois-Chauvel et al., 1994; Mäkelä et al., 1994; Pantev et al., 1995) and the N1m (Hari et al., 1980; Pantev et al., 1989, 1990). Both generators were oriented towards fronto-central regions of the head.

The P2m is suggested here as the magnetic counterpart of the electric P2¹², due to its time-course (which is almost identical to the time course of the P2 obtained in the previous experiments), its 'polarity', as well as the location and orientation of its generators.¹³ The dipole of the P2m had a stronger dipole moment in the right compared to the left hemisphere. This finding might reflect a preference of the right hemisphere for the processing of tones and chords (e.g. Auzou et al., 1995; Zatorre et al., 1992; Levänen et al., 1996).

The localization of the P2m in the Heschl's gyrus is extremely plausible, since this location is in the close vicinity of the generators of the P1m and the N1m. The localization of the P2m thus justifies the method of using individually shaped BEM-models derived from the Curry-Warped brain.

Neapolitan chords. The event-related magnetic fields (ERFs) elicited by Neapolitan chords at the fifth position of the chord-sequences distinctly differed from those elicited by in-key chords from the same position. Neapolitan chords elicited an early magnetic field effect that was maximal around 200 ms and is referred to in the present study as the ERANm. The ERANm had at any sensor nearly a uni-modal magnetic field strength distribution over time, suggesting that the ERANm is elicited by a single activation in each hemisphere (see also *Methods*).

The ERANm is regarded here as the magnetic counterpart of the (electric) ERAN. Four findings support this assumption: (1) The time-course of the ERANm was virtually identical to the time course of the ERAN (measured in the previous experiments). (2) In all subjects, the fields of the ERANm had virtually an inversed 'polarity' compared to the fields of the P2m (corresponding to the ERAN and the P2). (3) the ERANm is, like the ERAN, sensitive to the build up of musical context (since effects were considerably smaller when elicited

¹²To my knowledge, a localization of P2-generators is reported here for the first time.

¹³When active, the generators would generate a positive electric potential over fronto-central scalp regions.

by Neapolitans at the third position). (4) The ERANm turned out to be sensitive to chords containing unexpected notes.¹⁴

Dipole Localization of the ERANm. The magnetic field maps of both P2m and ERANm revealed a dipolar pattern over each hemisphere. The steepest field gradients of the ERANm were located more anteriorly compared to those of the P2m, indicating that the neural generators of the ERANm are located more anteriorly than those of the P2m.

This finding was supported by the results of dipole-solutions. Surprisingly, in contrast to the P2m the generators of the ERANm were *not* located within the temporal lobe. Compared to the P2m, the ERANm was generated approximately 2.5 cm anteriorly, and 0.5 cm superiorly (with respect to the coordinate-system defined by pre-auricular points and nose, see *Methods*). The x-coordinates of P2m dipoles did virtually not differ from those of the ERANm, indicating that the ERANm is, like the P2m, generated near the surface of the cortex.

The grand-averaged dipole-solutions yielded that the generators of the ERANm are located in each hemisphere within the lower part of the pars opercularis (which corresponds to the lower part of BA 44; see Appendix B for illustration).¹⁵ In the left hemisphere, this area is classically called Broca's area.

Notably, during language perception the area of Broca is thought to be responsible for the processing of syntactic elements and syntactic sequences, involved in the syntactic analysis of incoming language input (in the sense of determining grammatical relations in a sentence), and specialized for fast and automatic access to syntactic information (for review see Friederici, 1998).

It is interesting to note that the early *left* anterior negativity (ELAN) also seems to be generated, at least partially, in the Broca's area (and in the homologous area in the right hemisphere, Friederici et al., 1999). The ELAN has so far been found to be generated in auditory language experiments by the violation of syntactic rules, as well as by uncommon syntactic phrases (see p. 59, for review see Hahne, 1999). Due to its properties, the ELAN

¹⁴For the interpretation of the ERAN see discussion of Experiment 1.

¹⁵Even when dipole locations were shifted towards the temporal lobes by the value of the standard error, they remained in the inferior frontal gyrus, i.e. outside the temporal lobe.

may be hypothesized to reflect a parsing of incoming language input into an initial syntactic structure.

As stated in the discussion of Experiment 1, the ELAN highly simulates the ERAN. Though the ELAN is often more predominant over the left hemisphere, both ELAN and ERAN are early anterior negativities. Besides, both ELAN and ERAN seem to be (at least partly) generated in the area of Broca. It is therefore suggested here that the Broca's area may also be involved in determining harmonic relations within a musical phrase, and that the determination of harmonic relation is a 'syntactic' analysis of incoming musical input. As syntactic information of language, which is fast and automatically processed in the Broca's area, music-syntactic information processed in the same (and right homologous) brain structure also seems to be processed automatically (cf. Experiment 6).

Whereas the syntax of language is quite well-defined, the syntax of music becomes apparent only in the brain activity of individual listeners. This brain activity depends on musical expectancies, which seem in the first line to be connected to the music-theoretical principles of harmonic relatedness. Importantly, these expectancies may vary due to the experiences of listening (cf. Experiment 4), and have during the history of music composers led to invent new chords, modulations, sounds, etc.

The magnetic fields of ERANm were in four (out of six) subjects (but not in the grand average) distinctly stronger over the right than over the left hemisphere. This finding corresponds to the ELAN, which is also only prevalently (but not consistently) stronger over the left hemisphere. It is thus suggested here, as a working hypothesis, that the left pars opercularis is prevalently stronger involved in the processing of language syntax (compared to the homologous right area), and the right pars opercularis rather in the processing of musical syntax. This might account for the parallel processing of (written) language and music (as suggested by the data of Experiment 6).

It is important to note that the results strongly suggest that the ERAN is not a mismatch negativity (MMN, see p. 52). No Neapolitan-specific temporal lobe activation was yielded to be involved in the generation of the ERANm. This contrasts the MMN, which is known to be generated (at least to a considerable amount) in the temporal lobes (Hari et al., 1984;

Giard et al., 1990; Alho et al., 1992; Giard et al., 1995; Levänen et al., 1996; Opitz et al., 1999b, for review see Alho (1995)). With this respect, the ERAN seems to be an ERP-component which has been described for the first time in the present study.

Chapter 16

Summary and General Discussion

The present study aimed at investigating how and where the brain processes music. A particular interest was the exploration of differences and similarities between the neural processing of music and language. The employed experimental paradigm was therefore designed in a way that it reminded of experimental paradigms used in many language experiments.

The basic stimulus material consisted of sequences of four-part in-key chords which built up a musical context towards the end of each sequence. Such chord-sequences were taken as musical equivalent to a spoken sentence in language (where a semantic context is built up a towards the end of a sentence).

Infrequently, an in-key chord was replaced by a chord (or even a non-harmonic cluster) that contained out-of-key notes. Music-theoretically spoken, such an out-of-key chord is harmonically unrelated to the preceding harmonic context. From a music-psychological point of view, a hamonically unrelated chord is perceived as unexpected. Chords with out-of-key notes may be imagined as musical equivalent to incongruous words occurring within a sentence (in language experiments often used to investigate syntactic and semantic aspects of language processing).

All participants of the present study were ‘non-musicians’ who had no special musical expertise. Seven experiments were conducted in which the experimental conditions were varied with respect to the degree of harmonic sound expectancy violation, task-relevancy, probability, embeddedness of unexpected chords within a tonal modulation, and attention.

Experiment 1: Musical context build-up

The first experiment aimed at investigating reflections of musical context build-up, and of the processing of musical violations. Chords with out-of-key notes were Neapolitan chords, which occurred at either the third or the fifth position. Secondary dominants were infrequently presented at the second position of a chord-sequence. Subjects were instructed to ignore the harmonies and to detect chords which were infrequently played on a deviant instrument (instead of the frequently playing piano).

ERP-waveforms of in-key chords elicited a negative frontal deflection around 550 ms which declined towards the end of the chord-sequence. This deflection has to my knowledge not been described before and was, as a working label, termed the 'N5'. The N5 is suggested to reflect processes of musical integration. Cadences which consisted of in-key chords were arranged in such a way that the progressing chords built up a musical context (similarly to spoken words which build up the context of a sentence). The establishment of a musical context entails the build-up of a tonal hierarchy of stability (e.g. Krumhansl & Kessler, 1982; Bharucha & Krumhansl, 1983, see also Chapter 3). The amplitude-decline of the N5 is therefore taken to reflect the perceived increasing harmonic stability which is built up by the establishment of a musical context. That is, musical integration requires an on-line specification or modification of both tonal schema and hierarchy of harmonic stability.

It is interesting to note that such a similar amplitude reduction is known from language experiments where the amplitude of the 'N400' (elicited by open class words) declines towards the end of a sentence. This phenomenon is commonly interpreted as reflection of semantic context build-up during language processing (Van Petten & Kutas, 1990).

Notably, the amplitude of the N5 elicited by progressing in-key chords varied as a function of the position in a cadence, and not as a function of the number of different chord functions presented at each position of the cadences: The N5 was larger at the fourth compared to the fifth position (though only one chord function occurred at the fourth position), and the N5 was larger at the first compared to the fourth position (though at both positions only one chord function occurred). This finding indicates that the position-effect of the N5 cannot be due to regularities of the experiment itself.

Experiment 1: Processing musical violations

Neapolitan chords and secondary dominants elicited an early right anterior negativity with an onset around 150 – 200 ms. To my knowledge, this ERP-effect has not been reported before. In order to label this empirically observed effect, the early right anterior negativity was (as a convenient working term) named ‘ERAN’.

The ERAN is suggested to reflect the violation of sound expectancy. Data obtained in music-psychological experiments by behavioral measures (e.g. Krumhansl & Kessler, 1982; Bharucha & Krumhansl, 1983) demonstrated that the sound of chords containing out-of-key notes is perceived as unexpected by the listeners. The degree of unexpectedness generally varies according to music-theoretical principles. That is, a musical context induces expectations for related chords to follow by activating representations of distance and relatedness (see also Bharucha & Stoeckig, 1986, 1987; Krumhansl et al., 1982a; Berent & Perfetti, 1993; Bigand et al., 1999). The more distant a chord with respect of a preceding harmonic context, the less expected it is. Such expectancies were clearly violated in this experiment by the Neapolitan chords (and, though to a smaller degree, by the secondary dominants).

Following these hypotheses, it is proposed that listeners structured their perception of music according to the harmonic relations defined by the principles, or rules, of music theory. These principles are taken here as part of a musical syntax represented in the brains of listeners. Thus, the present data suggest that a musical syntax is (at least partly) constituted of harmonic relations (in the sense of harmonic distance or relatedness). Due to the degree of relatedness, harmonies are perceived as more or less expected.

Interestingly, syntactic violations in auditory language experiments have been found to be reflected in the ERP as an early *left* anterior negativity, or ELAN (for review see Friederici, 1998). Besides, an ERP-effect similar to the ERAN has recently been reported in a music experiment performed by Patel et al. (1998), in which unexpected chords elicited a right antero-temporal negativity (RATN), taken to reflect the application of music-specific syntactic rules. Thus the electrical reflections of the cognitive processing of syntactic aspects of music seem to be more right distributed, whereas analogous reflections of the processing of syntactic aspects of language seems to be more lateralized to the left.

The processes underlying the generation of the ERAN have a surprisingly short latency (similarly to both ELAN and mismatch negativity [MMN]). Notably, this fast musical response was present though subjects were ‘non-musicians’.

Besides the ERAN, Neapolitans and secondary dominants also elicited a late bilateral frontal negativity peaking around 500-550 ms (also termed ‘N5’), which had a surprisingly similar time-course and distribution over the scalp compared to the N5 elicited by in-key chords (connected to the musical context build-up). The N5 elicited by in-key chords was taken to reflect musical integration processes. Notably, the processing of both, progressing in-key chords and chords containing out-of-key notes involves integration (entailing either specification or modulation of the hierarchy of stability). Compared to in-key chords, chords with unexpected notes were harder to integrate into the preceding harmonic context. Neapolitans and secondary dominants contained notes which were not compatible with the established tonal schema. It is thus suggested that the larger late bilateral negativity elicited by out-of-key compared to in-key chords reflects a larger amount of harmonic integration.

