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Emotional Experiences of Tension and Suspense:

Psychological Mechanisms and Neural Correlates

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Contents

Summary

Tension and suspense are ubiquitous emotional phenomena that are experienced in a multitude of contexts (e.g., in music, literature, film, sports, or everyday life). However, the psychological and neuronal mechanisms underlying tension experiences remain largely unclear. This dissertation aims to advance the understanding of tension and suspense by presenting theoretical and empirical work that investigates the psychological underpinnings and neural correlates of tension phenomena.

The empirical studies focus on the special cases of musical tension (i.e., tension experiences evoked by music) and suspense evoked by a literary text. First, a behavioral study explored the role of different tonal and expressive structural features of a musical piece (harmony, melody, outer voices, dynamics, and expressive timing) as a mediator of musical tension. Results of this study indicate that musical tension largely depends on tonal features and their relative importance in the musical piece but can be enhanced by expressive features (such as dynamics). A subsequent study using functional magnetic resonance imaging (fMRI) investigated neural correlates of tension experiences during music listening. The subjective experience of felt musical tension was found to be related to neural activations in areas associated with affective processing in the orbitofrontal cortex and the amygdala, underlining the close connection between musical tension and music-evoked emotion. A methodologically similar fMRI study investigating neural correlates of suspense evoked by a literary text found suspenseful text segments to be associated with activity in medial prefrontal, inferior frontal, as well as posterior temporal and temporo-parietal brain areas, suggesting an involvement of processes of theory of mind and predictive inference.

In addition to these empirical studies, two articles explore tension phenomena from more theoretical perspectives. The first article discusses patterns of tension and resolution and their contribution to aesthetic emotions evoked by works of art. Building on this, the second

article reviews general, domain-independent cognitive processes underlying tension experiences and proposes a general psychological model of tension and suspense. According to this model, tension experiences result from states of conflict, instability, dissonance, or uncertainty that trigger processes of expectation and anticipation directed at future events of emotional significance.

In sum, the work presented in this dissertation explores both domain-specific (i.e., music and literature) as well as general, domain-independent aspects of emotional experiences of tension from empirical and theoretical perspectives. It includes the first neuroimaging studies of tension and suspense in music and literature, which—together with the theoretical articles—provide a foundation for subsequent research on tension phenomena which might be useful to researchers from a variety of disciplines including cognitive and affective neuroscience, psychological emotion research, media psychology, film and literature studies, as well as empirical aesthetics.

Zusammenfassung

Das Erleben von Spannung ist ein allgegenwärtiges emotionales Phänomen, das durch eine Vielzahl unterschiedlicher Kontexte ausgelöst werden kann (z.B. durch Musik, Literatur, Film, Sport oder diverse Alltagssituationen). Die psychologischen und neuronalen Mechanismen, die der emotionalen Erfahrung von Spannung zu Grunde liegen, sind jedoch weitgehend ungeklärt. Ziel der vorliegenden Dissertation ist es, die psychologischen Grundlagen und neuronalen Korrelate von Spannungsphänomenen empirisch und theoretisch zu untersuchen und auf diese Weise zum besseren Verständnis dieses Aspekts menschlicher Emotion beizutragen.

Die empirischen Studien befassen sich mit den Spezialfällen musikalischer Spannung (d.h. mit durch Musik hervorgerufenen Spannungserfahrungen) und mit Spannungsempfindungen beim Lesen eines literarischen Texts. Zunächst wurde in einer Verhaltensstudie der Einfluss verschiedener struktureller und expressiver Merkmale (Harmonie, Melodie, Außenstimmen, Dynamik, expressives Timing) zweier Musikstücke auf die Erfahrung musikalischer Spannung untersucht. Die Ergebnisse zeigen, dass musikalische Spannung in erster Linie von tonalen Merkmalen und deren relativer Bedeutung im jeweiligen Musikstück abhängt, jedoch durch expressive Merkmale (wie z.B. der Dynamik) verstärkt werden kann. In einer Folgestudie wurden die neuronalen Korrelate musikalischer Spannung mittels funktioneller Magnetresonanztomographie (fMRT) untersucht. Die Ergebnisse dieser Studie zeigen, dass das subjektive Erleben musikalischer Spannung mit neuronalen Aktivierungen des orbitofrontalen Kortex und der Amygdala einhergehen, d.h. Arealen, die mit der Verarbeitung von Emotionen zusammenhängen. In einer methodisch ähnlichen fMRT-Studie, die die neuronalen Korrelate von Spannung (Suspense) beim Lesen eines literarischen Texts untersuchte, wurde ein Zusammenhang zwischen empfundener Spannung und Aktivierungen in medial-präfrontalen, inferior-frontalen, und posterior-temporalen

Hirnarealen gefunden. Diese Aktivierungen legen einen Einfluss von Prozessen der sogenannten „Theory of Mind“ (d.h. der Fähigkeit, anderen Personen geistige Zustände zuzuschreiben) und Prädiktionsprozessen während des Lesens spannender Textabschnitte nahe.

Zusätzlich zu diesen empirischen Studien, wurden Spannungsphänomene in zwei Artikeln aus theoretischer Perspektive genauer beleuchtet. Der erste Theorieartikel diskutiert Spannungs- und Auflösungsstrukturen und deren Zusammenhang mit durch Kunstformen wie Musik, Literatur oder Film hervorgerufenen Emotionen. Darauf aufbauend untersucht der zweite Theorieartikel allgemeine, domänenübergreifende kognitive Prozesse, die Spannungserfahrungen zu Grunde liegen, und entwickelt ein psychologisches Spannungsmodell. Diesem Modell zufolge resultieren Spannungserfahrungen aus Zuständen, die mit Konflikt, Instabilität, Dissonanz und Unsicherheit assoziiert sind, welche Erwartungs- und Antizipationsprozesse hervorrufen, die sich auf zukünftige Ereignisse emotionaler Bedeutung richten.

Die im Rahmen dieses Dissertationsprojekts durchgeführten Arbeiten untersuchen sowohl domänenspezifische (in Musik und Literatur) als auch domänenenunabhängige Aspekte von Spannungserlebnissen. Die Dissertation beschreibt die ersten fMRT-Studien zu Spannungserfahrungen in Musik und Literatur, und schafft so, zusammen mit den Theorieartikeln, eine Grundlage für zukünftige neurowissenschaftliche und psychologische Forschung zu Spannungsphänomenen.

List of publications

The dissertation is based on the following five articles. The co-authors can confirm that I have been the main responsible person for the realization of all of these projects. Occasionally, the text of the original articles has been slightly modified to facilitate reading of the dissertation (e.g., cross-references between articles refer to the respective chapters of this dissertation).

Lehne, M., Rohrmeier, M., Gollmann, D., & Koelsch, S. (2013). The influence of different structural features on felt musical tension in two piano pieces by Mozart and Mendelssohn. *Music Perception, 31*(2), 171-185.

Lehne, M., Rohrmeier, M., & Koelsch, S. (2013). Tension-related activity in the orbitofrontal cortex and amygdala: an fMRI study with music. *Social Cognitive and Affective Neuroscience*. doi: 10.1093/scan/nst141.

Lehne, M., & Koelsch, S. (in press). Tension-resolution patterns as a key element of aesthetic experience: psychological principles and underlying brain mechanisms. In J. P. Huston, M. Nadal, F. Mora, L. Agnati & C. J. Cela-Conde (Eds.), *Art, Aesthetics and the Brain*. New York: Oxford University Press.

Lehne, M., Engel, P., Menninghaus, W., Jacobs, A. M., & Koelsch, S. (under review). On first looking into Hoffmann's “The Sandman”: Neural correlates of suspense during the first reading of a literary text.

Lehne, M., & Koelsch, S. (under review). Towards a general psychological model of tension and suspense.

1 General introduction[1]

Emotional experiences in response to music, film, literature, sports, art, or everyday life events often alternate between the opposite poles of tension and resolution. The emotions evoked, for example, by a suspenseful movie, a captivating novel, a piece of music, or an important job interview typically involve episodes of tension and resolution, and often the associated tension experiences are a main motivator for someone to engage (or not engage) in a certain activity (e.g., watching a movie because it creates suspense or avoiding situations in which tension is experienced as negative). The previous examples show that experiences of tension are ubiquitous phenomena which occur in a variety of different contexts and which can evoke strong emotions and significantly influence people's actions and behavior. Understanding the psychological and neuronal processes underlying tension experiences can therefore contribute to a better understanding of human emotion. The aim of this dissertation project is to explore the (neuro-)cognitive mechanisms of tension experiences, and thereby advance the understanding of this important aspect of human emotional experience.

The idea that tension phenomena play an important role in emotion can be traced back to the beginnings of modern psychology, in particular to the works of Wilhelm Wundt, who proposed tension (*Spannung*) and resolution (*Lösung*) as constituting the opposite poles of one of three dimensions that define the space of emotional experience (the other two dimensions are arousal and valence; Wundt, 1896, 1911). Wundt's emotion theory is an example of so-called dimensional theories of emotion, which assume that emotions can be reduced to the interactions of a limited set of dimensions. Such dimensional theories can be distinguished from other prominent accounts of emotion, for example, theories assuming a basic set of discrete emotions (Ekman, 1999), appraisal theories (Arnold, 1960; Lazarus,

[1] As this is a cumulative dissertation based on individual studies and articles, more introductory information is given at the beginning of the individual chapters describing the studies and in the theoretical articles presented in Chapters 4 and 6. To avoid boring the reader with too much repetition, this general introduction is therefore kept relatively short.

1991), the two-factor theory of emotion (Schachter & Singer, 1962), the component model of emotion (Scherer, 2005), or physiological and neuroscientific accounts of emotion (e.g., Damasio, 1994; James, 1884; Panksepp, 1998). Among proponents of dimensional theories, Wundt's original three-dimensional conception has been largely replaced by Russell's two-dimensional circumplex model (Russell, 1980), according to which emotions can be located along the two dimensions of valence and arousal (or what has also been termed "core affect", Russell, 2003; Russell & Barrett, 1999). As a consequence, research on tension phenomena has largely disappeared from "mainstream" psychological emotion research. However, tension phenomena have continued to play an important role in specific sub-disciplines of psychology. For example, in music psychology, the continuous ebb and flow of tension and resolution apparent in most works of Western tonal music has been discussed as a key element of the emotional experience associated with music listening (Huron, 2008; Koelsch, 2012, 2014; Meyer, 1956; Schenker, 1935). Similarly, media psychological research has investigated tension phenomena in narrative plots, for example, suspense in movies or novels (Auracher, 2007; Brewer & Lichtenstein, 1980; Gerrig & Bernardo, 1994; Vorderer et al., 1996; Zillmann, 1980; for more elaborate accounts of musical tension and suspense, see also Chapters 4 and 6). However, the psychological and neuronal underpinnings of tension experiences remain largely unclear.

This dissertation presents a series of articles exploring emotional experiences of tension and suspense from empirical and theoretical perspectives with the aim of advancing the understanding of tension phenomena and their underlying psychological and neuronal mechanisms. The articles comprise a music psychological study investigating which aspects of a musical piece contribute to the subjective experience of musical tension, two functional magnetic resonance imaging (fMRI) studies that investigate neural correlates of tension experiences, focusing on the exemplary cases of tension in music and literature, and two theoretical articles that explore tension-resolution patterns in artistic contexts, discuss their underlying psychological mechanisms, and propose a general domain-independent model of tension and suspense.

Before presenting the empirical studies and theory articles, the introductory parts of this dissertation give a short overview of tension phenomena in music and literature and their relation to emotion, a brief introduction to functional magnetic resonance imaging, as well as a statement of the general objective of this dissertation project and of the single studies included in it.

1.1 Tension and emotion in music and their neural correlates

Music can induce intense emotional experiences. In fact, its emotional power is one of the main reasons why people listen to music (Sloboda & O'Neill, 2001), and music is often used to deliberately induce or amplify specific emotions (e.g., in film, cf. Cohen, 2001). In empirical research, emotional reactions to music can be investigated at (neuro-)physiological, behavioral, or subjective levels. Importantly, investigating music-evoked emotions is not only relevant to music psychology but may provide insights that can foster the understanding of emotion in general.

Seminal studies by Sloboda (1991) and Panksepp (1995) exploring so-called "chill" experiences, i.e., intense emotional responses to music, have shown that participants can experience intense bodily reactions such as laughing, tears, or shivers down the spine when listening to specific passages of their favorite music. Moreover, experiments indicate that music pieces expressing basic emotions like fear, sadness, or joy are associated with specific changes in physiological measures such as heart rate, blood pressure, respiration frequency, skin conductance, or body temperature (Krumhansl, 1997). Investigating emotional reactions to music at the neuronal level, an fMRI study by Koelsch et al. (2006) indicates that pleasant music is associated with neuronal activity in the inferior frontal gyrus (IFG), the ventral striatum, Heschl's gyrus, the insula and the frontal operculum, whereas unpleasant music is related to activity in the amygdala, hippocampus, parahippocampal areas, and temporal poles. Comparing happy and sad music, Mitterschiffthaler et al. (2007) report activation in the ventral and dorsal striatum, cingulate cortex, parahippocampus and auditory association areas related to happy music whereas sad music is associated with activity in the amygdala and hippocampus. Experiments investigating neural correlates of chill experiences during music listening found activations of brain areas associated with reward, motivation, and emotion such as the ventral striatum, amygdala, orbitofrontal cortex (OFC), and ventromedial prefrontal cortex (Blood & Zatorre, 2001). Similar results were reported by Menon & Levitin (2005) who found mesolimbic structures such as the ventral tegmentum and the nucleus accumbens to be activated during music listening (as opposed to listening to “scrambled” music in which short excerpts from the original music stimuli were randomly concatenated).

Although these empirical studies underline the emotional power of music and provide first insights into the neural correlates of music-evoked emotions, the exact mechanisms by which music elicits emotions remain largely unclear. From a music psychological perspective, expectancy processes (e.g., expectancy violations or fulfillments that arise during the temporal unfolding of a musical piece) have been proposed as a key component giving rise to emotional experiences during music listening (Huron, 2006; Koelsch, 2012; Meyer, 1956; Vuust & Frith, 2008). The effects of music-syntactic expectancy violations have been extensively investigated in the electroencephalogram (EEG) and have been associated with an early right-anterior negativity (ERAN; Koelsch, 2000; Koelsch et al., 2002; Koelsch, 2009; Koelsch et al., 2013; Jentschke & Koelsch, 2009). Moreover, changes in skin conductance in response to unexpected chords appear to confirm the emotional effects of music-syntactic expectancy violations (Steinbeis et al., 2006). This gains further support from an fMRI study by Koelsch et al. (2008) showing amygdala activations in response to unexpected chords. Furthermore, a study by Salimpoor et al. (2011) shows that the anticipation of chill experiences is associated with activity in the dorsal striatum whereas the pleasurable feeling during the actual chill experience is associated with ventral striatum (nucleus accumbens) activation; anticipation and experience of chills thus activate areas that have previously been related to reward processing. These studies provide empirical evidence that expectation processes indeed play a key role in the evocation of emotions during music listening.

The experience of musical tension, i.e., the continuous ebb and flow of tension and resolution that is usually experienced when listening to a piece of Western tonal music, is closely related to these expectation processes, in particular to episodes of expectancy build-up, violation, anticipation of resolution, and resolution (cf. Koelsch, 2012, 2014). For example, the build-up of expectancies is usually associated with an experience of increasing tension which may further increase when expectancies are repeatedly violated and which resolves when expectancies are finally fulfilled. Studying musical tension can therefore contribute to understanding the neuronal and psychological mechanisms underlying these expectation processes, thus elucidating the mechanisms by which music evokes emotion (see also Chapter 2).

1.2 Tension and emotion in literature

Like listening to music, reading literature can induce emotions, and these emotional experiences are often a main motivator for people to read (e.g., for enjoyment or relaxation). Emotional responses during reading can be evoked by different aspects of a literary text. Kneepkens & Zwaan (1995), for example, distinguish between fiction and artefact emotions aroused by literary texts. Whereas fiction emotions are evoked by events of the (fictional) plot of a text, artefact emotions are elicited by aspects of the surface structure of a text, e.g., syntactical, stylistic, metric, or rhetorical elements. This is related to the distinction between background and foreground according to which texts can be divided into a background of familiar elements (e.g., common words and grammatical structures) associated with a natural mode of reading which can be contrasted against foregrounding elements that, via a process of defamiliarization or alienation (e.g., by presenting unfamiliar phonetic, syntactic, or semantic structures), disrupt the natural reading flow and direct the reader's attention to these elements (cf. Miall & Kuiken, 1994; Mukařovsky, 1964; Shklovsky, 1965). Authors often deliberately use foregrounding to make readers aware of the stylistic elements of a text, thus potentially inducing processes of aesthetic perception and emotion. The distinction between background and foreground is also captured by Jacobs' neurocognitive poetics model of literary reading (Jacobs, 2011; Jacobs, in press) which differentiates between two routes of text processing: a fast and automatic route associated with background text processing and a slower route processing foregrounded text information. According to the model, the two routes can be distinguished at neuronal, cognitive-affective, and behavioral levels of description. For example, background reading is assumed to be associated with immersive processes and fiction emotions induced by events of the plot whereas foregrounded reading is related to artefact emotions and aesthetic and more self-reflective text processing.

A similar distinction can be made for tension phenomena in literary texts. On the one hand, tension experiences in literature are evoked by events of the plot, which create feelings of suspense like the ones commonly experienced when reading literature genres such as thrillers, mystery fiction, detective stories, or spy novels. These suspense experiences are typically induced by conflicts which protagonists of a story have to overcome or by intellectual puzzles that the reader wants to see resolved (for more information on tension and suspense in literature, see also Chapters 4, 5, and 6). These suspense experiences mediated by events of the plot usually derive from a purposeful play with information—a careful disclosing or holding back of information, creating an urge in the reader to resolve uncertainties and reach a state in which all relevant information of the narrative plot is available. This kind of tension experience has been referred to as “plot suspense” (Rabkin, 1973) because it results from the structure of events on the level of the narrative plot. The relation between how information is provided to the reader and experiences of suspense has also been confirmed empirically: In a study by Brewer & Lichtenstein (1980) manipulating the order in which information about events of short plots was disclosed to the reader was found to significantly affect subjective ratings of suspense.

Apart from tension experiences on the level of the plot, tension can also be induced on more micro-structural levels of a text. In a single sentence, for example, tension can be created by the use of complex syntactical structures (e.g., nested relative clauses or embedded parenthetical statements). To distinguish them from tension and suspense experiences aroused by events of the plot, such tension experiences have been termed "subliminal suspense" (Rabkin, 1973).

Until now, no neuroimaging studies investigating tension experiences in literature have been conducted, and knowledge about the neuronal processes underlying experiences of tension and suspense during reading therefore is scarce. One of the aims of this dissertation project is to provide first insights into neural correlates of tension and suspense in literature.

1.3 Functional magnetic resonance imaging (fMRI)

As two of the studies presented in this dissertation use functional magnetic resonance imaging (fMRI) to investigate tension-related processes in the human brain, a short overview of the method seems appropriate. Since its introduction by Ogawa et al. in 1990, fMRI has seen an overwhelming rise in popularity and its increasing use as a method for studying mental processes has propelled the field of cognitive neuroscience to the forefront of many psychological research endeavors (note that this development is not without its critics; see, for example, Slaby, 2010). FMRI provides a unique way to indirectly measure neuronal activity non-invasively in the living brain by detecting subtle changes in the oxygen level of the blood. It is based on the phenomenon of nuclear magnetic resonance, first described in the 1930s and 1940s (Bloch et al., 1946; Rabi et al., 1938; Purcell et al., 1946). Due to nuclear magnetic resonance, atomic nuclei in a magnetic field resonate at a certain frequency (the so-called Larmor frequency) when subjected to electromagnetic radiation. The resulting oscillation decays over time, and the decay time is dependent on the resonance frequency which in turn depends on the strength of the magnetic field as well as magnetic properties of the atom. By measuring the resonance of atomic nuclei and their decay in response to short high-frequency radio wave impulses, information about different tissue types and blood oxygenation can be acquired. Moreover, by creating magnetic field gradients that make the resonance frequency change in a location-dependent manner, spatial information can be obtained. Crucial for investigating neuronal processes with fMRI is a coupling between the metabolic activity of nerve cells and the oxygen level of surrounding blood vessels. By a mechanism that is not yet fully understood, the blood flow to brain areas in which neuronal activity is high increases, resulting in a higher concentration of oxygenated blood in these areas. FMRI takes advantage of the different magnetic properties of oxygenated hemoglobin (the molecule that carries oxygen from the lungs to different parts of the body) in comparison with deoxygenated hemoglobin, and the measurement of this blood oxygen level-dependent (BOLD) signal allows for an indirect detection of neuronal activity.

In comparison to other non-invasive methods used in cognitive neuroscience (in particular electroencephalography), the spatial resolution of fMRI is relatively high, and the smallest volume unit measured with fMRI, a so-called voxel, usually covers 1-3 mm^3 of brain tissue (however, even such a relatively small patch of the brain can contain hundred thousands of neurons). The temporal resolution of fMRI is restricted by the time it takes to measure the signal, and in typical fMRI studies, one image of the whole brain is acquired every 1-3 seconds. Furthermore, the changes of the blood oxygen level in response to neural activity changes are “sluggish”, meaning that they take some time to set in and decrease again (approx. 6-8 seconds until a maximal response is reached). This sluggishness of the BOLD response acts as a temporal smoothing kernel, also limiting the resolution of high temporal frequencies.

Subsequent to the measurement and prior to the statistical analysis, different preprocessing procedures are usually applied to the fMRI data, which typically include the realignment of images to correct movement-induced displacements between images, the coregistration of functional MRI data to an anatomical reference image, normalization of the data to a standard brain image, and spatial smoothing of the data. Standard statistical analysis of fMRI data then usually follows a mass-univariate general linear model (GLM) approach, which estimates how well specific experimental conditions predict BOLD signal changes in each voxel. Due to the mass-univariate analysis (meaning that statistics are computed independently for each voxel), it is important that some kind of correction for multiple comparisons be used when calculating the statistics to avoid taking false rejections of the null hypothesis to reflect actual effects (for example, when calculating independent statistical tests for 100,000 voxels, even in the absence of a true effect, 5,000 of them can be assumed to become statistically significant by chance at an alpha-level of .05).