The integration of harmonically unexpected chords is presumably connected to a modulation of the hierarchy of the established tonal stability (a Neapolitan chord might for example introduce a shift to a new key). Krumhansl & Kessler (1982) demonstrated that a shift to a new key by a chord belonging not to the old but to the new key results in a prompt activation of a modulated tonal hierarchy (directed towards the new key), while the tonal hierarchy of the old key is still present. The process of loosening from the established harmonic hierarchy also entails an increase in ‘need of resolution’ (Bharucha & Krumhansl, 1983; Bharucha, 1984). Thus the presence of the N5 could also entail reflections of the perception of musical tension induced by unexpected chords. The resulting increase of expectation for further musical events is an effect of what Krumhansl & Kessler (1982) termed the ‘strong dynamic aspect of music in time’. This dynamic aspect seems to have become apparent in the ERPs of the present study.

It is important to note that effects elicited by chords with out-of-key notes could only be due to the fact that participants differentiated musically the in-key chords from Neapolitans (and secondary dominants, respectively), as both in-key and out-of-key chords occurred in different variations, but were on average physically identical. Thus, chords with out-of-key notes were not merely physical or frequency ‘oddballs’. Results rather demonstrate

that participants applied their implicit musical knowledge (e.g. about tonal distance and relatedness) while processing the chords.

Interestingly, processes similar to those of harmonic integration are known from language perception, where semantically anomalous words in a sentence elicit an N400. The N400 is commonly taken to reflect semantic integration (see e.g. Brown & Hagoort, 1993; Holcomb & Neville, 1991). Given the similarities of N4 and N5 (with respect of context build-up and integration), the present data suggest that the brain may process harmonies as 'semantic', that is meaningful, elements of music.

That is, the meaning of a chord as a sign (in a linguistic sense) was 'extracted' by the active process of integrating the harmony into a larger tonal context, according to the system of harmonic relations described by music theory. Up to now, musical semantics has rather been a matter of theoretical debate (c.f. Sloboda, 1985; Raffmann, 1993; Swain, 1997; Paynter et al., 1997); the aspect of musical semantics as suggested by the results of the present study has, to my knowledge, empirically not been evidenced before.

Experiment 1: Effects of position

Corresponding to the amplitude-decline of the N5 elicited by in-key chords, the amplitudes of both ERAN and N5 elicited by Neapolitan chords increased when presented at the end of a chord-sequence compared to when presented in the middle of a sequence. This finding is suggested to indicate that both ERAN and N5 are sensitive to the degree of specificity of the musical expectations induced by a preceding musical context. The musical context was built up towards the end of the cadence. During this process, the stability of the tonal hierarchy increased, inducing more specific musical expectancies: subsequent chords were to be expected as related to the established key (e.g. Bharucha & Stoeckig, 1987).

Consequently, out-of-key notes became more unexpected towards the end of each cadence, resulting in (or at least contributing to) a larger ERAN. Correspondingly, the integration of out-of-key notes became more difficult (entailing an increased modulation of a more specified hierarchy of stability), resulting in an enhancement of the N5. Thus the amplitudes of both ERAN and N5 seem to be functions of the specificity of the preceding harmonic context, or - in other words - sensitive to the degree of expectancy violation.

Notably, all participants of the present study were ‘non-musicians’. Since Neapolitan chords at the third and fifth position were on average the same chords, physically identical acoustic events were differently processed due to the preceding musical context. That is, within a musical context the human brain non-intentionally extrapolates expectations about forthcoming auditory input. These extrapolated events are consistent with music theory even in musically untrained listeners. Independently of whether participants got familiar with the major-minor tonal system due to cultural experiences, or whether the tonal system might be inborn in the brain: Participants processed the chords musically, and hence provided electrophysiological evidence for an implicit musical ability of the human brain.

Experiment 2: Degree of violation

If the amplitudes of ERAN and N5 were really sensitive to the degree of sound-expectancy violation, one would expect an amplitude-increase of both components (at both the third and at the fifth position) when elicited by musical events which are violating the sound expectancy to a higher degree than Neapolitans. In order to test this hypothesis, the same paradigm as in Experiment 1 was employed in a second experiment, except that Neapolitan chords were replaced by half-tone clusters. The clusters did not only contain unexpected notes, but were additionally highly dissonant (i.e. non-harmonic). Clusters thus violated the sound expectancy with respect to out-of-key notes, and to harmony.

Results revealed that clusters elicited both larger ERAN and N5 than Neapolitans (especially at the third position), supporting the hypothesis that both ERAN and N5 are functions of the degree of expectancy. Importantly, both early and late negativities elicited by clusters (which are non-harmonic, i.e. dissonant) as well as Neapolitans (which were consonant triads) differed with respect of the amplitudes, but not with respect of scalp distribution or time-course. Thus the present data do not indicate that different neural generators are involved in the processing of dissonance compared to the processing of unexpected (consonant) triads. As in Experiment 1, both ERAN and N5 had the largest amplitudes when elicited at the end of the chord-sequences.

Besides, the findings of Experiment 2 suggest that the smaller amplitudes of ERAN and N5 elicited by Neapolitans at the third compared to the fifth position could not merely be due to the point that Neapolitans at the third position are culturally more accepted (due to

their function as a subdominant variation). Like Neapolitans, clusters also elicited smaller effects at the third position, though they are culturally equally uncommon at both the third and the fifth position.

Experiment 3: Effects of task-relevance

In both Experiments 1 and 2, the harmonies were not to be attended by the participants (i.e. Neapolitan chords, secondary dominants, and clusters were not task-relevant). It was therefore interesting to investigate effects of attention, or ‘task-relevancy’, on music processing (as reflected in the ERAN and the N5). Therefore, the same experimental stimulation as in Experiment 1 was presented under the instruction to detect the Neapolitan chords.

Compared to Experiment 1, the ERAN was virtually not affected by the task-relevance, contrary to the N5, which was not observable in the ERPs of detected Neapolitans. The reduction of the N5-amplitude is assumed to be due to positive potentials connected to the conscious detection of the Neapolitans (P300), visible in the ERPs up to around 800 ms after the onset of the detected chords. It is thus likely that the P300 compensated the negative potentials of the N5. Importantly, this does not implicate that the processes underlying the N5 have been subdued. On the contrary - when Neapolitans at the third position were undetected (and therefore did not elicit a P3), Neapolitans still elicited a distinct N5. The detection of harmonies thus reduces the negative potential of the N5, but does not seem to reduce the neural processes of musical integration reflected in the N5.

Besides, data of Experiment 3 indicate that the ERAN is connected to the behavioral discrimination performance. No ERAN was elicited by undetected Neapolitan chords, whereas chords were detected after an ERAN was elicited. Since undetected Neapolitans elicited no ERAN, but an N5, the processes reflected in both ERAN and N5 seem to be independent from each other.

The early negativity elicited by Neapolitans at the third position in Experiment 1 and 3 was right predominant, though it did not turn out to be statistically significant when analyzed for the two experiments separately. When the data of both experiments were pooled (resulting in a better signal to noise ratio), the lateralization of the ERAN elicited by Nea-

politans at the third position was significant. This strongly suggests that the same neural generators of the ERAN are active at both the third and at the fifth position of a chord-sequence.

Notably, Neapolitan chords at the third position of Experiments 1 and 3 elicited both early and late negativities, though the behavioral data of the present experiment revealed that Neapolitan chords at the third position are rather unsalient. That is, though participants realized merely about half of the Neapolitans, their brain responses significantly differed between Neapolitans and in-key chords.

Surprisingly, secondary dominants also elicited both early and late effects, though they are from both a music-theoretical and a music-psychological point of view to be predicted as even less salient compared to Neapolitans at the third position. To test this prediction, a supplementary behavioral study was conducted in which participants were asked to detect the secondary dominants.

Only one third of the secondary dominants was detected (that is, even less than Neapolitans at the third position). Notably, secondary dominants did nevertheless evoke distinct brain responses in the ERPs of Experiments 1-3, suggesting that non-musicians process unexpected musical events according to music-theory, even when most of these events are consciously not detectable.

Experiment 4: Effects of probability

Experiment 4 was designed to investigate how music processing is influenced by the probability of the occurrence of unexpected chords. Besides, contrary to ERP-studies found in the literature (see Chapter 8), chords with unexpected notes elicited in the present study early and late negativities (which have, to my knowledge, so far not been reported). Experiment 4 should therefore also clarify whether this difference is due to the probability of unexpected chords (which was merely 0.25 in Experiments 1-3). Participants were asked to detect the Neapolitan chords (which occurred at the fifth position only with a probability of 0.5).

Compared to Experiment 3, the amplitudes of both ERAN and N5 were markedly diminished in amplitude. It is suggested that the anticipation of an unexpected musical event reduces the ERAN (if a rule is permanently violated, the violation becomes the new rule),

and that the frequent presentation of the Neapolitans led to an ease of integration (reflected in the diminished N5).

Notably, results also demonstrated that the larger negativities elicited by Neapolitans at the fifth vs. third position in Experiments 1 and 3 were not merely due to a violation of a memory-based template (most specific for the chord at the fifth position being a tonic, which occurred in Experiments 1 and 3 in 75% of all cadences): in the fourth experiment, no tonic-specific template for the fifth chord could be established, since 50% of the chords at the fifth position were Neapolitans, and 50% tonic chords. Nevertheless, Neapolitan chords elicited both an ERAN and a slight N5. This finding supports the hypothesis that listeners (though ‘non-musicians’) had indeed a musical expectancy which reflected the principles of harmonic relatedness inherent in the major/minor tonal system.

Experiment 5: Tonal modulations

Like Neapolitan chords, changes of key are a prominent stylistic means in western tonal music. An investigation of the neural processes connected to tonal modulations (i.e. to changes in the tonal key) was intended with Experiment 5. Therefore, similar stimuli as in Experiments 1-4 were employed, but unexpected chords were embedded in a modulating chord-sequence. Participants were instructed to ignore the harmonies and to detect infrequently occurring deviant instruments.

In-key (and modulating) chord-sequences elicited a sustained negativity which was widely distributed over the scalp and increasing in amplitude towards the end of the sequences. The observation of this effect led to a re-analysis of data from Experiments 1-4 and revealed that it was also present in the previous experiments. Interestingly, such a similar effect has first been described by Walter et al. (1964) as the ‘contingent negative variation’ (CNV), which was originally taken as an ‘expectancy’ wave. Sustained and increasing negativities associated with the CNV have also been found to be elicited during the processing of sentences (e.g. Kutas & Hillyard, 1980). The sustained and increasing negativity elicited by chord-sequences is suggested to reflect the increasing expectancy for tonally related chords to follow. The increasing expectancy correlates with the build-up of musical context, which is connected to the specification of the hierarchy of harmonic stability.

Modulating chords elicited both ERAN and N5. Both components were considerably larger in amplitude when elicited by modulating compared to Neapolitan chords. This amplitude-difference might indicate that during the experimental session, participants soon realized that unexpected chords occurring at the third position introduced a shift to a new key. That is, participants might have realized that the modulating chords at the third position contained relevant information with respect to the following modulation. It is suggested that the awareness of this particular function of a modulating chord at the third position led to a different processing compared to the processing of Neapolitan chords. However, an influence of informational relevance on ERAN and N5 remains to be tested in further experiments.

The N5 elicited by modulating chords at the third position was lateralized to the right, contrasting results of the previous experiments (where the N5 was distributed bilaterally over frontal regions). It is suggested that the lateralization is due to a habituation of the participants to the processing of modulations, since the stimulation of Experiment 5 was less diversified compared to Experiments 1-4. Participants might have realized that only one type of violation was employed in the experimental paradigm (namely modulations). For the reason of efficiency, the brain-system which is processing the modulations might have reduced its activity in the left hemisphere. A thorough investigation of this brain system remains matter of further experiments.