Because an experimental task usually effects changes in large areas distributed across the whole brain, most analyses compute so-called contrasts between minimally different experimental conditions to find localized activations pertaining to a specific aspect of the experimental task (e.g., comparing brain activations in response to happy music as opposed to fearful music to determine neural correlates of music-evoked fear and joy). In most cases, the statistical results are represented graphically by overlaying color-coded statistical values on anatomical images of the brain. The resulting brain images, which suggest that specific brain areas “light up” while specific mental processes are performed, have arguably contributed substantially to the popularity of fMRI as a neuroscientific research method and its increasing recognition by popular media and the general public.

In addition to the standard GLM approach to fMRI data analysis described above, recent years have seen an increasing use and sophistication of alternative analysis methods including, for example, multivoxel pattern analyses (Haynes & Rees, 2006), dynamic causal modeling (Friston et al., 2003), Granger causality mapping (Roebroeck et al., 2005), analyses of resting-state connectivity (Biswal, 2012; Buckner et al., 2008), independent component analysis (Calhoun et al., 2009), eigenvector centrality mapping (Lohmann et al., 2010), or the analysis of intersubject correlations (Hasson et al., 2004).

1.4 Research aims of the dissertation project

The overall aim of this dissertation project is to further the understanding of tension phenomena from theoretical, psychological, and neuroscientific perspectives. Starting with the special cases of tension evoked by music and suspense evoked by a literary text, structural stimulus features and brain mechanisms associated with experiences of tension and suspense are investigated in three empirical studies. Moreover, the psychological mechanisms underlying tension-resolution patterns in artworks are discussed in a theoretical article. Finally, a general psychological model of tension and suspense is proposed. The following paragraphs describe the aims of the different empirical studies and theoretical articles in more detail.[1]

Study 1: The influence of different structural features on felt musical tension in two piano pieces by Mozart and Mendelssohn

The aim of this study was to investigate how structural features of a musical piece influence the subjective experience of tension. For this, a behavioral experiment was conducted in which subjective ratings of felt musical tension were acquired for six different versions of two piano pieces by Mendelssohn and Mozart. The different versions included the original piece and versions without dynamics and without agogics (i.e., without expressive variations in tempo) as well as versions in which the music was reduced to its melodic, harmonic, or outer voice components. To evaluate the contribution of different features to subjectively experienced tension, tension ratings of the modified versions were compared to the ones of the original versions in a correlation analysis. In addition, tension ratings were

[1] Note that the order in which the articles are presented in this dissertation follows the order in which they were written and in which the studies were conducted. However, the comprehension of later articles does not require knowledge of previous articles, and readers of this dissertation are encouraged to read the chapters in the order they prefer or to omit chapters altogether according to their interests. Moreover, the ideas presented in the two theoretical articles partially overlap, and readers short on time are advised to read only the latter of the two ("Towards a general psychological model of tension and suspense") as it discusses ideas from a more general perspective and builds on the ideas presented in the former ("Tension-resolution patterns as a key element of aesthetic experience: psychological principles and underlying brain mechanisms").

compared with the loudness variations of the music as predicted by a standard loudness model. The study also includes a qualitative music-theoretical analysis of the tension ratings.

Study 2: Tension-related activity in the orbitofrontal cortex and amygdala: an fMRI study with music

This fMRI study aimed to identify brain areas associated with the subjective experience of musical tension. Similar to Study 1, subjective ratings of musical tension were obtained for four piano pieces in a behavioral experiment. Subsequently, fMRI data were acquired while participants listened to the pieces again. The behavioral rating data were then used in the fMRI data analysis to investigate in which brain areas the BOLD signal correlates with tension ratings, and which brain areas are active during music periods associated with increasing tension as compared with decreasing tension. It was hypothesized that tension modulates activity in limbic and paralimbic brain regions involved in emotional processing (see Section 1.1). More specifically, due to its relation to expectation processes, tension was assumed to be associated with amygdala activations as suggested by a previous experiment finding amygdala activations in response to expectancy violations in short chord sequences (Koelsch et al., 2008, see Section 1.1).

Theory article 1: Tension-resolution patterns as a key element of aesthetic experience: psychological principles and underlying brain mechanisms

This article explores tension-resolution patterns in works of art and their underlying psychological and neuronal mechanisms. Focusing mainly on temporal art forms (i.e., art forms that unfold in time such as music, film, or literature), the article proposes patterns of tension and resolution as an important mediator of the emotions evoked by these art forms. Possible psychological processes (e.g., processes of expectancy, prediction, and anticipation) giving rise to tension experiences are reviewed, and the special case of musical tension is considered in more detail.

Study 3: On first looking into Hoffmann's “The Sandman”: Neural correlates of suspense during the first reading of a literary text

Similar to Study 2, this fMRI study investigates which brain areas are related to the subjective experience of suspense in response to a literary text. For this, fMRI data were acquired while participants read a coherent literary text (E.T.A. Hoffmann's, The Sandman) that was subdivided into short text passages after each of which participants rated their subjectively experienced level of suspense. As in Study 2, participants' suspense ratings were put into relation to the fMRI data to investigate which brain areas are associated with the experience of suspense during literary reading. Due to the lack of previous neuroimaging research on tension experiences in literature, it was difficult to state well-informed hypotheses for this study. However, as a working hypothesis, suspense was—in analogy to the fMRI study on musical tension—assumed to be related to activity in limbic and paralimbic brain structures. Moreover, the relation of tension experiences and areas associated with theory-of-mind and predictive inference was investigated.

Theory article 2: Towards a general psychological model of tension and suspense

This paper extends the first theory article by discussing tension phenomena from a more general perspective. The importance of tension phenomena for general emotion research is highlighted, and key components of typical tension experiences (independent of the specific domain in which they are evoked) are identified. Finally, a general, domain-independent model of tension and suspense is proposed. The model provides a framework that (hopefully) may be helpful to researchers interested in untangling the psychological processes that give rise to experiences of tension and suspense.

2 The influence of different structural features on felt musical tension in two piano pieces by Mozart and Mendelssohn[1]

Abstract

In tonal music, patterns of tension and resolution form one of the core principles evoking emotions. The experience of musical tension and resolution depends on various features of the music (e.g., dynamics, agogics, melody, and harmony), however, the relative contribution of different features to the experience of tension is less clear. To investigate the influence of different features on subjectively experienced musical tension, we compared continuous ratings of felt musical tension for original and modified versions of two piano pieces by Mendelssohn and Mozart. Modifications included versions without dynamics and without agogics as well as versions in which the music was reduced to its melodic, harmonic or outer voice components. Additionally, we compared tension ratings with a loudness model. Tension ratings for versions without dynamics, versions without agogics and without dynamics, and outer voice reductions correlated highly with ratings for the original versions for both pieces. Tension rating correlations between melodic or harmonic reductions and original versions, as well as loudness and original ratings, differed between pieces and appeared to depend on the relative importance of the feature in the respective piece. In addition, qualitative analyses suggested that felt tension and resolution depend on phrase structure, local harmonic implications and global syntactic structures of the pieces. Altogether, results indicate that discarding expressive features such as dynamics and agogics largely preserves tension-resolution patterns of the music, whereas the contributions of harmonic and melodic structure depend on the way in which they are employed in the composition.

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2.1 Introduction

A striking feature of music is its ability to evoke strong emotional experiences in the listener (Juslin & Västfjäll, 2008; Koelsch, 2010). However, the principles underlying the evocation of emotions by music are still not fully understood. In particular, it is not clear how structural features of major-minor tonal music (melody, meter, rhythm, harmony, loudness, and timbral structure including instrumentation and texture) relate to the emotional experience of the listener. A concept that can help to elucidate this relationship is *musical tension*.

Musical tension refers to the continuous change of tension and relaxation that is usually experienced when listening to a piece of Western tonal music. Because musical tension is strongly linked to processes such as expectancy build-up, violation or fulfillment of expectancies, to the anticipation of resolution after a breach of expectancy, and to the eventual resolution of such a breach, musical tension plays an important role in the emotional aspects of music listening (see also Huron, 2008; Koelsch, 2012; Margulis, 2005; Meyer, 1956; Narmour, 1990; Rohrmeier & Koelsch, 2012). This is corroborated by empirical research showing that subjective ratings of musical tension correlate with ratings of discrete emotions (sadness, fear, and happiness) and physiological responses during music listening (Krumhansl, 1997). It has furthermore been shown that subjective ratings of musical tension correlate highly within individuals between different exposures to the same musical piece (Krumhansl, 1996) as well as between different groups of persons such as musicians and nonmusicians or school children of different ages (Fredrickson, 1997, 1999, 2000), suggesting relatively consistent and stable underlying cognitive and affective processes.

Various structural features have been identified in mediating musical tension ranging from dynamics, timbre, melodic contour, harmony, tonality, and repetition (Nielsen, 1983), phrase structure, and note density (Krumhansl, 1996) to pitch height, loudness, onset frequency, and tempo (Farbood, 2012). From a theoretical perspective, the hierarchical structure of music (e.g., Lerdahl & Jackendoff, 1983; Rohrmeier, 2007, 2011; Schenker,

1935) can inform models of tension. For instance, Lerdahl's model of tension (Lerdahl, 1996, 2001; Lerdahl & Krumhansl, 2007) combines predictions based on surface structure and tonal distance as well as higher order hierarchical dependency structure. The notion of an influence of local tonal structure on musical tension has been supported by behavioral studies (Bigand & Parncutt, 1999; Bigand et al., 1996). The most elaborate model of musical tension has been devised by Farbood (2012), taking into account dynamics, pitch height of melody, bass and inner voices, tempo, onset frequency, and harmony. Additionally, the model accounts for the dynamic nature of the music listening process by incorporating attentional and memory processes.

The aforementioned studies (Bigand & Parncutt, 1999; Bigand et al., 1996; Farbood, 2012; Krumhansl, 1996) show that different structural features are related to the subjective experience of musical tension, and that experienced tension can be modelled based on such features. However, research investigating how the experimental manipulation of specific structural features in real musical pieces affects experienced tension is scarce. The aim of the present study, therefore, was to investigate how the elimination or isolation of different structural features affected subjectively experienced musical tension using ecologically valid music stimuli. To achieve this, a behavioral experiment was conducted in which continuous ratings of felt musical tension were acquired for original recordings and different modified versions of two piano pieces by Mendelssohn and Mozart. The structural features investigated were dynamics, agogics, harmony, melody, outer voices (as the most salient voices embodying substantial parts of the musical structure), and loudness. For the modified versions, these features were experimentally manipulated yielding versions without dynamics, without dynamics and without agogics, and versions in which harmony, melody, or outer voices were played in isolation (without dynamics and without agogics). Apart from the modified versions, a loudness model was used to investigate to which degree loudness changes accounted for the experienced tension in the original recording. By comparing the tension ratings of the different versions as well as the loudness estimated by the model, the contribution of the different features on subjectively experienced musical tension was evaluated. In addition, we performed a qualitative music-theoretical analysis investigating which musical events corresponded to the peaks and troughs of the tension profiles.

2.2 Methods

2.2.1 Participants

Data from 28 participants (aged 20 – 46 years, M = 25.4, 16 female) were included in the analysis (data from three additional participants had been excluded due to missing ratings, negative correlations between a participant's tension rating and average tension ratings, or very fast and up-and-down slider movements of one participant throughout the experiment). Ten participants had received instrument or singing lessons in addition to basic music education at school (instruments and years of training: clarinet: 3 years; violin: 10 and 8 years; piano: 6, 7, 7, and 8 years; guitar: 1 year; trumpet: 6 years; voice: 7 years). All participants gave their written consent and were compensated with course credit for participation.

2.2.2 Stimuli

As stimulus material, Mendelssohn Bartholdy's Venetian Boat Song (Op. 30, No. 6) and the first 24 measures of the second movement of Mozart's Piano Sonata KV 280 were used (the musical scores are included in the Appendix). To keep the duration of the experiment reasonable, repetitions indicated in the scores were omitted.

The pieces were performed by a professional pianist on a Clavinova CLP-130 (Yamaha Corporation, Hamamatsu, Japan) from which MIDI data were recorded. This allowed for a selective manipulation of specific parameters of the music. From the original recordings, the following five modified versions were created: (a) a version without dynamics, i.e., all notes were played with the mean MIDI velocity value of the piece (Mendelssohn: 42; Mozart: 36); (b) a “deadpan” version without dynamics and without agogics (i.e., all notes were played with the same MIDI velocity and without any variations in tempo); (c) a version containing only a harmonic reduction of the piece (i.e., non-chord tones were eliminated and remaining notes of one chord were played synchronously, see Figure 2.1), presented without dynamics and without agogics (henceforth referred to as *harmony version*); (d) a version containing only the outer voices (i.e., only the highest and lowest voice of the piece, see Figure 2.1), presented without dynamics and without agogics; (e) a version that consisted of the top voice only (i.e., a version that contained only the “melody part”, see Figure 2.1), presented without dynamics and without agogics (henceforth referred to as *melody version*). That is, versions (c)-(e), did not vary in terms of tempo, nor dynamics. The total length of the versions without agogics matched the ones of the original versions with agogics (Mendelssohn: 2:27 min; Mozart: 2:01 min).

All resulting MIDI files were used to trigger the VST Plugin “The Grand”, an authentic grand piano simulation based on samples of real grand piano recordings, in Steinberg Cubase SL (Steinberg Media Technologies, Hamburg, Germany). From this, audio files were created (16 bit, 44.1 kHz sampling rate) which were used as final stimulus material.

Figure 2.1. Score excerpts of measures 6-11 of original and modified versions of the Mendelssohn piece: (a) original; (b) harmonic reduction; (c) outer voice reduction; (d) melodic reduction.

2.2.3 Experimental Design

Original and modified versions of the two pieces were presented to participants in random order. In addition, the original version of the Mozart piece was presented again at the end of the experiment to evaluate the within-participant consistency of the tension ratings over repeated exposures to a musical piece. Thus, in total 13 stimuli were presented to each participant (2 pieces x 6 versions + 1 repetition of the original Mozart piece). Tension ratings were obtained every 10 ms from the position of a slider that was shown vertically on a computer screen and could be moved with the mouse according to the subjectively felt musical tension. A high position of the slider corresponded to a high degree of tension while lower positions indicated lower levels of tension.

2.2.4 Experimental Procedure

For stimulus presentation and data acquisition the software Presentation (Neurobehavioral Systems, Albany, USA) was used. Participants listened to the stimuli via headphones at a comfortable volume level. They were instructed to use the slider to continuously indicate the tension of the music as they subjectively experienced it (participants were explicitly instructed not to indicate the amount of tension they thought the music was supposed express). That is, ratings of *felt* musical tension (in contrast to *perceived* tension, cf. Gabrielsson, 2002) were acquired.

To familiarize participants with the task, they completed a practice trial during which they could ask questions concerning the task (a three minute excerpt from the second movement of Schubert's Piano Sonata D. 960 was used for the practice trial). After participants had become acquainted with the task, the experiment started. Before each stimulus presentation, the slider was reset to the lowermost position. Between stimulus presentations, participants were given the opportunity to take a short rest. After finishing the experiment, participants completed a short questionnaire assessing previous musical education, music listening habits, familiarity with the pieces and additional demographic data (age, sex, and occupation). In total, the duration of one experimental session was approximately 45 min.

2.2.5 Data Analysis

Each participant's data were converted to z-scores (to discard differences between participants with respect to the slider range used for the tension ratings). To compare ratings of versions that contained agogics (i.e., the original version and the version without dynamics) and versions with constant tempo (i.e., deadpan, harmony, outer voices and melody versions), tension ratings were temporally aligned. This was done by stretching or compressing ratings within each measure of the versions with agogics to the length of the corresponding measure in the versions without agogics using linear interpolation.

Tension ratings were averaged across participants, separately for each version. This way, potential order effects in the individual ratings were minimized and variance due to individual rating styles was reduced. Comparisons between different versions were performed on the resulting averaged tension ratings. When comparing continuous rating data, it is common practice to calculate Pearson product-moment correlation coefficients. However, this procedure has been criticized (Schubert, 2002, 2010) due to two problems. First, continuous rating data are usually not normally distributed, rendering parametric statistics inappropriate. Second, the data are serially correlated (i.e., adjacent points of the time series have more similar values than more distant points) which can lead to inflated correlation results (this is particularly problematic when significance tests are performed, because the large number of data points inflates the degrees of freedom, thus greatly reducing the threshold at which correlation results become significant). To mitigate these problems, this study uses Spearman's rank correlation coefficients as a non-parametric measure of correlation (cf. Schubert, 2010; Vines et al., 2006). To reduce serial correlations, the data were downsampled to a sampling rate of 1/3 Hz before calculating correlations between tension ratings (cf. Schubert, 2010).

In addition to the correlation between different versions, the correlation between loudness of the music and tension ratings for the different versions was calculated. Loudness was computed from the unmodified recordings using a Matlab implementation (www.genesis-acoustics.com/en/loudness_online-32.html) of the loudness model for time-varying sounds by Zwicker and Fastl (1999). Taking a time-varying acoustical signal as input, this model estimates the loudness of the signal as it is subjectively experienced (measured in *sone*). When comparing loudness of the music to the tension ratings, it has to be considered that tension ratings temporally lag behind the musical events they refer to (due to the time the participants need to process the stimulus, and to give a physical response on the slider). To quantify this time lag and correct for it, cross-correlations between loudness and the average tension ratings of the unmodified recordings were calculated. The time point with the highest cross-correlation between the two series was then used as an estimate of the temporal lag of the tension ratings. Before calculating correlation coefficients between loudness and tension ratings, the predictions of the loudness model were temporally shifted to correct for this lag. To make loudness data comparable to the tension ratings, loudness data were temporally aligned to versions without agogics and downsampled to 1/3 Hz (analogous to the procedures described above).

To test the consistency of the tension ratings within participants, the test-retest reliability of the tension ratings was evaluated by calculating Spearman's rank correlation coefficients between the first and second presentation of the original recording of the Mozart piece. (In contrast to the other correlations, this correlation coefficient was not calculated on average ratings but on each participant's individual ratings.)

To gain a better understanding of the musical events mediating the experience of musical tension, we also performed a post-hoc music-theoretically informed qualitative analysis in which we investigated which musical events corresponded to the peaks and troughs of the average tension profiles.

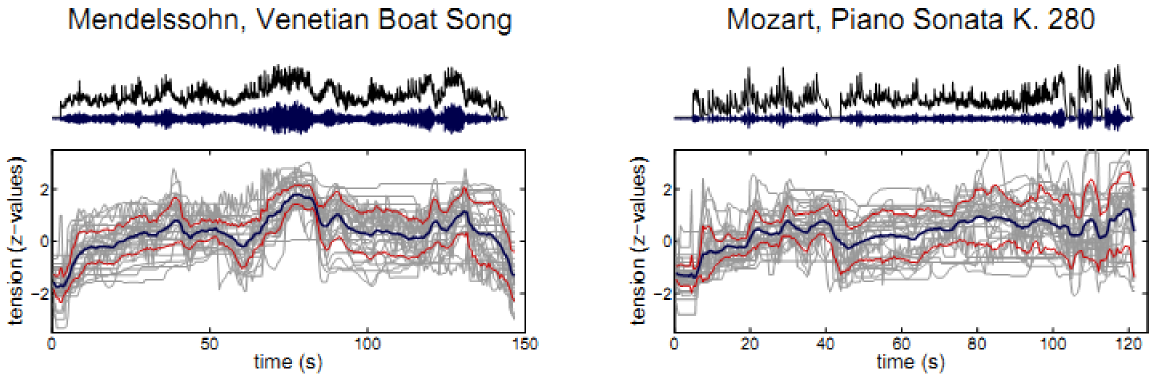

Figure 2.2. Top: Audio waveform (blue) with predictions of the loudness model (black) for the original recordings of the two pieces. Bottom: Individual (gray lines) and average tension ratings (blue line) ± standard deviation (red lines).

2.3 Results

Rating reliability within participants was assessed by calculating the correlation between individual tension ratings of the two presentations of the Mozart piece. Correlation coefficients ranged from –.06 to .88 (M = .52). For five participants rating reliability was relatively low ($\rho < .3$), but we nevertheless included these data sets in the analysis so that results are representative for the general population (notably, excluding these participants yielded results that were highly comparable to the results reported here).

Figure 2.2 shows individual tension ratings for the two original recordings as well as their average and standard deviation together with the waveform of the audio signal and loudness. The graphs reveal tension profiles with distinct peaks and troughs. Furthermore, visual comparison of the tension profiles with the audio waveform and loudness indicates a relation between tension and loudness (especially for the Mendelssohn piece) that will be investigated in more detail below.