Experiment 5: Working memory effects

In addition to the sustained and increasing negativity, modulations elicited an additional effect, namely a slow-going negativity, which was maximal around 500 – 1500 ms and right-frontally predominant. The amplitude of the slow negative potential (that is the duration of the processes of integration connected to the change of key) correlated with the time-course of the modulation, declining with the establishment of the new tonic.

No such slow negativity could be found for the chord-sequences of the previous experiments, therefore the slow negativity elicited by modulations is suggested to reflect cognitive operations characteristic for the processing of tonal modulations.

These cognitive operations presumably reflect more global integration with respect to the change of key, namely the restructuring of the hierarchy of harmonic stability. From a music-psychological point of view, the hierarchy of stability established by the chord-sequences preceding a modulation had to be entirely restructured. That is, a new tonal center had to be established, entailing the notion of key membership of other chords, of intrakey and contextual distances, of intrakey and contextual asymmetries, and of contextual identity (Bharucha & Krumhansl, 1983, e.g.).

Because time is involved in the restructuring of the tonal hierarchy, it is suggested here that working memory operations are highly involved in this process. Especially because frontal brain areas are presumably involved with central executive processes (Baddeley, 1995, 1999), it is plausible to assume that the frontal slow shift found to be elicited by modulations is related to working memory processes. This interpretation is supported by findings from Zatorre & Samson (1991) and Zatorre et al. (1994), who reported interactions between temporal and frontal cortices to be entailed in working memory for pitch. It is interesting to note that slow negative potential-shifts have also been observed during the processing of language and associated with working memory operations (King & Kutas, 1995; Vos, 1999).

Experiment 5: Chord inversions

In Experiment 5, chords were equiprobably presented in root position, as sixth-chords, and as six-four chords. The ERPs elicited by these chord-types were very similar to each other, though from around 450 – 650 ms, the ERPs of six-four chords were at frontopolar sites, and at Fz and F4, slightly more negative compared to chords presented in root-position. Though this effect was statistically not significant, it presumably will become significant in an experiment employing more trials, resulting in an enhanced signal-to-noise ratio.

Experiments 1-5: Deviant instruments

Deviant instruments also elicited (in all experiments) an early negativity (around 150-200 ms) which tended to be right predominant, and a late frontal negativity (around 500-550 ms) which was larger at right than left electrode sites. Several effects might account for the

early negativity, e.g. a refractory N1 and a mismatch negativity (MMN). However, due to the huge potential elicited by deviant instruments, additional processes are presumably involved in the generation of the early negative potential. Since the expectation of a piano sound was violated by the sound of a deviant instrument, processes underlying the ERAN (when elicited by a harmonic deviancy) are thus assumed to be also involved in the processing a deviancy in timbre. This finding might be specific for the present experimental paradigm, in which the standard stimuli consisted of harmonically meaningful chord-sequences.

The late negativity is suggested to be due to integration processes and thus also termed N5: chords that were spectrally deviant (and thus violating the sound-expectancy of listeners) were nevertheless harmonically correct and fitted well into the musical context.

Interestingly, participants were tempted to respond to clusters in Experiment 2 (reflected in a P3b elicited by clusters) though they were instructed to ignore the harmonies. Correspondingly, participants were tempted to respond to deviant instruments when they were instructed to detect the Neapolitans in Experiments 3 and 4. This indicates that participants responded to a violation of *sound*-expectancy in general, rather than to a violation of harmony specifically. Therefore, the interpretation of the ERAN as reflecting a violation of musical sound-expectancy in general (rather than of harmony in specific) seems to be more appropriate.

Experiment 6: Automaticity of musical processing

In Experiments 1, 2, and 5, both ERAN and N5 were elicited under a condition in which participants were not instructed to attend to the harmonies. That is, the decisive experimental stimuli (Neapolitan chords, clusters, and secondary dominants) were not task-relevant. However, since the detection of the deviant instruments was not a demanding task, it is not assumed that participants actually ignored the harmonies. It was thus interesting to investigate whether effects found in the previous experiments might be present even under real ignore conditions.

Experiment 6 consisted of two blocks. In the first block, participants were reading a self-selected book while a stimulation similar to that employed in Experiment 1 was presented. Such a procedure is commonly applied to investigate auditory processing in the absence of

attention (cf. Näätänen, 1992; Schröger, 1998). In a second block, participants were asked to detect the Neapolitan chords, enabling to an investigation of a possible effect of attention on musical processing.

Similarly to Experiment 1, progressing in-key chords elicited an N5 which declined in amplitude towards the end of the cadences (suggested to reflect the musical integration of in-key chords into the preceding harmonic context and the build-up of musical context). Notably, the decline of the N5 was present though participants were reading a book during the stimulation, suggesting (1) that a musical context was build up pre-attentively in the brains of participants (that is even though the musical stimuli were ignored), and (2) that participants processed both language and music simultaneously.

Neapolitan chords elicited both ERAN and N5. Contrary to Experiments 1-4, but similarly to Experiment 5, the N5 was lateralized to the right. This finding strengthens the hypothesis that the neural generators of the N5 reduced their activity in the left hemisphere due to a habituation of the participants to the processing of the Neapolitan chords. Compared to the previous experiments, the duration of the first block of Experiment 6 was about three times longer. Besides, the stimulation was less diversified compared to Experiments 1-4 (where the N5 was not lateralized).

Importantly, both ERAN and N5 were elicited pre-attentively (since participants were reading). This finding indicates that ‘non-musicians’ process chords with out-of-key notes in a different way from in-key chords even in the absence of attention.

As in Experiments 1 – 4, the amplitude-difference between effects elicited at the third vs. the fifth position could not be due to any physical difference between chords (or clusters) at the third and fifth position. The amplitude-difference could only be due to the harmonic expectancy of listeners, which was induced by the preceding harmonic context, and which was more specific at the fifth compared to the third position of the cadence. Thus Neapolitans at the fifth position violated this harmonic expectancy to a higher degree compared to Neapolitan chords at the third position of a cadence.

The differing degree of harmonic expectancy violation is reflected in the brain responses, and corresponds with the logic of music theory (cf. discussion of Experiment 1). Given that participants were ‘non-musicians’ who ignored the musical stimulation, the present results are thus taken to indicate a pre-attentive musicality of the human brain.

Comparing results of Block 1 and 2, the ERAN did at most electrodes virtually not differ between blocks. Only at peripheral right fronto-temporal electrodes, the ERAN was slightly more negative when elicited under attend conditions. Therefore, the processes underlying the generation of the ERAN are, for the time being, taken here as only marginally influenced by attention.

Experiment 7: Localizing music processing

Experiment 7 aimed at localizing the neural generators of the ERAN using MEG. The same experimental paradigm as in Experiment 1 was employed.

A distinct magnetic field effect was found to be elicited by in-key chords which was maximal around 200 ms. This effect was referred to as the P2m, and taken as the magnetic counterpart of the (electric) P2. Dipole-solutions yielded two generators of the P2m, one located in each hemisphere in the middle of Heschl’s gyrus, within (or in the close vicinity of) the primary auditory cortex (near to the generators of the P1m and the N1m).

Neapolitan chords elicited an early magnetic field effect (being maximal around 200 ms) which was referred to as the ERANm. The ERANm is regarded as the magnetic counterpart of the ERAN. Surprisingly, the generators of the ERANm were not located within the temporal lobes, but in each hemisphere within the lower part of the pars opercularis (which corresponds to the lower part of Brodman’s area 44), in the left hemisphere classically called Broca’s area.

The area of Broca is known to be responsible for the processing of syntactic elements and syntactic sequences during language perception, involved in the syntactic analysis of incoming language input (in the sense of determining grammatical relations in a sentence), and specialized for fast and automatic access to syntactic information (Friederici, 1998).

It is interesting to note that the early *left* anterior negativity (ELAN) also seems to be generated, at least partially, in the Broca’s area (and in the homologous area in the right

hemisphere, Friederici et al., 1999). The ELAN has so far been found to be generated in auditory language experiments by the violation of syntactic rules, as well as by uncommon syntactic phrases (see Chapter 7). Due to its properties, the ELAN may be hypothesized to reflect a parsing of incoming language input into an initial syntactic structure.

The ELAN highly simulates the ERAN. Though the ELAN is often more predominant over the left hemisphere, both ELAN and ERAN are early anterior negativities. Besides, both ELAN and ERAN seem to be (at least partly) generated in the area of Broca. It is therefore suggested here that the Broca's area may also be involved in determining harmonic relations within a musical phrase, and that the determination of harmonic relation is a 'syntactic' analysis of incoming musical input. As syntactic information of language, which is fast and automatically processed in the Broca's area, music-syntactic information processed in the same (and right homologous) brain structure also seems to be processed automatically (cf. Experiment 6).

Whereas the syntax of language is quite well-defined, the syntax of music thus becomes apparent only in the brain activity of individual listeners. This brain activity depends on musical expectancies, which seem in the first line to be connected to the music-theoretical principles of harmonic relatedness. Importantly, these expectancies may vary due to the experiences of listening (cf. Experiment 4), and have during the history of music composers led to invent new chords, modulations, sounds, etc.

Comparison to other ERP-studies

It is interesting to note that a negativity similar to the ERAN has already been described: the 'right antero-temporal negativity' (RATN, Patel et al., 1998). As the ERAN, the RATN was taken to reflect a music-specific application of syntactic rules. However, the RATN differs in respect of time-course and distribution from the ERAN. Besides, functional significance and nature of the RATN has not yet been further investigated. Therefore the term ERAN seems for the effects described in the present study for the time being more appropriate.

In a study from Besson & Faita (1995) an ERAN might have been present in the ERPs of diatonic incongruent melody-endings, though (possibly due to the probability of 50%) not significantly lateralized. Unfortunately, this effect was only speculatively discussed and

not further examined. In the study from Hantz et al. (1997) a negative component with a latency of 273 ms was described, but this component was largest at CZ, and due to the decision-task presumably an N2b.

To my knowledge, no N5 has explicitly been described in previous ERP-studies concerned with the investigation of music processing. Slow late frontal negativities have been described (for review see Näätänen, 1992), which are rather connected to the CNV and related to stimulus significance (for instance, whether or not the stimulus is a target). This contrasts the N5 which can even be elicited by undetected chords (see Experiment 3), and which can be elicited pre-attentively (see Experiment 6).

There are some factors which might account for the differences of the effects between previous studies and the present study: the present results yield that both the ERAN and the N5 are affected by the probability, and the N5 by the task-relevancy of unexpected chords. Besides, in the present study the chord-sequences were presented one directly after the other, sounding rather like a musical piece than a series of experimental stimuli. This contrasts especially the studies conducted by Hantz et al. (1997) and Janata (1995), where the experimental design was trial-based, each trial consisting of a few chords only. Moreover, in all mentioned studies with harmonic stimulation, participants were musicians, whereas the present study employed non-musicians only. A recent ERP-study revealed a difference in pre-attentive auditory processing of musically relevant information between musicians and non-musicians (Koelsch et al., 1999), thus it is not yet to exclude that ERPs of both groups differ with respect of the stimulation employed in the present study.

Other deviance-related negativities

In Experiments 3-4, and in the second block of Experiment 6, the ERAN elicited by Neapolitan chords was presumably followed, and probably partly overlapped by an N2b. However, ERPs of Experiment 3 allow to separate the ERAN from the N2b, since both components differ in their time-course: whereas the waveforms of detected Neapolitans suggest the presence of an N2b peaking around 290 ms and being maximal at right-central electrode sites, the ERAN was found to be present already around 190 ms (being right-anteriorly maximal). ERPs of detected Neapolitans thus indicate that the ERAN is not just a frontally distributed N2b.

Besides, the ERAN shows some similarities compared with the mismatch negativity (MMN). The amplitudes of both, the ERAN and the MMN (a) increase with the amount of violation, (b) increase with increasing position in a stimulus train, and (c) are connected to behavioral discrimination performance. Both MMN and ERAN have (d) a right-frontally preponderant distribution, are (e) similar in time-course, are (f) rather insensitive to the relevancy of the task, can (g) be elicited pre-attentively (though it seems that the ERAN is more influenced by attention than the MMN), and (h) invert polarity at mastoidal leads when nose-reference is used.