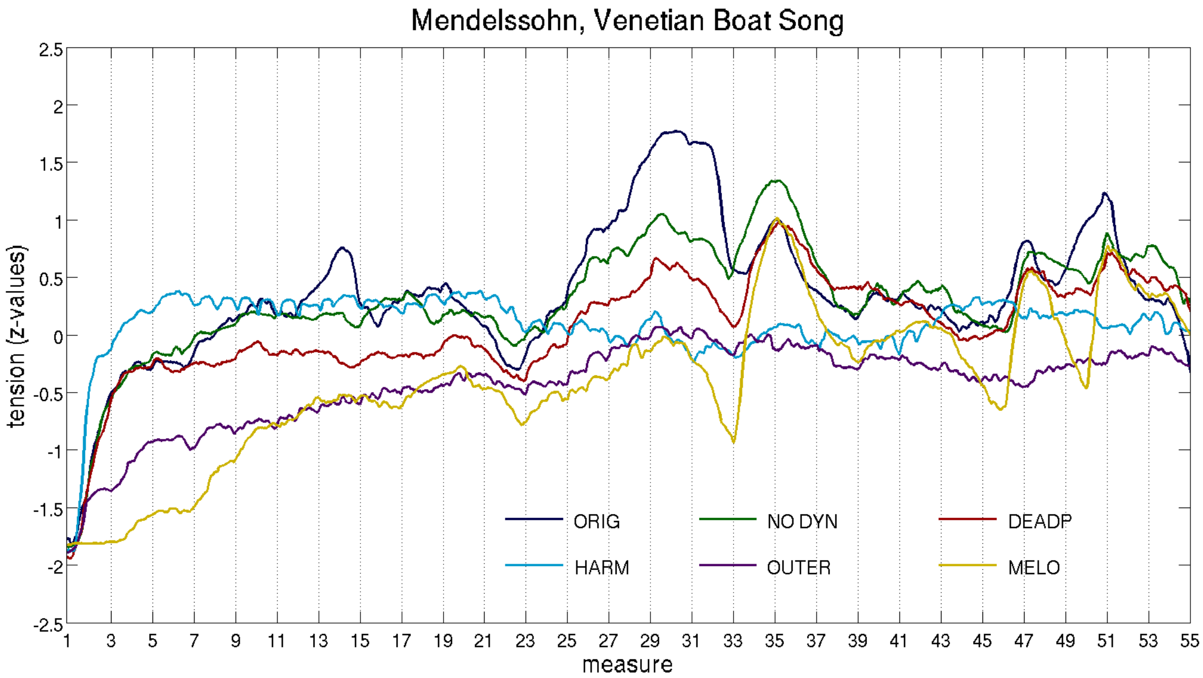

Figure 2.3. Average tension ratings for all versions of the Mendelssohn piece (ORIG: original version; NO DYN: version without dynamics; DEADP: deadpan version without dynamics and without expressive timing; HARM: harmony only; OUTER: outer voices only; MELO: melody only).

Average tension profiles for the different versions of the two pieces are shown in Figures 2.3 and 2.4. For both pieces, the clearest and highest tension peaks were observed for the original recordings, which on average received higher tension ratings than the versions without expressive features: For the Mozart piece, Wilcoxon signed-rank tests revealed differences between the original and the version without dynamics (z = –4.06, p < .05), as well as between the original and the deadpan version (z = –1.98, p < .05); for the Mendelssohn piece only differences between the original and the deadpan version were significant (z = –4.48, p < .05). Furthermore, changes in experienced tension appeared to be more pronounced for the Mendelssohn piece than for the Mozart piece.

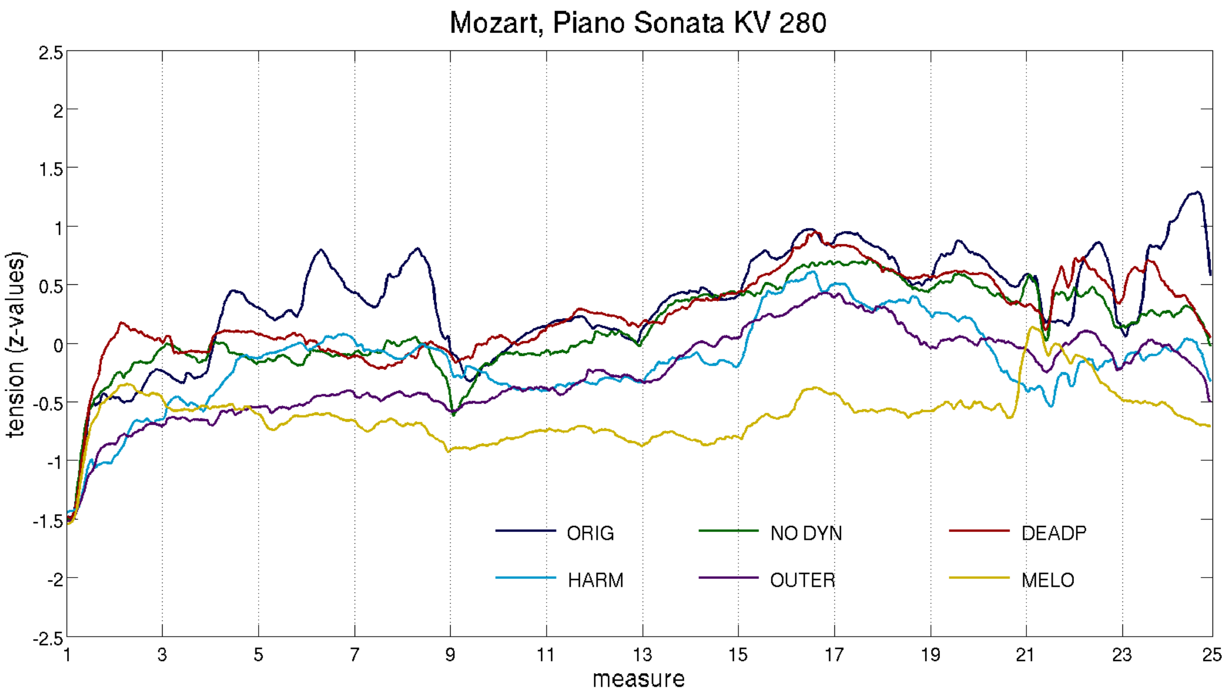

Figure 2.4. Average tension ratings for all versions of the Mozart piece.

2.3.1 Correlation Analysis

Figure 2.5 shows Spearman's rank correlation coefficients between all possible combinations of average tension ratings of the different versions (the correlation matrices also show correlations to the loudness model which will be treated below).

For the Mendelssohn piece, the rating of the original recording correlated highly with the rating of the version without dynamics (ρ = .83), the deadpan version (ρ = .70), and the outer voices (ρ = .71). Correlation with the melody version was moderate (ρ = .54). The correlation with the harmonic reduction was negative (ρ = –.41). A similar pattern was observed for the Mozart piece: The rating of the original recording correlated moderately to highly with the rating of the version without dynamics (ρ = .71), the deadpan version (ρ =.59), and the outer voices (ρ = .73). However, in contrast to the Mendelssohn piece, the harmonic reduction correlated highly with the original version (ρ = .85) and the correlation with the melody version was lower and not significant (ρ = .25). This piece-dependant difference for tension ratings of harmony and melody versions was observed consistently in the two correlation matrices: For the Mendelssohn piece, correlations between the rating of the melody version and ratings of the other versions (except harmony) were relatively high, whereas correlation between harmony and the other versions were all negative. This pattern was virtually reversed for the Mozart piece. Here, ratings for the harmony version correlated highly with ratings for the other versions (except melody), while correlations between ratings for the melody version and the other versions were lower and (except for the deadpan version) not statistically significant. Apart from these differences between harmony and melody, the general pattern of the correlations between ratings for different versions were relatively similar for the two pieces. Except for correlations between tension ratings of the melody version and other versions of the Mozart piece (original, no dynamics, harmony, and outer voices), all tension rating correlations were statistically significant ($df_{\text{Mendelssohn}} = 44$; $df_{\text{Mozart}} = 36$; $p < .05$).

Before calculating correlations between loudness and tension, the temporal lag of the tension ratings to corresponding musical events was determined by computing the cross-correlation between loudness and the average tension ratings of the original recordings. For the Mendelssohn piece, the highest correlation was observed at a time lag of 3.2 s. For the Mozart piece, correlation was highest at a lag of 2.0 s. The correlation coefficients reported in the following (also shown in Figure 2.5) were obtained after correcting for the time lag of the tension ratings. For the Mendelssohn piece, a high positive correlation between loudness and the average tension rating of the original recording was observed ($\rho = .74$). Interestingly, loudness also correlated significantly with tension ratings of versions without dynamics. For the Mendelssohn piece, all correlations with loudness were positive and statistically significant ($df = 44$; $p < .05$). For the Mozart piece, none of the correlations between tension ratings and loudness were statistically significant.

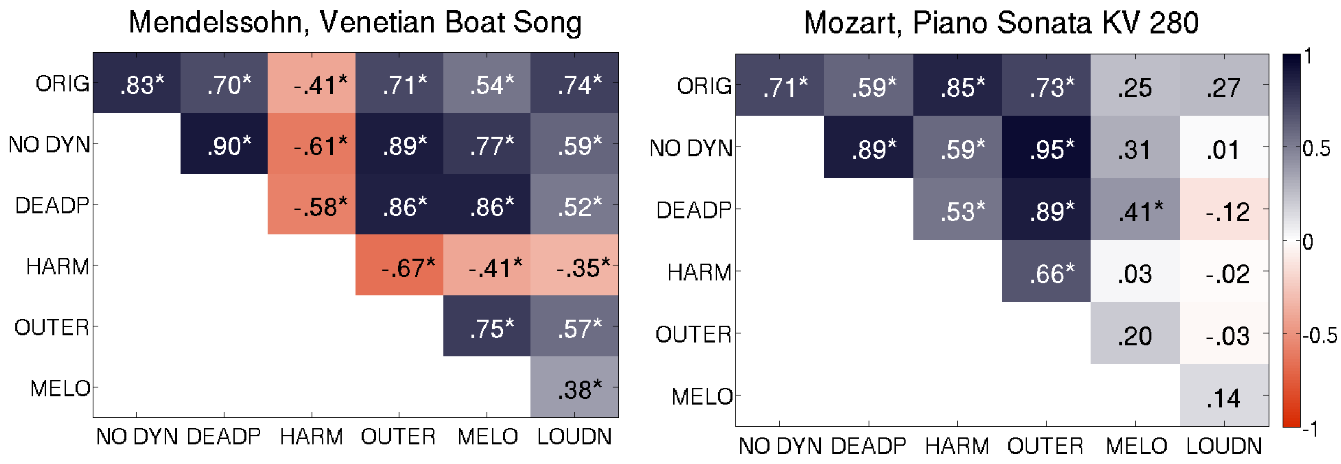

Figure 2.5. Spearman's ρ for average tension ratings of the different versions as well as the loudness model (LOUDN). Significant correlations (p < .05) are marked with a star ($df_{\mathrm{Mendelssohn}}$= 44; df_{Mozart}= 36).

2.3.2 Qualitative Analysis[1]

For the Mendelssohn piece, the most prominent peaks at measures 13, 30, 34, and 50 corresponded to events with dominant function: m. 13 features the first strongly pronounced dominant function of the piece (with $\hat{5}$ in the bass after a long series of $\hat{1}$ pedal bass notes), mm. 30-32 feature the main structural dominant, the diminished chord at m. 34 fulfills an applied dominant function to the *IV*, and the two chords at mm. 46, 60 constitute dominants of the final phrase of the piece (the second and final dominant features the stronger tension rating). However, participants did not simply give high tension ratings to local (or applied) dominants, because other dominants were not associated with peaks, such as the dominant in m. 20 towards the end of the first phrase, m. 23 initiating the motion of the middle section, and m. 42 ending the middle section. In contrast, it appears that participants also attended to the overall organization of the piece when experiencing tension: The lowest rating, except ratings for the beginning, was given at m. 21, the end of the first section and beginning of the middle section, as well as at m. 43 at the end of the middle section and beginning of the final closure.

[1] This section of the article was primarily written by Martin Rohrmeier.

Many of the events associated with peaks correspond to salient events in the melody line (trills or high notes) as well as dynamics (e.g., sforzato or forte notes at measures 13, 30, 46, and 50). However, when dynamics and agogics were removed, most peaks remained present, yet less pronounced. This suggests that some of the expressive features employed in the piece enhance the effects of tension that are created by melodic means. In contrast, the tension profile of the harmony version did not show clear peaks and remained relatively flat throughout the piece with a slight overall downward trend. Hence, harmony did not serve as the sole or predominant compositional device to create tension in this piece.