Since the MMN can also be elicited by an abstract feature (e.g. Paavilainen et al., 1998), the ERAN could be taken as a MMN elicited by the abstract feature 'in-key / out-of-key'. However, the present study also provides substantial differences between ERAN and MMN. In Experiment 7, no Neapolitan-specific temporal lobe activation was yielded to be involved in the generation of the ERANm. This contrasts the MMN, which is known to be generated (at least to a considerable amount) in the temporal lobes (Alho, 1995, e.g.). Another decisive difference was found in Experiment 5, where an ERAN was elicited by three (modulating) chords in a row. Such a phenomenon would not be expected for the MMN which is known to decrease clearly when elicited by two directly succeeding deviants (cf. Sams et al., 1984; Giese-Davis et al., 1993; Näätänen, 1992). Besides, the comparison of Experiments 3 and 4 suggests that the ERAN is sensitive for effects of anticipation and expectancy. This contrasts the MMN, for which effects similar to those revealed in the present study would not be predicted (cf. e.g. Scherg et al., 1989, for an experiment with a similar time-course).

Results of the present study thus strongly suggest that the ERAN is not a MMN, but that the processes reflected in the ERAN are rather specific for the processing of musical syntax. With this respect, the ERAN seems to be an ERP-component which has been described for the first time in the present study.

Perspectives

Several questions arise in view of the present results which can probably be answered by further experiments. It would be important to investigate if ERAN and N5 were also elicited without the repetitive character of the chord-sequences in the present paradigm. To answer

this question, chord-sequences with varying rhythm and length could be employed. If the present hypothesis about ERAN and N5 were right, both components should then still be present.

Besides, it was argued that the amplitude difference of ERP-effects elicited at the fifth compared to the third position were in the first line due to the build up of the harmonic context. Nevertheless, it could also be argued that this effect is merely due to the fact that a Neapolitan chord at the fifth position distinctly contrasted with the tonic (at the third position, Neapolitans were presented among some other chord functions, leading to a lower contrast between Neapolitans and in-key chords). To support the hypothesis of the influence of musical context build-up, it would be necessary to conduct an experiment with chord-sequences that contain the equal amount of chord functions at both the third and the fifth position (ERP-effects should then still be larger at the fifth vs. the third position).

It would also be interesting to investigate whether the brain responses (e.g. ERAN and N5) of musicians differ from those of non-musicians using the present experimental paradigms. There is evidence for superior processing of auditory information in musicians (e.g. Koelsch et al., 1999; Brattico et al., 1999), but also evidence for a general musicality (e.g. the present study, as well as e.g. Bharucha & Stoeckig, 1986; Sloboda et al., 1994).

There is also considerable debate about whether the representation of the major-minor tonal system is inborn or culturally acquired. This issue could be investigated by presenting Experiment 6 to newborn infants. In Experiment 6, both ERAN and N5 were elicited in ‘non-musicians’ under ignore conditions. It would be surprising if these responses were present in infants. Such a finding would either indicate that the representation of the major-minor tonal system is inborn, or that such a representation can be acquired even before birth.

The MEG-study revealed that the N5 is only hardly measurable with MEG. This is presumably due to a source configuration in which the neural generators are topographically distributed. The same phenomenon is to be expected for the slow negative shift elicited by modulations. fMRI-studies could probably serve to find the generators of both the N5 and the slow negative shift.

Besides, results of Experiment 5 suggested a difference in the ERPs elicited by chord-inversions. This difference was statistically not significant, but might become more clear in an experiment that proliferates data with a higher signal-to-noise ratio (therefore, more stimuli than in Experiment 5 would be needed to be employed). Data might then help to investigate psychological properties of chord-perception.

Data obtained in Experiment 5 also suggested that working memory is involved in the processing of modulations, reminding to working memory operations active during the perception of language (e.g. during the processing of Subject vs. Object Relative sentences). Both non-modulating and modulating sequences could easily be constructed which were the musical counterpart to the Subject and Object Relative sentences in language. Results would serve a further investigation of similarities and differences between the processing of music and language.

In the present experiments, the stimuli were played under computerized control, each chord with exactly the same decay (and attack) of loudness, and each chord with the same duration. This was done in order to exclude further experimental factors. Now that the effects elicited with the stimulation of the present experiments are quite well-investigated, it would be interesting whether a stimulation played by a 'real' pianist would cause other, or additional effects. This would to be expected, since the stimulation could then be played emotionally. Such an experiment could therefore lead over to an investigation of emotion.

Appendix A

Color Figures

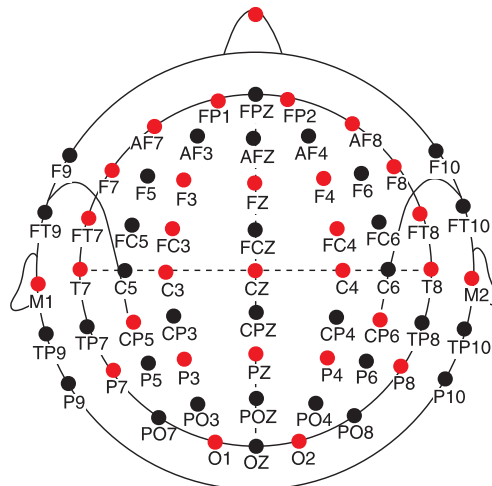


Figure A.1: Electrode positions according to Sharbrough (1991). Electrodes used in the present studies are marked red.

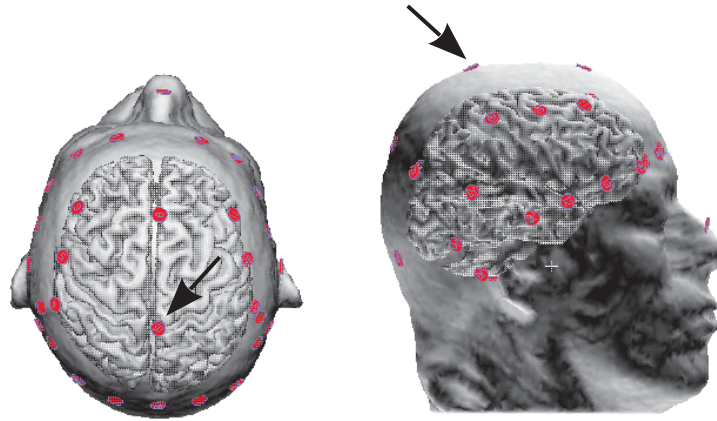


Figure A.2: Illustration of the electrodes used in the present studies. The arrow indicates Cz.

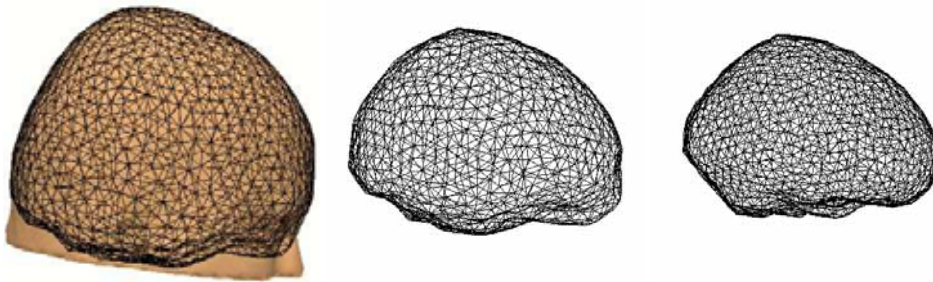


Figure A.3: Boundary element model of the human brain. Left: skin, middle: skull, right: liquor. Each of the boundaries is discretized into triangular elements.

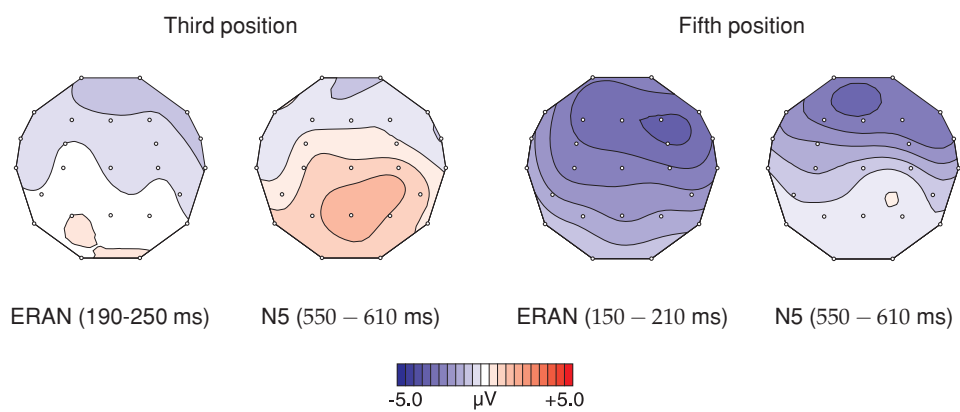


Figure A.4: Experiment 1, 3rd vs. 5th position, Potential-maps of effects elicited by Neapolitan chords (difference-ERPs: in-key chords subtracted from Neapolitans). Left: ERAN and N5 elicited by Neapolitan chords at the third position. Right: ERAN and N5 elicited by Neapolitans at the fifth position. Effects were smaller when elicited by Neapolitans at the third compared to Neapolitans at the fifth position.

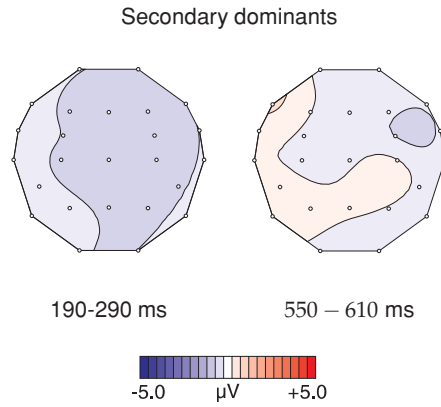


Figure A.5: Experiment 1, 2nd position, Potential-maps of effects elicited by secondary dominants (difference-ERPs: in-key chords subtracted from secondary dominants). Left: early time window, right: late time window.

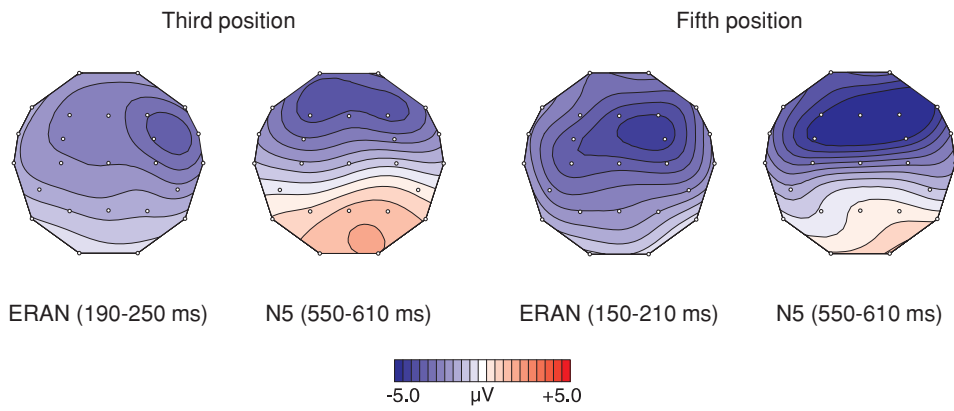


Figure A.6: Experiment 2, 3rd vs. 5th position, potential-maps of effects elicited by clusters (grand average difference-ERPs: in-key chords subtracted from clusters, view from top). Left: ERAN and N5 elicited by clusters at the third position. Right: ERAN and N5 elicited by clusters at the fifth position. Comparing clusters at the third vs. fifth position, ERAN and N5 were similarly distributed, but smaller when elicited at the third position.

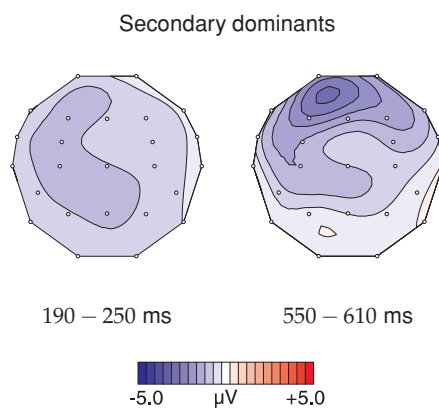


Figure A.7: Experiment 2, 2nd position, potential-maps of effects elicited by secondary dominants (difference-ERPs: in-key chords subtracted from secondary dominants). Left: early time window, right: late time window.

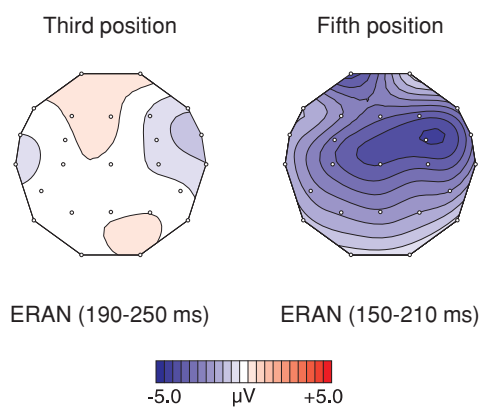


Figure A.8: Experiment 3, 3rd vs. 5th position, potential-maps of early effects elicited by Neapolitans (grand average difference-ERPs: in-key chords subtracted from Neapolitans, view from top). ERAN elicited by Neapolitans at the third (left) and fifth (right) position.

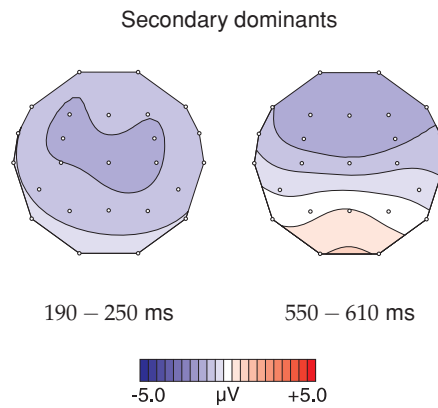


Figure A.9: Experiment 3, 2nd position, potential-maps of effects elicited by secondary dominants (grand average difference-ERPs: in-key chords subtracted from secondary dominants). Left: early time window, right: late time window.

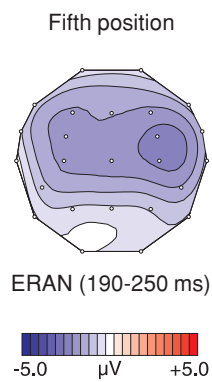


Figure A.10: Experiment 4, 5th position, potential-map of the early effect elicited by Neapolitans (difference-ERPs: in-key chords subtracted from Neapolitans, view from top).

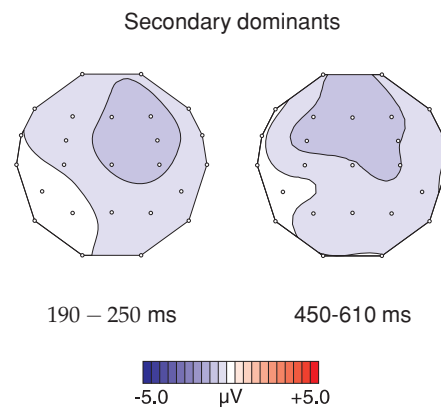


Figure A.11: Experiment 4, 2nd position, potential-maps of effects elicited by secondary dominants (difference-ERPs: in-key chords subtracted from secondary dominants). Left: early time window, right: late time window.

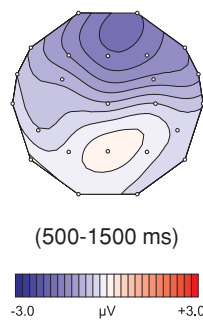


Figure A.12: Experiment 5, 0.5 Hz low-pass filtered data; potential-map of the slow negative shift elicited by modulations (difference of grand-average ERPs: in-key subtracted from modulating sequences, view from top), interpolated over a time window from 500 to 1500 ms. Data from C3 were excluded from map interpolation.

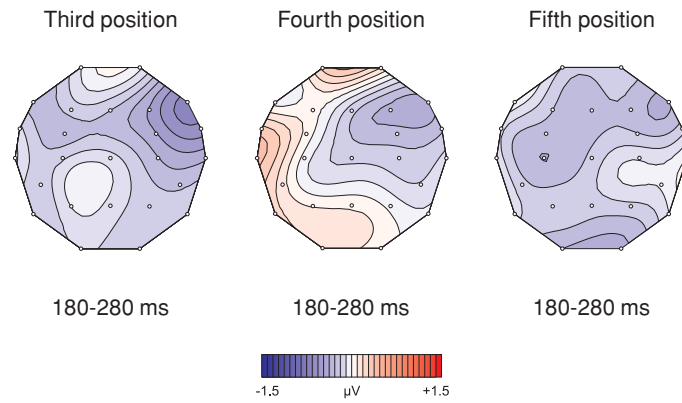


Figure A.13: Experiment 5, early right anterior negativity: Potential-maps of early effects elicited by modulations (difference-ERPs: in-key subtracted from modulating chords). Left: modulating chords at the third position (middle: fourth position, right: fifth position). ERPs were interpolated in the time-interval from 180-280 ms with respect to the onset of each chord.

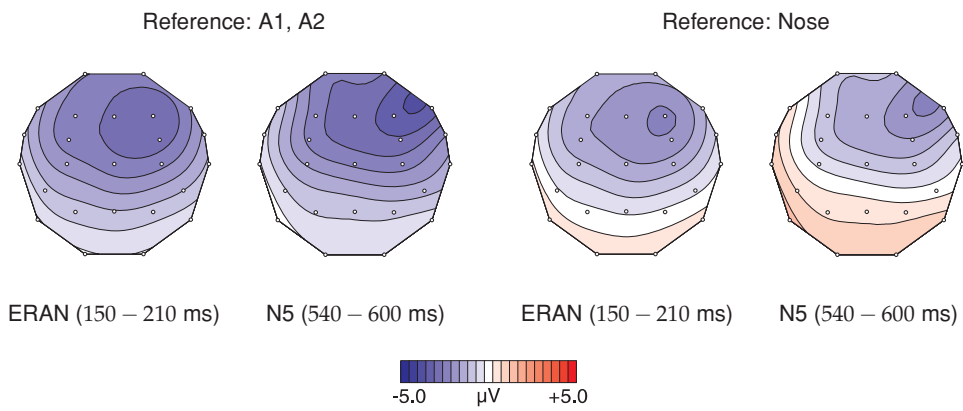


Figure A.14: Experiment 6, 5th position, potential-maps of effects elicited by Neapolitan chords (grand average difference-ERPs: in-key chords subtracted from Neapolitans), reading condition. Left: early and late effects referenced to the mean of A1 and A2. Right: early and late effects with nose-reference.

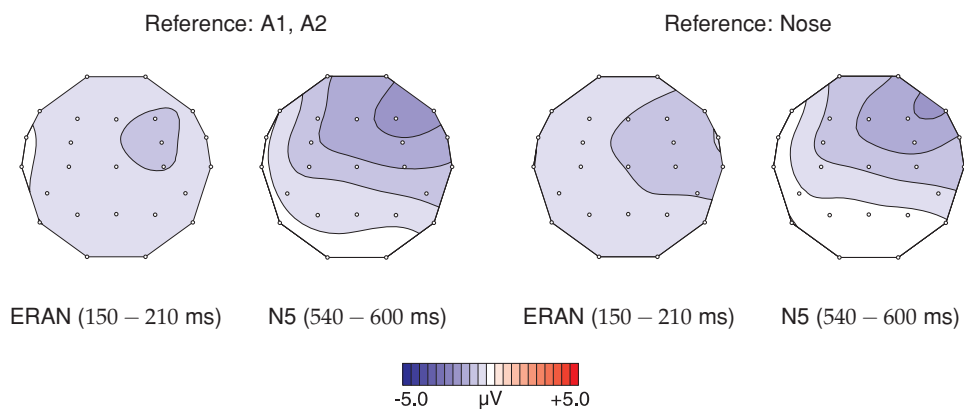


Figure A.15: Experiment 6, 3rd position, potential-maps of effects elicited by Neapolitan chords (difference-ERPs: in-key chords subtracted from Neapolitans), reading condition. Left: early and late effects referenced to the mean of A1 and A2. Right: early and late effects with nose-reference.

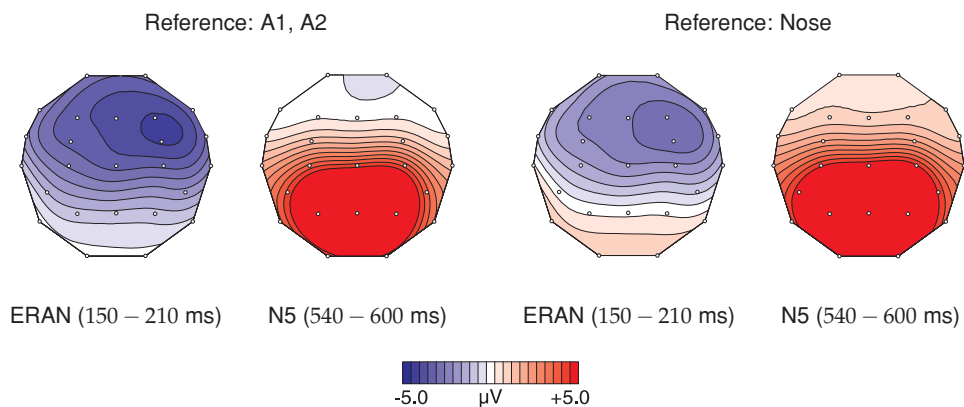


Figure A.16: Experiment 6, 5th position, potential-maps of effects elicited by Neapolitan chords (difference-ERPs: in-key chords subtracted from Neapolitans), reading condition. Left: early and late effects referenced to the mean of A1 and A2. Right: early and late effects with nose-reference.

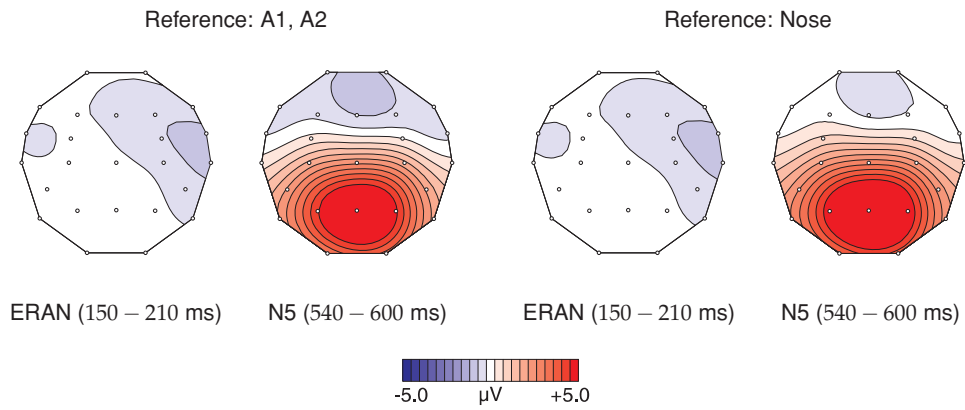


Figure A.17: Experiment 6, 3rd position, potential-maps of effects elicited by Neapolitan chords (difference-ERPs: in-key chords subtracted from Neapolitans), attend condition. Left: early and late effects referenced to the mean of A1 and A2. Right: early (sic!) and late effects with nose-reference.