For the Mozart piece, tension profiles also reflect the overall organization of the piece. As in the Mendelssohn piece, the transitions between first, middle and final parts are reflected in low tension ratings (mm. 9, 21). The first section, mm. 1-8, features five ascending peaks at mm. 2, 3, 4, 6, 8. Each of these peaks corresponds to harmonic events with strong implications: II_5^6, V, VI_4^6, I_2^4. The relaxations of the tension profile correspond with the implied local resolution of the suspensions in mm. 5, 7, 8. The fact that the tension profile constantly rises towards m. 8, even though m. 4 and 6 are musically identical, seems to reflect the overarching tendency towards the resolution and completion of the phrase towards the final tonic. The tension profile of the middle part reflects the departure from the initial tonic to the IV as well as the half cadence with a resolution to the dominant $V_4^6 - V_3^5$ marking the end of the half of this phrase (m. 12). Similarly to the beginning, the harmonically strongly implicative German sixth, diminished and dominant seventh chords (mm. 13, 15, 16) are associated with ascending sets of peaks along with small local relaxations (reflecting melodic and harmonic relaxation). The musical relaxation around the tonic at mm. 17-18 (after the preceding dominants) is also reflected by a local trough in the tension profile. Deceptive cadences (mm. 19, 23) yield a sudden increase in experienced tension. The subsequent resolution towards the tonic (as in mm. 19-21) is reflected as a decrease in the tension profile.

The cadential V_4^6, as well as the entire final cadential schema at mm. 21-24, provide strong signals of the upcoming end (of the part) and receive the strongest and most pronounced local tension ratings.

2.4 Discussion

The aim of the present study was to investigate how the elimination or isolation of different structural features (dynamics, agogics, harmony, outer voices, and melody) influences felt musical tension by comparing tension ratings of ecologically valid original and modified versions of two piano pieces. Modifications featured versions without dynamics, without dynamics and without agogics, and versions in which the music was reduced to its harmonic, melodic or outer voice component. In addition, we compared tension ratings with the loudness of the music estimated by a standard loudness model.

We found that the overall shape of the profiles of original versions, versions without dynamics, and deadpan versions (without dynamics and without agogics) resembled each other closely. This was reflected in high correlations between the tension ratings of these versions, indicating that discarding dynamics and agogics preserves a large part of the tension-resolution patterns of the music, and that felt tension is not primarily governed by these expressive features. This is consistent with findings by Krumhansl (1996) who reported a high correspondence between tension ratings of versions with and without expressive features (i.e., dynamics and agogics). Our results support that models of tension based on the tonal structure of a musical piece abstracting from expressive features (e.g., Lerdahl, 1996, 2001) capture a large part of the information relevant for the experience of musical tension. The high correlations between tension ratings of the original recordings and versions reduced to the outer voices furthermore suggest that even when limiting information to these most salient voices, considerable parts of the tension patterns are retained. This confirms that outer voices embody major aspects of the musical structure.

Despite the high correlations between original tension ratings and ratings for versions without dynamics and agogics, discarding these features does have a notable effect on felt musical tension. Average tension ratings of versions without expressive features were significantly lower than for original versions, and the tension profiles were generally flatter with some of the tension peaks existent in the profiles of the original versions not present or strongly attenuated. This indicates that musical tension can be strongly enhanced by expressive features.

For the Mendelssohn piece, we found a high correlation between loudness and the tension profile of the original version. Interestingly, loudness also correlated significantly with versions without dynamics.[1] This finding indicates a strong redundancy between the dynamics and other structural aspects of a musical piece (such as harmony or melody). It underpins that the alignment of expressive features (e.g., dynamics and agogics) and tonal aspects (e.g., melodic or harmonic structure) can enhance the experience of tension, and is a core compositional and performative device that can help to maximize the emotional effect of the music. In the Mendelssohn piece, for example, the highest tension peak (m. 29) reflects the main structural dominant and is prepared by a long crescendo, the rising melody line, the lowest local bass note, the *fortissimo* and *sforzato* of both repetitions of the chords (as well as expressive details played by the pianist) so that the co-aligned combination of dynamics, melody, and harmony results in a strong experience of increasing tension apparent in the prominent peak in the corresponding tension profile. The redundant use of different features as a compositional device gains further support from a study by Lalitte et al. (2009), who report high correlations between musical arousal ratings of two original Beethoven sonatas and two atonal counterparts. This stability of musical arousal profiles even in absence of tonal structure indicates that participants responded to features that remained relatively unaltered

[1] Note that even the versions without dynamics still retained some minor loudness variations due to varying note density or short intervals of silence in the music, however, these were negligible compared with the dynamic variations due to the expressive performance.

between the two versions (such as rhythm, note density, or global structure). Assuming that participants' ratings to a large extent depend on tonal structure (as suggested by our results and by previous research, see Krumhansl, 1996; Lerdahl & Krumhansl, 2007) this indicates that tonal aspects tend to co-vary with non-tonal features of the music.

With regard to differences between pieces, our results suggest that melody and harmony contributed differently to experienced tension in the two pieces. For the Mendelssohn piece, correlation with the tension profile of the original version was higher for tension ratings of the melody version than for ratings of the harmony version, whereas the reverse pattern was observed for the Mozart piece. This difference seems to reflect a compositional difference between both pieces: Whereas the rate of harmonic change is slow in the Mendelssohn piece and its melody part plays a major role in shaping the structure (long trills, overarching melodic ascents or descents), dense successions of harmonic implication and resolution patterns govern the Mozart piece to a larger extent. However, the qualitative analysis suggested that central tensions peaks in both pieces were driven by harmonic patterns, which is inconsistent with the negative correlations between the tension profile of the harmony versions and the other versions observed for the Mendelssohn piece. These negative correlations may have resulted from the slow rate of harmonic change of the Mendelssohn piece, which rendered the harmonic reduction rather uninteresting to listen to, thus accounting for the relatively flat tension profile of the harmony version and its slight downward trend. The larger contribution of harmony on experienced tension observed for the Mozart piece is also in concordance with results by Williams et al. (2011) who showed that focusing more on harmony of a Mozart piece was related to higher tension ratings as compared with attending more to the melody, which indicates a higher importance of harmony in comparison to melody for inducing an experience of tension in Mozart pieces.

Another feature differing between pieces was loudness, which correlated significantly with tension profiles of the Mendelssohn piece but not of the Mozart piece. This also seems to reflect a different importance of this feature in the respective piece that already becomes apparent when comparing the scores of the pieces. Whereas the score of the Mendelssohn piece includes marked *crescendi* and dynamic indications ranging from *pianissimo* to *fortissimo*, the Mozart piece makes more limited use of dynamics with indications ranging from *piano* to *forte*. It seems probable that the larger dynamic variations of the Mendelssohn piece made them stand out more clearly against other musical features thus accounting for the high correlations between loudness and tension for this piece. This piece-dependant influence of different features on experienced tension indicates that it is problematic to model musical tension based on the assumption that the contribution of different features on experienced tension remains constant over different pieces. Instead, to increase the accuracy of models of musical tension, features should be weighted dynamically depending on the musical context (as, for example, in the model by Farbood, 2012).

With respect to the time lag between tension ratings and corresponding musical events, our results are consistent with observations by Schubert (2004) who reported emotion responses 1 to 3 seconds after the respective musical event. Interestingly, the time lag was shorter for the Mozart than for the Mendelssohn piece, which raises the question as to how properties of the music influence the response times of participants. It has been conjectured that faster tempos and loud sudden sounds decrease response times (Schubert, 2008; Schubert & Dunsmuir, 1999, cited in Schubert, 2010) which is in line with our results.[1]

The qualitative analysis suggests that participants' tension ratings strongly reflected the form of the piece, i.e., different parts and sections, local harmonic implications and resolutions as well as global overarching syntactic features (cf. Lerdahl & Jackendoff, 1983; Rohrmeier, 2011). For instance, the overarching tension increase mediated by several smaller local tension-resolution patterns in the first phrase of the Mozart piece (mm.1-8) reflects how local and global structure interact in forming patterns of tension and release. The harmonic

[1] Although the notated tempo of the Mozart piece is slower than that of the Mendelssohn piece (*Adagio* vs. *Allegretto tranquillo*), the rate of harmonic and melodic change is higher.

structure exhibits recursive nesting of harmonic implications from each chord to its successor by cascading syntactic dependencies that are all directed towards the final tonic of the phrase. The tension profile shows that each of these single implications between two chords feature a small tension-release pattern which is itself embedded in the overall rise of tension towards to final tonic of the phrase. This illustrates that experienced tension can be governed by local and global structure at the same time. On the other hand, the finding that not all local dominants, but mostly those that reflect deep structure (in terms of analytic reduction) affected the tension profile underscores that dominants do not trigger a rise in tension per se, but that their impact depends on the context of the overarching global structure. Both of these examples demonstrate the interplay between local implications and global syntactic implications for establishing musical tension; both local and global implications and dependencies are embraced by theories of tonal syntax (cf. Lerdahl & Jackendoff, 1983, or Rohrmeier, 2011) without the need for two separate models.[1]

Finally, we would like to point out some limitations of the study. First, tension ratings were only tested for two musical pieces. To maximize the ecological validity of the study, we used stimuli based on real music pieces instead of artificial stimuli, which comes at the price that stimuli had relatively long durations (thus limiting the amount of different stimuli that can be delivered in one experimental session). To investigate to which degree the results reported here can be generalized to other pieces, research on musical tension has to be extended to stimuli differing on various dimensions such as music genre, tempo, or orchestration. Second, the within-subjects design of the present study, which exposed participants repeatedly to different versions of the same piece, may have resulted in interference effects between different tension ratings because the tension rating of a stimulus may have been influenced in part by a participant's (implicit) memory of prior presentations

[1] Note, however, that this does not entail that the correlation of tension profiles predicted by syntactic theories with human data provides strong evidence that humans do in fact employ such hierarchical representations in music perception.

of the stimulus in a different version (for online learning during experimental tasks compare Rohrmeier, 2009). This may have led to a slight under- or overestimation of the correlation coefficients: Correlations between tension ratings of different versions may either have become stronger (the memory of previous exposures may have made tension ratings of different versions more similar) or weaker (repeated exposures may have made differences between versions more apparent, resulting in more dissimilar ratings). However, because of the randomized stimulus presentation and the averaging across participants, this possible bias would have affected all correlations between different tension ratings in the same way, keeping the relative comparisons between different correlations valid. Last, we only tested the influence of one psycho-acoustical feature, loudness, on experienced musical tension. However, other low-level psycho-acoustical features may play a role in mediating tension. In particular, sensory dissonance is likely to have an effect on experienced tension, which is indicated by previous research showing that for single chords subjective roughness ratings correlate with tension ratings (Pressnitzer et al., 2000) and that predictions of a roughness model correlate with tension ratings of musicians (Bigand et al., 1996). To investigate whether these findings generalize to longer musical pieces, future research on musical tension should therefore consider also including measures of sensory dissonance into the analysis.