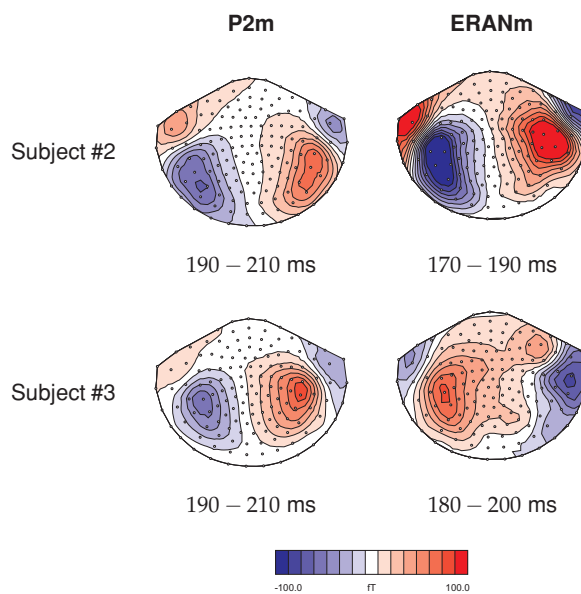


Figure A.18: Experiment 7, P2m and ERANm (elicited at the fifth position): Magnetic field maps.

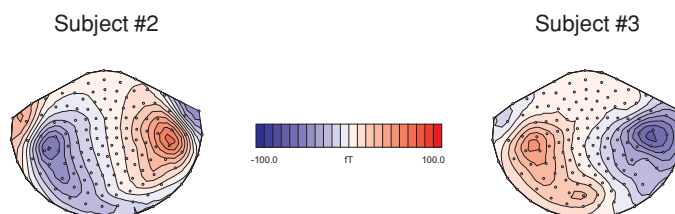


Figure A.19: Experiment 7, 3rd position, magnetic field maps from two representative subjects (magnetic signals from the same subjects are shown in Fig. 15.3). Maps were calculated by subtracting the ERFs elicited by in-key chords from ERFs of Neapolitans.

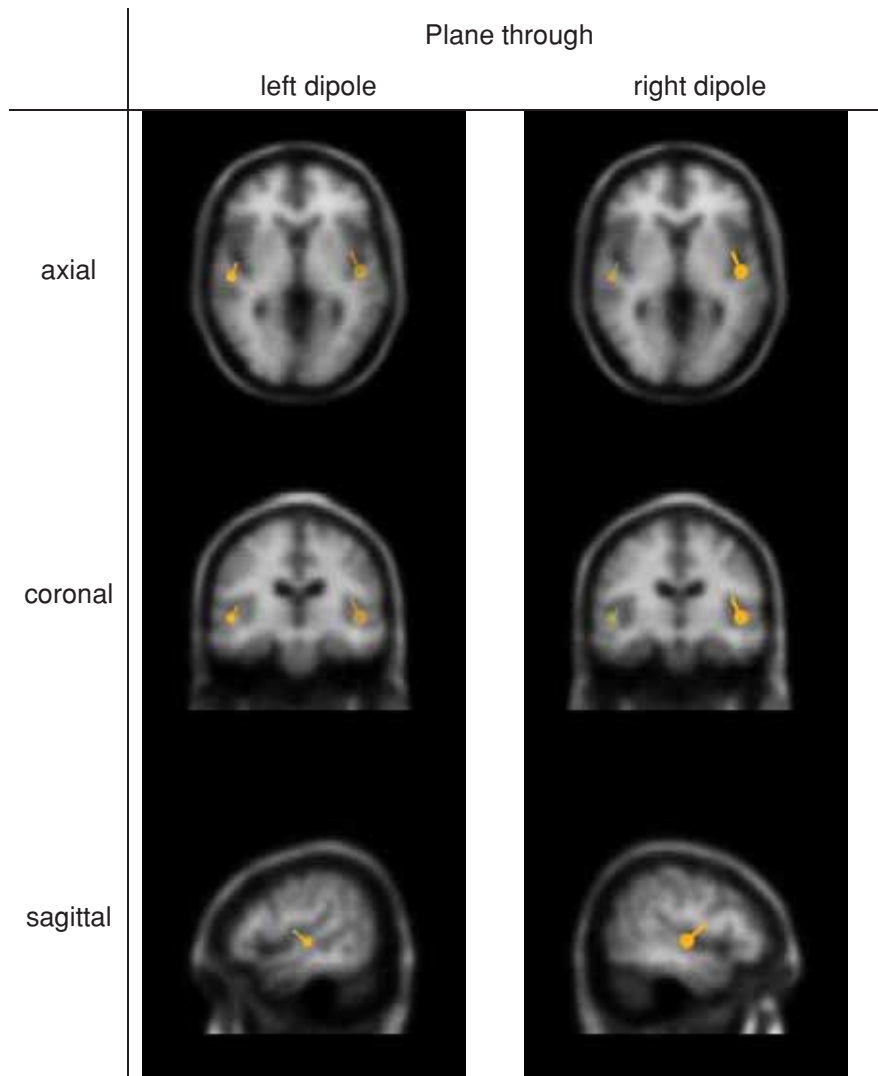


Figure A.20: Experiment 7, grand-average dipole solution of the P2m.

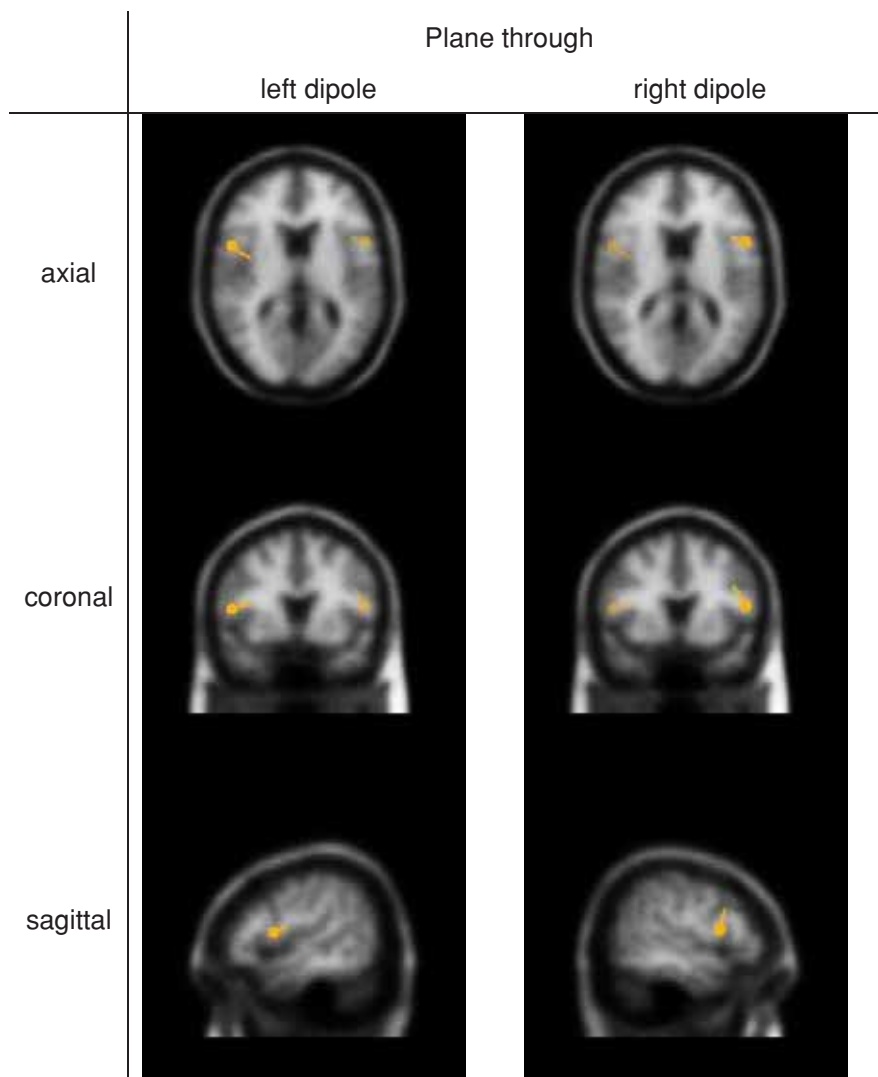


Figure A.21: Experiment 7, grand-average dipole solution of the ERANm.

Appendix B

Supplementary ERPs

Entire in-key chord-sequence ERPs from
Experiments 1 – 6

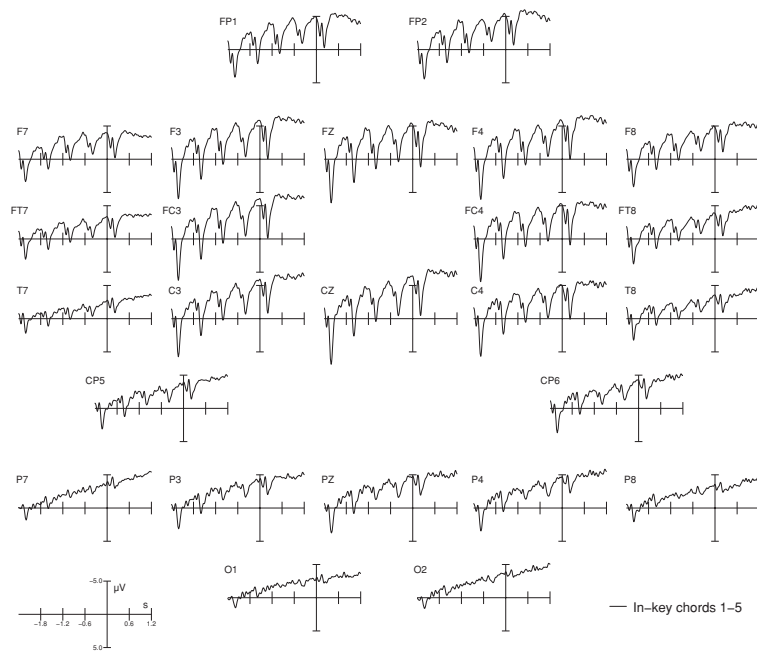


Figure B.1: Experiment 1 with Neapolitans ('ignore harmonies').

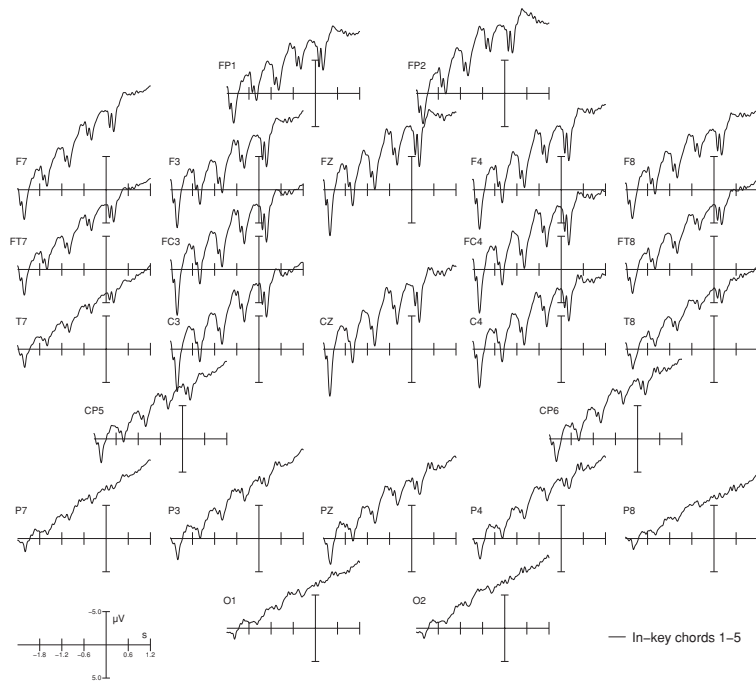


Figure B.2: Experiment 2 with Clusters ('ignore harmonies').

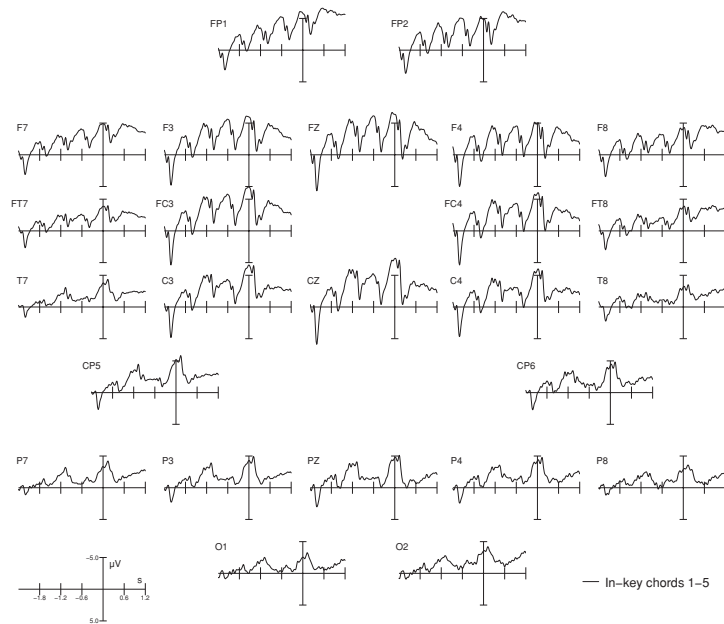


Figure B.3: Experiment 3 with Neapolitans ('detect Neapolitans').

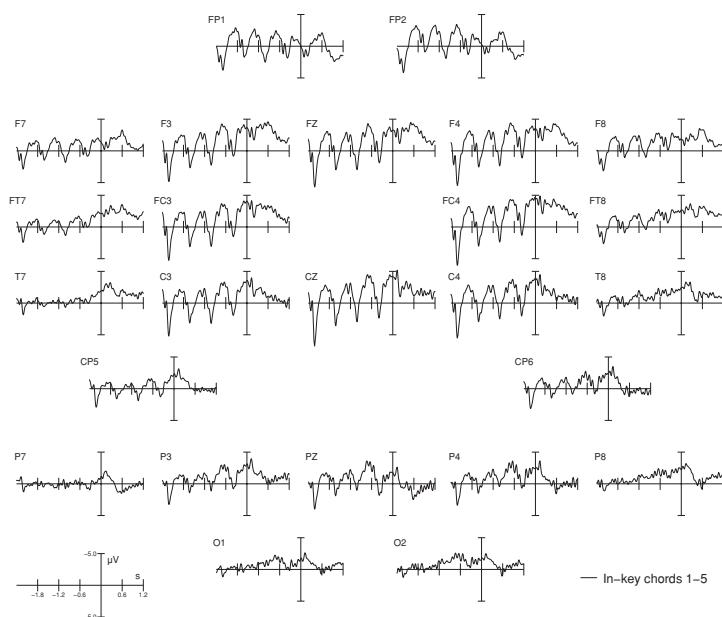


Figure B.4: Experiment 4 ('detect Neapolitans', $p=0.5$, Neapolitans occurred at the 5th position only).

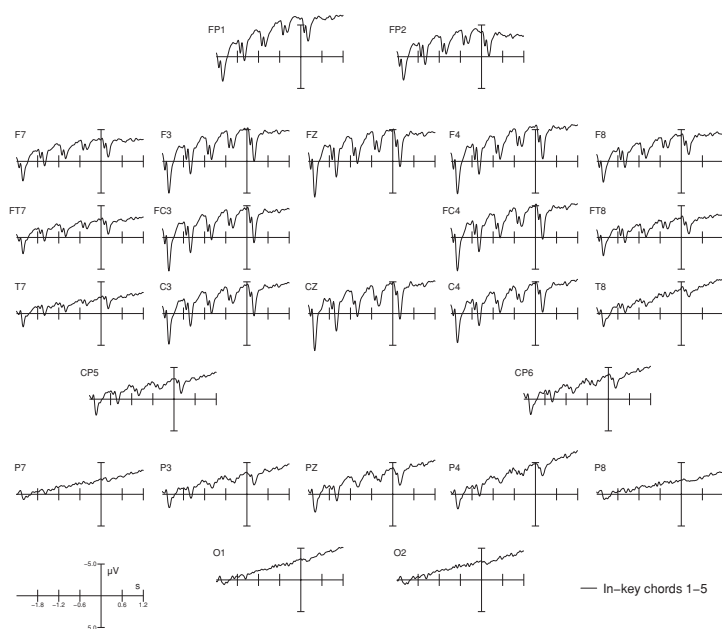


Figure B.5: Experiment 5 with modulations ('ignore harmonies').

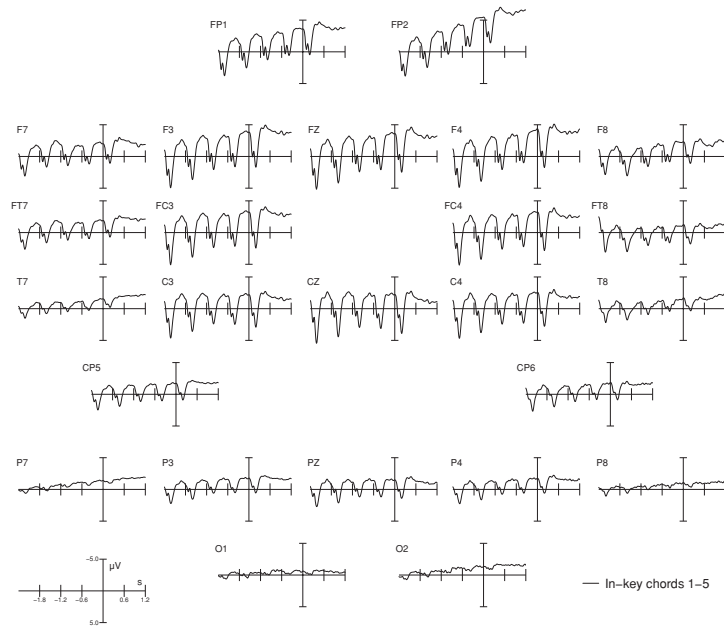


Figure B.6: Experiment 6, Block 1 (reading condition).

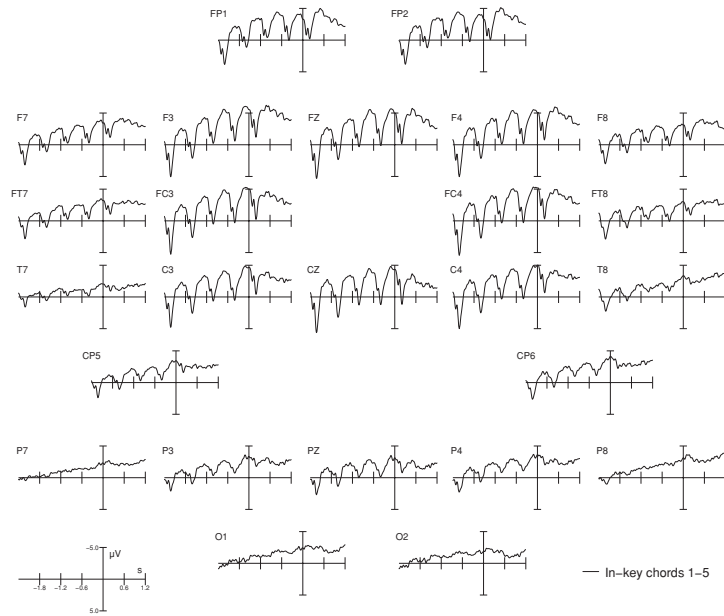


Figure B.7: Experiment 6, Block 2 (detect Neapolitans).

Appendix C

Brain anatomy

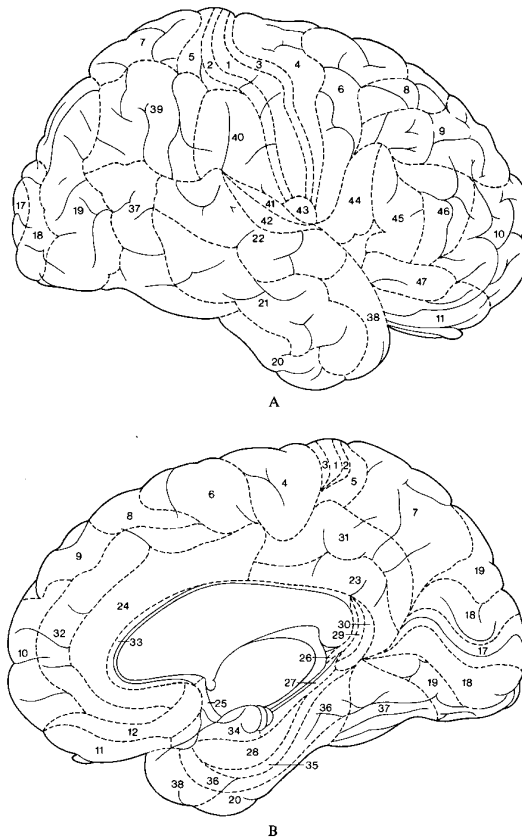


Figure C.1: Subdivision of the cortex of the right cerebral hemisphere into cytoarchitectonic fields according to Brodman. A: lateral view; B: medial view (from Nieuwenhuys et al. (1995)).

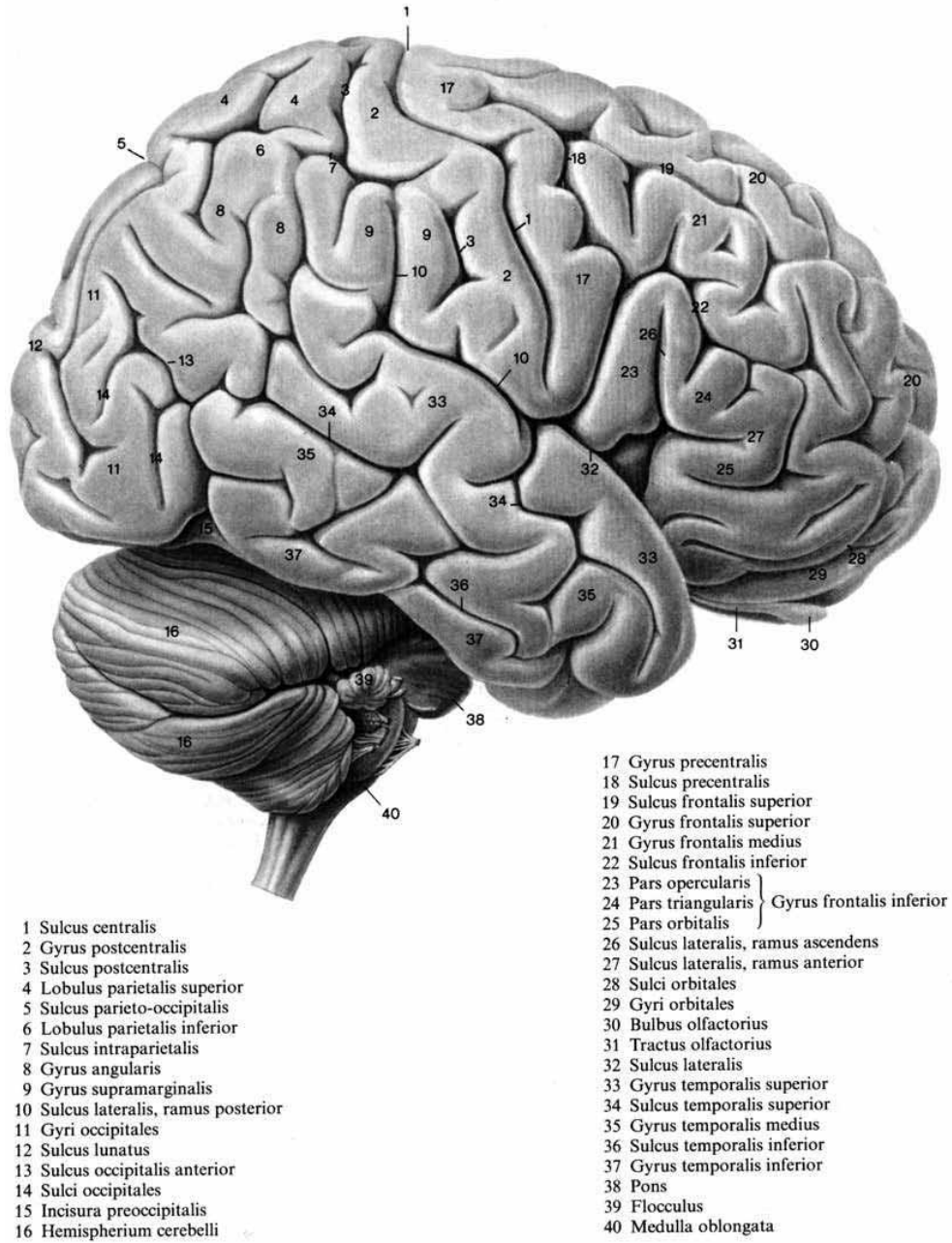


Figure C.2: Lateral view of the brain (from Nieuwenhuys et al. (1995)).