As a critical note, and general limitation of research on musical tension using one-dimensional tension scales, we would also like to emphasize that the fine-structure of emotional activity underlying tension phenomena (including its neural correlates) cannot be grasped adequately by one-dimensional tension values, and subjective ratings of high-level concepts such as tension (and emotion ratings in general) only provide limited insight into the multiple cognitive and affective mechanisms underlying the subjective emotional experience. As laid out previously (Koelsch, 2012), this is because different structural principles with different affective qualities can give rise to tension or resolution: The *build-up of a musical structure* (which may lead to a rise in tension), a *breach of expectancy* (which also leads to a rise in tension), the *anticipation of resolution* after the breach of expectancy (which usually either maintains, or even increases tension), and the *resolution of a breach* (leading to release of tension) are qualitatively different phenomena, yet they are not differentiated when measuring tension with a one-dimensional scale. Thus, for example, the tension value of a tonic chord at the beginning of a harmonic sequence with a structural breach is similar, or even identical, to the tension value of a tonic chord at the end of a sequence (both tonic chords have low tension values). However, the underlying affective phenomena are different (*build-up* vs. *resolution*). Such differences in cognitive and affective phenomenology are relevant for investigations in related fields such as neuroscientific investigations of tension phenomena: A working hypothesis suggested recently (Koelsch, 2012) is that a specific brain region (the dorsal striatum) is involved in emotional activity due to anticipation: In a functional neuroimaging study by Koelsch et al. (2008) this region was activated during blocks of chord sequences with irregular chords evoking the anticipation for resolution. A study by Salimpoor et al. (2011) showed release of the neurotransmitter dopamine in this region while listeners anticipated a music-evoked frisson (an intensely pleasurable experience often involving goosebumps or shivers down the neck, arms, or spine). Activity changes in another brain region (the amygdaloid complex) appear to be related to the processing of breaches of expectancy (Koelsch et al., 2008), and yet another brain region might be involved in the processing of resolution: In the study by Salimpoor et al. (2011), the anticipated, and rewarding, frisson itself evoked dopaminergic activity in another brain structure (the ventral striatum, presumably the so-called nucleus accumbens). Thus, the pleasurable and rewarding experience of the resolution of a breach of expectancy might involve activity in different brain structures than those involved in the anticipation of the resolution. Such considerations illustrate that a multidimensional approach to tension might be necessary for fruitful future research.

2.5 Conclusion

The present study investigated the effect of different structural features of music (dynamics, agogics, harmony, outer voices, melody, and loudness) on felt musical tension. Overall, tension ratings for versions without expressive features (dynamics and agogics) correlated highly with ratings of the original recordings, indicating that the general tension-resolution pattern of a musical piece is governed essentially by its tonal structure, rather than by expressive features. Adding expressive features, however, can enhance the experience of musical tension. The relative contribution of loudness, as well as melody and harmony, depended more on the special characteristics of individual pieces with more salient features apparently having a stronger impact on felt musical tension. A qualitative analysis suggested that participants are sensitive to core features of harmonic, melodic, and global syntactic musical structure.

3 Tension-related activity in the orbitofrontal cortex and amygdala: an fMRI study with music[1]

Abstract

Tonal music is characterized by a continuous flow of tension and resolution. This flow of tension and resolution is closely related to processes of expectancy and prediction and is a key mediator of music-evoked emotions. However, the neural correlates of subjectively experienced tension and resolution have not yet been investigated. We acquired continuous ratings of musical tension for four piano pieces. In a subsequent functional magnetic resonance imaging experiment, we identified blood oxygen level-dependent signal increases related to musical tension in the left lateral orbitofrontal cortex (pars orbitalis of the inferior frontal gyrus). In addition, a region of interest analysis in bilateral amygdala showed activation in the right superficial amygdala during periods of increasing tension (compared with decreasing tension). This is the first neuroimaging study investigating the time-varying changes of the emotional experience of musical tension, revealing brain activity in key areas of affective processing.

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3.1 Introduction

The processing of music involves a complex machinery of cognitive and affective functions that rely on neurobiological processes of the human brain (Koelsch, 2012; Pearce & Rohrmeier, 2012; Peretz & Zatorre, 2005). The past years have seen a growing interest in using music as a tool to study these functions and their underlying neuronal mechanisms (Zatorre, 2005). Because of its power to evoke strong emotional experiences, music is particularly interesting for affective neuroscience, and an increasing number of neuroimaging studies use music to unveil the brain mechanisms underlying emotion (for reviews see Koelsch, 2010; Peretz, 2010). Corresponding research has shown that music-evoked emotions modulate neural responses in a variety of limbic and paralimbic brain areas that are also activated during emotional experiences in other contexts. For example, pleasant emotional responses to music are associated with the activation of the mesolimbic reward system (Blood & Zatorre, 2001; Menon & Levitin, 2005; Salimpoor et al., 2011) that also responds to stimuli of more direct biological reward value such as food or sex (Berridge, 2003). Music thus appears to recruit evolutionarily ancient brain circuits associated with fundamental aspects of affective behavior, and research on music-evoked emotion is therefore not only relevant for music psychology but promises new insights into general mechanisms underlying emotion.

Furthermore, because music unfolds over time, it is especially well-suited to studying the dynamic, time-varying aspects of emotional experience. These continuous fluctuations of emotional experience have been largely neglected by neuroimaging research on emotions, which predominantly has focused on more stationary aspects of affective experience during short emotional episodes. Corresponding studies, for example, investigated discrete emotions (such as happiness, sadness, anger, or fear) or emotional valence (pleasant vs. unpleasant) in response to static experimental stimuli such as facial expressions (Blair et al., 1999; Breiter et al., 1996; Morris et al., 1996), affective pictures (Liberzon et al., 2003; Phan et al., 2004; Taylor et al., 2003), or words (Kuchinke et al., 2005; Maddock et al., 2003). Likewise, the focus on static aspects of emotions is also reflected in neuroimaging studies on music-evoked emotions, which generally assume that an emotional response to a piece of music remains relatively constant over the entire duration of the piece. Neural correlates of music-evoked emotions have, for example, been investigated by contrasting consonant/dissonant (Blood et al., 1999), pleasant/unpleasant (Koelsch et al., 2006), or happy/sad (Khalfa et al., 2005; Mitterschiffthaler et al., 2007) music stimuli, or by comparing different emotion dimensions (e.g., nostalgia, power, or peacefulness) of short music excerpts (Trost et al., 2011). However, emotions are rarely static states, and their dynamic, time-varying nature is in fact one of their defining features (Scherer, 2005). These dynamic fluctuations of emotional experience are poorly captured by fixed emotion labels globally attributed to an experimental stimulus (like happy vs. sad, or pleasant vs. unpleasant). Using music to investigate the temporal fluctuations of affective experiences can, therefore, provide new insights into mechanisms of neuro-affective processing.

A few studies have begun to investigate dynamic changes of emotions and their underlying brain mechanisms by using continuous self-report methods (Nagel et al., 2007; Schubert, 2010), in which emotions are continuously tracked over time. Chapin et al. (2010), for example, investigated neural correlates of emotional arousal during a Chopin étude in an fMRI study, and Mikutta et al. (2012) used arousal ratings for Beethoven's 5th symphony to investigate their relation to different frequency bands in the EEG. In the film domain, Goldin et al. (2005) used continuous ratings of emotional intensity to uncover brain activations in response to sad and amusing film clips that were not detected by conventional block contrasts. Similarly, Wallentin et al. (2011) identified brain activations in language and emotion areas (temporal cortices, left inferior frontal gyrus, amygdala, and motor cortices) related to continuous ratings of emotional intensity and valence during story comprehension.

The present study aims to extend previous research by using *musical tension* to investigate the dynamic change of emotional experience over the course of a musical piece.

Musical tension refers to the continuous ebb and flow of tension and resolution that is usually experienced when listening to a piece of Western tonal music. In particular, tension is triggered by expectancies that are caused by implication relationships between musical events, which are implicitly acquired through exposure to a musical system (Rohrmeier & Rebuschat, 2012). For example, a musical event that sets up harmonic implications, such as an unstable dominant seventh chord, may build up tension, which is finally resolved by the occurrence of an implied event, such as a stable tonic chord. The implicative relationships can be local or non-local, i.e., the implicative and implied events do not necessarily have to follow each other directly but may stretch over long distances and can be recursively nested (cf. Lerdahl, 2004; Rohrmeier, 2011). Thus, prediction and expectancy, which have been proposed as one key mechanism of emotion elicitation in music (Huron, 2006; Juslin & Västfjäll, 2008; Koelsch, 2012; Meyer, 1956), are inherently linked to musical tension (other factors related to tension are, e.g., consonance/dissonance, stability/instability, and suspense emerging from large-scale structures, see also Chapters 4 and 6). The pertinent expectancy and prediction processes are not only relevant for music processing (for reviews see Fitch et al., 2009; Pearce & Wiggins, 2012; Rohrmeier & Koelsch, 2012) but have been proposed as a fundamental mechanism underlying human cognition (Dennett, 1996; Gregory, 1980) and brain functioning (Bar, 2007; Bubic et al., 2010; Friston, 2010). Therefore, studying the neural bases of musical tension can shed light on general principles of predictive processing, predictive coding (Friston & Kiebel, 2009), and their connections to dynamic changes of affective experience.

In the music domain, neural processes related to expectancy violations have been studied using short chord sequences that either ended on expected or unexpected chords (e.g., Koelsch et al., 2005; Tillmann et al., 2006). The music-syntactic processing of such expectancy violations has mainly been associated with neural responses in Brodmann area 44 of the inferior fronto-lateral cortex (Koelsch et al., 2005). However, activations in areas related to emotive processing, such as the orbitofrontal cortex (Koelsch et al., 2005; Tillmann et al., 2006) and the amygdala (Koelsch et al., 2008a) as well as increases in electrodermal activity (Koelsch et al., 2008b; Steinbeis et al., 2006) indicate that affective processes also play a role in the processing of syntactically irregular events. The affective responses to breaches of expectancy in music were investigated more closely in an fMRI study by Koelsch et al. (2008a) who reported increased activation of the amygdala (superficial group) in response to unexpected chord functions, thus corroborating the link between affective processes and breaches of expectancy.

In the present study, we acquired continuous ratings of felt musical tension for a set of ecologically valid music stimuli (four piano pieces by Mendelssohn, Mozart, Schubert, and Tchaikovsky), thus extending the more simplistic chord-sequence paradigms of previous studies (Koelsch et al., 2008a; Koelsch et al., 2005; Steinbeis et al., 2006; Tillmann et al., 2006) to real music. Subsequently, we recorded fMRI data (from the same participants) and used the tension ratings as continuous regressor to identify brain areas related to the time-varying experience of musical tension. In addition, we compared stimulus epochs corresponding to increasing and decreasing tension. Based on the studies reported above (Koelsch et al., 2008a; Koelsch et al., 2005; Tillmann et al., 2006), we investigated whether musical tension modulates neuronal activity in limbic/paralimbic brain structures known to be involved in emotion processing. We also tested the more specific regional hypothesis that tension is related to activity changes in the amygdala, assuming that structural breaches of expectancy are key to the elicitation of tension (Koelsch, 2012; Meyer, 1956), and that such breaches of expectancy modulate amygdala activity as reported in the study by Koelsch et al. (2008a).