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Index

- 10-20 system, 39
- Action potentials, 38
- Asymmetry
 - in chord-pair ratings, 32
 - in tone-pair ratings, 24
- Auditory cortex, 10
 - primary $\bar{\gamma}$ 176, 194
 - primary \sim , 10
- Auditory nerve, 8, 9
- Averaging, 41
- Basilar membrane, 7
- Biot-Savart law, 46
- Brain Stem, 10
- Brainstem-responses, 38, 51
- Broca's area, 177, 194
- Brodman
 - area 41, 10
 - area 42, 10
 - area 44, 174, 177, 194
- Cadence, 66, 70
- Cell assembly, 38
- Central auditory path, 10
- Cerebral cortex, 37
- Characteristic dissonance
 - of dominant, 19
 - of subdominant, 19
- Characteristic frequency, 9
- Chord
 - profile, 28
- Chord functions, 19, 27
- Chromatic scale, 15, 16, 25, 28
- Circle of fifths, 18, 26, 27, 67
- Cochlea, 7
- Cognitive functions, 37
- Commissura
 - anterior, 174
 - posterior, 174
- Contextual Asymmetry, 32
- Contextual Distance, 31
- Contextual Identity, 33
- Correlation matrix, 26, 27
- Cortex, 37
- Cranial nerve VIII, 10
- DC-potentials, 63
- Degree, 18
- Diatonic, 23–25, 33, 64, 66
- Diminished chord, 18, 28
- Dominant, 19, 29, 31
 - \sim seventh chord, 25
 - \sim seventh chord, 19, 28
- Double-helix, 13
- Ear, 7
- Electro-encephalogram (EEG), 38
- Electro-oculogram (EOG), 74
- Electrode, 38
- Equivalent current dipole (ECD), 46
- ERFs, 176
 - ERANm, 172, 174, 176, 194
 - N1m, 176, 194
 - P1m, 176, 194
 - P2m, 171, 174–176, 194
- ERP-components
 - CNV, 144, 196
 - ELAN, 59, 60, 83, 84, 177, 183, 194
 - endogenous \sim , 51
 - ERAN, 79, 83–85, 87, 89, 92, 99–101, 103, 112–115, 119, 122, 127, 133, 135, 136, 138, 142–144, 146, 147, 149, 153, 154, 160–162, 164, 178, 183, 194, 203–206, 208–210
 - exogenous \sim , 51
 - LAN, 59
 - LPC, 64, 65
 - MMN, 52, 147, 178, 197
 - N1, 52
 - N2b, 53, 91, 97, 98, 100, 101, 105, 106, 113, 120, 140, 142, 160, 196
 - N400, 56–59, 63, 64, 82, 84, 99, 185
 - N5, 79, 82–87, 99–103, 109, 112–114, 119, 122, 128, 129, 142–144, 149, 154, 156, 160, 161, 190, 203, 204, 208–210
 - Novelty P3, 54
 - P1, 52
 - P2, 176
 - P300, 187
 - P3a, 53, 66, 77, 78, 86, 87, 90, 92, 97, 101, 105, 106, 120, 129, 140, 141

- P3b, 54, 56, 60, 63, 64, 66, 92, 97, 100, 101, 105, 106, 108, 111, 113, 120, 129, 140, 153
- P600, 59–61, 67
- RATN, 67, 84, 183
- Event-related field (ERF), 45
- Event-related potential (ERP), 42
- Excitatory postsynaptic potential (EPSP), 37
- Glutamate, 8
- Gyrus
 - inferior frontal γ 174
 - superior temporal \sim , 10
 - temporalis transversus (Heschl), 10, 174, 176, 194
- Hair cells, 7
- Harmonic core, 31
- Helicotrema, 7
- Hierarchy
 - of stability, 30, 70
 - of tones, 24
- Hippocampus, 40
- Incus, 7
- Inferior colliculus, 10
- Inion, 39
- Interval, 15–17, 19
- Intrakey Asymmetry, 32
- Intrakey Distance, 31
- Inverse problem, 47
- Key, 17–20, 23–33, 61, 66, 67, 69, 233
 - dominant \sim , 17
 - interkey distance, 26, 27
 - parallel \sim , 27
 - profile, 25
 - regions, 27
 - relative \sim , 26, 27
 - sense of \sim , 29
 - subdominant \sim , 17
- key Membership, 31
- Limbic system, 40
- Malleus, 7
- Mastoid, 40
- Mean global field power, 171
- Meatus, 7
- Medial geniculate body, 10
- Mediant, 19, 29
- Middle-latency responses, 51
- Modulation, 29, 131
 - diatonic \sim , 132
- Multidimensional scaling (MDS), 24, 26, 28, 30
- Multiple spheres model, 47
- Musical context, 69, 70, 75, 81–83, 99, 112, 152, 163, 183
- Musical context build-up, 69, 75, 81, 84, 86, 114, 152
- Musical expectancy, 64, 70, 71, 85
- Musical expectancy violation, 69
- Musical integration, 69
- Nasion, 39, 171
- Neapolitan sixth chord, 20, 70, 73, 81, 85–87, 99–101, 104–106, 108, 111–116, 119–121, 127, 128, 143, 150, 154–157, 159–163, 167, 176, 182, 193, 206
- Noise, 41
- Non-diatonic, 23–25, 33, 64–66, 70
- Nucleus
 - superior olivary \sim , 10
 - ventral cochlear \sim , 10
- Organ of Corti, 7
- Oval window of the cochlea, 7
- Overtone, 19
- Pars opercularis, 174, 177, 194
- Pitch
 - \sim chroma, 12
 - \sim height, 12
- Pivot chord, 132
- pre-auricular point, 171
- Pyramidal cells, 37
- Radiatio acustica, 10
- Re-orienting, 102
- Reference electrode, 39, 40, 74, 135, 151–154, 160, 161
- Root
 - position, 19
 - tone, 19
- Round window of the cochlea, 7
- Scala media, 7
- Scala tympani, 7
- Scala vestibuli, 7
- Scale, 16
- Secondary dominant, 20, 71, 73, 80, 87, 88, 95–97, 101, 110, 111, 114–117, 119, 120, 123, 124, 126, 128, 182, 188, 204, 205
- Semantic, 182, 185
- Semantics, 1–3, 55–57, 59, 63, 66, 69, 82, 84
- Semitone, 15
- Signal, 41

- Signal-to-noise ratio (SNR), 41, 48, 49, 88, 147, 167
- Similarity
 - matrix, 30
 - ratings, 30
- Single sphere model, 47
- Six-four chord, 20, 73, 139, 142, 147, 191
- Sixte ajoutée, 19
- Sixth chord, 19, 83, 139, 142, 147, 191
- Sound pressure level (SPL), 9
- Spiral ganglion, 8
- SQUID, 45
- Standard error of mean, 42
- Stapes, 7
- Stereocilia, 8
- Subdominant, 19, 29, 31
- Submediant, 19, 29
- Supertonic, 19, 29
- Sylvian fissure, 40
- Syntax, 2, 3, 5, 35, 58, 59, 69, 70, 83, 84, 113, 166, 167, 177, 178, 183, 194, 195, 197

- Tectorial membrane, 8
- Tempered intonation, 15
- Tetrachord, 16
- Thalamus, 10, 38
- Tonal center, 69
- Tonal context, 30
- Tonic
 - chord, 18, 23, 24, 28, 31, 69
 - tone, 18
- Tonicization, 29
- trapezoid body, 10
- Traveling wave, 9
- Tympanic membrane, 7

- Vertex, 39

- Working Memory, 146, 191

Curriculum Vitae

- 07.07.1968 Geboren in Wichita Falls, Texas, USA
- 1987 Abitur am Kurt-Schumacher Gymnasium, Bremen
- 1989-1994 Studium der Instrumental- und Vokalmusik an der Hochschule für Künste Bremen, Hauptfach Violine, Abschluss: Künstlerische Reifeprüfung
- 1994 Aufnahme der Diplomstudiengänge Psychologie und Soziologie an der Universität Leipzig
- 1996 Vordiplome in Psychologie und Soziologie
- WS 1996/97 Studium an der University of East London als ERASMUS-Stipendiat
- 1998 Diplom im Studiengang Psychologie
- seit Jan. 1999 Stipendiat der Max-Planck-Gesellschaft als Doktorand am Max-Planck-Institut für neuropsychologische Forschung, Leipzig

Bibliographische Beschreibung

Kölsch, Stefan

Brain and Music

A contribution to the investigation of central auditory processing with a new electrophysiological approach

Universität Leipzig, Dissertation

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Referat

In der vorliegenden Arbeit wurde mit Hilfe ereigniskorrelierter Potentiale (EKP) und ereigniskorrelierter magnetischer Felder (EKF) die Verarbeitung von Musik im menschlichen Gehirn untersucht. In sechs EEG-Experimenten und einer MEG-Studie wurden Akkord-Sequenzen dargeboten. Diese bestanden entweder aus leitereigenen Akkorden (und etablierten einen musikalischen Kontext), oder sie enthielten einen als unerwartet empfundenen leiterfremden Akkord. Der Grad an Unerwartetheit wurde musiktheoretischer Logik folgend systematisch variiert. Ziel war es, EKPs als Korrelate musikalischen Kontext-Aufbaus und der Verarbeitung unerwarteter Akkorde zu erzeugen und zu untersuchen, und deren neuronale Generatoren anhand der EKFs zu lokalisieren. Probanden waren 'Nicht-Musiker'.

Die Daten der Experimente zeigen, daß musikalischer Kontext-Aufbau in einer späten (maximal um 550 ms), bilateral-frontal über den Schädel verteilten EKP-Komponente reflektiert sind (als 'N5' bezeichnet). Unerwartete Akkorde evozierten zwei EKP-Komponenten: eine frühe rechts-anterior prädominante Negativierung (maximal um 200 ms), und eine spätere frontale Negativierung (maximal um 550 ms). Die frühe Negativierung wurde mit 'ERAN' bezeichnet (early right anterior negativity), die späte mit 'N5' (sic!). Die Größe der Amplituden von ERAN und N5 zeigte sich als abhängig vom Grad der aufgrund musiktheoretischer Überlegungen vorhergesagten Unerwartetheit. Die Prozesse, die der Generation der ERAN und der N5 unterliegen, waren abhängig von der Auftrittswahrscheinlichkeit unerwarteter Akkorde. Sowohl ERAN als auch N5 waren prä-attentiv evozierbar. Die ERAN zeigte sich nur marginal beeinflußt von Aufmerksamkeit, und abhängig von der Detektierbarkeit eines Akkordes. ERAN und N5 scheinen voneinander unabhängige Prozesse widerzuspiegeln. Die neuronalen Generatoren der ERAN wurden im unteren Pars Opercularis (links und rechts, in der linken Hirnhälfte auch Broca-Areal genannt) lokalisiert.

Die ERAN wird interpretiert als Korrelat der Verletzung einer Klangerwartung, die N5 als Korrelat musikalischer Integrationsprozesse. Die ERAN wird assoziiert mit der Verarbeitung musikalischer Syntax, die N5 mit der Verarbeitung musikalischer Semantik. Sowohl ERAN als auch N5 wurden meines Wissen zuvor noch nicht beschrieben, ebenso wie eine Aktivierung des frontalen Operculums durch Musik. Die Ergebnisse der Studie demonstrieren eine implizite (und sogar prä-attentive) Musikalität des menschlichen Gehirns.

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