3.2 Methods

3.2.1 Participants

Data from 25 right-handed participants (13 female, age range 19 – 29 years, *M* = 23.9, *SD* = 2.9) were included in the analysis (data from three additional participants were excluded because of excessive motion in the fMRI scanner or because they did not understand the experimental task correctly). None of the participants was a professional musician. 13 participants had received instrument lessons in addition to basic music education at school (instruments: piano, guitar, and flute; range of training: 1 – 13 years, *M* = 6.4, *SD* = 3.6). All participants gave written consent and were compensated with 25 euros or course credit. The study was approved by the ethics committee of the Freie Universität Berlin and conducted in accordance with the Declaration of Helsinki.

3.2.2 Stimuli

Four piano pieces were used as stimulus material: (1) Mendelssohn Bartholdy's Venetian Boat Song (Op. 30, No. 6); (2) the first 24 measures of the second movement of Mozart's Piano Sonata KV 280; (3) the first 18 measures of the second movement of Schubert's Piano Sonata in B-flat major (D. 960); (4) the first 32 measures of Tchaikovsky's Barcarolle from The Seasons (Op. 37). The pieces had been performed by a professional pianist on a Yamaha Clavinova CLP-130 (Yamaha Corporation, Hamamatsu, Japan) and recorded using the musical instrument digital interface (MIDI) protocol. From the MIDI data, audio files were generated (16 bit, 44.1 kHz sampling frequency) using an authentic grand piano sampler (The Grand in Cubase SL, Steinberg Media Technologies AG, Hamburg, Germany). Stimulus durations were 2:25 min (Mendelssohn), 1:59 min (Mozart), 1:34 min (Schubert), and 1:44 min (Tchaikovsky).

Because musical tension correlates to some degree with loudness of the music (Farbood, 2012; see also Chapter 2), we also included versions without dynamics (i.e., without the loudness changes related to the expressive performance of the pianist) in the stimulus set to rule out the possibility that brain activations related to musical tension were simply due to these loudness changes (in addition, loudness was modeled as a separate regressor in the data analysis, see Section 3.2.5). Versions without loudness variations were created by setting all MIDI key-stroke velocity values to the average value of all pieces (42). In the following, we refer to the original unmodified versions as *versions with dynamics* whereas versions with equalized velocity values are referred to as *versions without dynamics*.

3.2.3 Experimental procedure

Behavioral session

From each participant, continuous ratings of musical tension for each piece were acquired in a separate session that preceded the functional neuroimaging session. Continuous tension ratings were obtained using a slider interface presented on a computer screen. The vertical position of the slider shown on the screen could be adjusted with the computer mouse according to the musical tension experienced by participants (with high positions of the slider corresponding to an experience of high tension and lower slider positions indicating low levels of experienced tension). Participants were instructed to use the slider to continuously indicate musical tension as they subjectively experienced it while listening to the stimuli (“Please use the slider to indicate the amount of tension you feel during each moment of the music.”). It was emphasized that they should focus on their subjective experience of tension, and not on the tension they thought the music was supposed to express. That is, ratings of *felt* musical tension (in contrast to *perceived* tension, cf. Gabrielsson, 2002) were acquired. As in previous studies of musical tension (Farbood, 2012; Fredrickson, 2000; Krumhansl, 1996, 1997; Lychner, 1998; Vines et al., 2006), in order not to bias participants' understanding of the concept of musical tension towards one specific aspect of the tension experience (e.g., consonance/dissonance, stability/instability, local vs. non-local implicative relationships, see

Section 3.1), musical tension was not explicitly defined, and none of the participants reported difficulties with the task. To familiarize participants with the task, they completed a short practice trial before starting with the actual experiment (a three minute excerpt from the second movement of Schubert's Piano Sonata D. 960 was used for the practice trial). The vertical position of the slider (i.e., its y-coordinate on the screen) was recorded every 10 ms (however, to match the acquisition times of the functional imaging, tension ratings were subsequently downsampled, see Section 3.2.5). Each stimulus was presented twice, yielding a total of 16 stimulus presentations (four pieces with dynamics plus four pieces without dynamics, each repeated once). Before each stimulus presentation, the slider was reset to its lowermost position. Stimuli were presented via headphones at a comfortable volume level and in randomized order. The total duration of one behavioral session was approximately 45 minutes.

Functional MRI experiment

Within maximally one week after the behavioral session (*M* = 2.6 days, *SD* = 1.6 days), participants listened to the stimuli again while functional imaging data were acquired. Stimuli were presented via MRI-compatible headphones, and special care was taken that stimuli were clearly discernible from scanner noise and presented at a comfortable volume level (an optimal volume level was determined in a pilot test, however, to make the experiment as comfortable as possible, slight individual volume adjustments were made if requested by participants).

To make sure that participants focused their attention on the music, they were given the task to detect a short sequence of three sine wave tones (660 Hz, 230 ms duration) that was added randomly to four of the sixteen stimulus presentations. Each stimulus presentation was followed by a 30 s rating period, during which participants indicated whether they had detected the sine wave tones using two buttons (*yes* or *no*) of an MRI-compatible response box. To assess the global emotional state of participants during each stimulus presentation, we also acquired valence and arousal ratings after each stimulus using the five-point self-assessment manikin (SAM) scale by Lang (1980). Participants were instructed to listen to the stimuli with their eyes closed. After completion of each piece a short tone (440 Hz, 250 ms duration) signaled them to open their eyes, give their answer for the detection task, and provide the valence and arousal ratings for the preceding stimulus. The fMRI session comprised two runs with each run containing eight stimulus presentations (four pieces with dynamics and four pieces without dynamics) played in randomized order (duration per run: 19:34 min). To make participants familiar with the experiment and the detection task, they completed two practice trials inside the scanner before starting with the actual experiment.

No tension ratings were acquired during the functional imaging session to avoid contamination of fMRI data related to felt musical tension with those related to cognitive processes associated with the rating task (e.g., motor and monitoring processes). To guarantee the within-subject reliability of tension ratings, participants performed additional tension ratings immediately after fMRI scanning, which were compared with ratings from the behavioral session. To keep the duration of the experiment at a reasonable length, the post-scan ratings were not acquired for the complete stimulus set but only for two representative examples (the Mendelssohn and Mozart piece played with dynamics).

3.2.4 Image acquisition

MRI data were acquired using a 3 Tesla Siemens Magnetom TrioTim MRI scanner (Siemens AG, Erlangen, Germany). Prior to functional scanning, a high-resolution (1x1x1 mm) T1-weighted anatomical reference image was obtained using a rapid acquisition gradient echo (MP-RAGE) sequence. For the functional session, a continuous echo planar imaging (EPI) sequence was used (37 slices; slice thickness: 3 mm; interslice gap: 0.6 mm; TE: 30 ms; TR: 2 s; flip angle: 70°; 64x64 voxel matrix; field of view: 192x192 mm) with acquisition of slices interleaved within the TR interval. A total of 1174 images was acquired per participant

(587 per run). To minimize artifacts in areas such as the orbitofrontal cortex and the temporal lobes, the acquisition window was tilted at an angle of 30° to the intercommissural (AC-PC) line (Deichmann et al. 2003; Weiskopf et al. 2007).

3.2.5 Image processing and statistical analysis

Data were analyzed using Matlab (MathWorks, Natick, USA) and SPM8 (Wellcome Trust Centre for Neuroimaging, London, UK). Prior to statistical analysis, functional images were realigned using a 6-parameter rigid body transformation, co-registered to the anatomical reference image, normalized to standard Montreal Neurological Institute (MNI) stereotaxic space using a 12-parameter affine transformation, and spatially smoothed with a Gaussian kernel of 6 mm full-width at half-maximum. Images were masked to include only gray matter voxels in the analysis (voxels with a gray matter probability of less than 40% according to the ICBM tissue probabilistic atlases included in SPM were excluded). Low-frequency noise and signal drifts were removed using a high-pass filter with a cut-off frequency of 1/128 Hz. An autoregressive AR(1) model was used to account for serial correlations between scans.

Statistical analysis was performed using a general linear model (GLM) with the following regressors: (1) music periods; (2) rating periods; (3) loudness; (4+5) tension (modeled separately for versions with and without dynamics); (6) tension increases; (7) tension decreases. Music and rating periods of the experiment were entered as block regressors into the model. Loudness changes of the music were modeled as a continuous regressor that was calculated using a Matlab implementation (http://www.genesis-acoustics.com/en/loudness_online-32.html) of the loudness model for time-varying sounds by Zwicker and Fastl (1999). (Note that even versions without dynamics, i.e., versions with equalized MIDI key-stroke velocity values, retained some loudness variations because of varying note density of the music, which made it necessary to include a loudness regressor in the GLM to avoid confounding tension with loudness.) Tension was modeled as a continuous regressor using z-normalized tension ratings averaged across participants and the two presentations of each stimulus during the behavioral session (see Figure 3.1, using individual instead of averaged tension ratings yielded similar but statistically weaker results). Tension increases and decreases were modeled in a block-wise fashion based on the first derivative of the average tension rating: values more than one standard deviation above the mean of the derivative were modeled as tension increases, whereas values more than one standard deviation below the mean were modeled as tension decreases (see Figure 3.1). Thus, these regressors distinguish between rising and falling tension, showing in which structures activity correlates with a transient increase or decrease of tension, whereas the tension regressor indicates in which structures activity correlates with absolute tension values. (The continuous regressor of the tension derivative yielded similar but statistically weaker results compared with the regressors modeling increase and decrease of tension.) Estimates of the motion correction parameters obtained during the realignment were added as regressors of no interest to the model.

To match the time points of image acquisition, continuous regressors (i.e., loudness and tension) were downsampled to 1/2 Hz using the Matlab function *interp1.m*. The hemodynamic response was modeled by convolving regressors with a canonical double-gamma hemodynamic response function. Model parameters were estimated using the restricted maximum likelihood approach implemented in SPM.

Whole-brain statistical parametric maps were calculated for the contrast *music vs. rating*, the continuous regressors *loudness* and *tension,* and the contrast *tension increase vs. tension decrease.* To compare tension-related brain activations between versions with and without dynamics (see Section 3.2.2), we also contrasted tension for the different versions with each other, i.e., *tension (versions with dynamics) vs. tension (versions without dynamics*). After calculating contrasts at the level of individual participants, a second-level random effects analysis using one-sample t-tests across contrast images of individual participants was performed. *P*-values smaller than .05 corrected for family-wise errors (FWE) were considered significant.

In addition to the whole-brain analysis, we tested the regional hypothesis that tension is related to activity changes in the amygdala (see Section 3.1). For this, we tested the contrasts *tension* and *tension increase vs. tension decrease* with bilateral amygdalae as regions of interest (ROI). The anatomical ROI was created using maximum probabilistic maps of the amygdala as implemented in the SPM anatomy toolbox (Amunts et al., 2005; Eickhoff et al., 2005). These maps were also used to assess the location of significant activations within the three subregions of the amygdala (i.e., laterobasal, centromedial, and superficial groups). A statistical threshold of $p < .05$ (FWE-corrected) was used for the region of interest analysis.

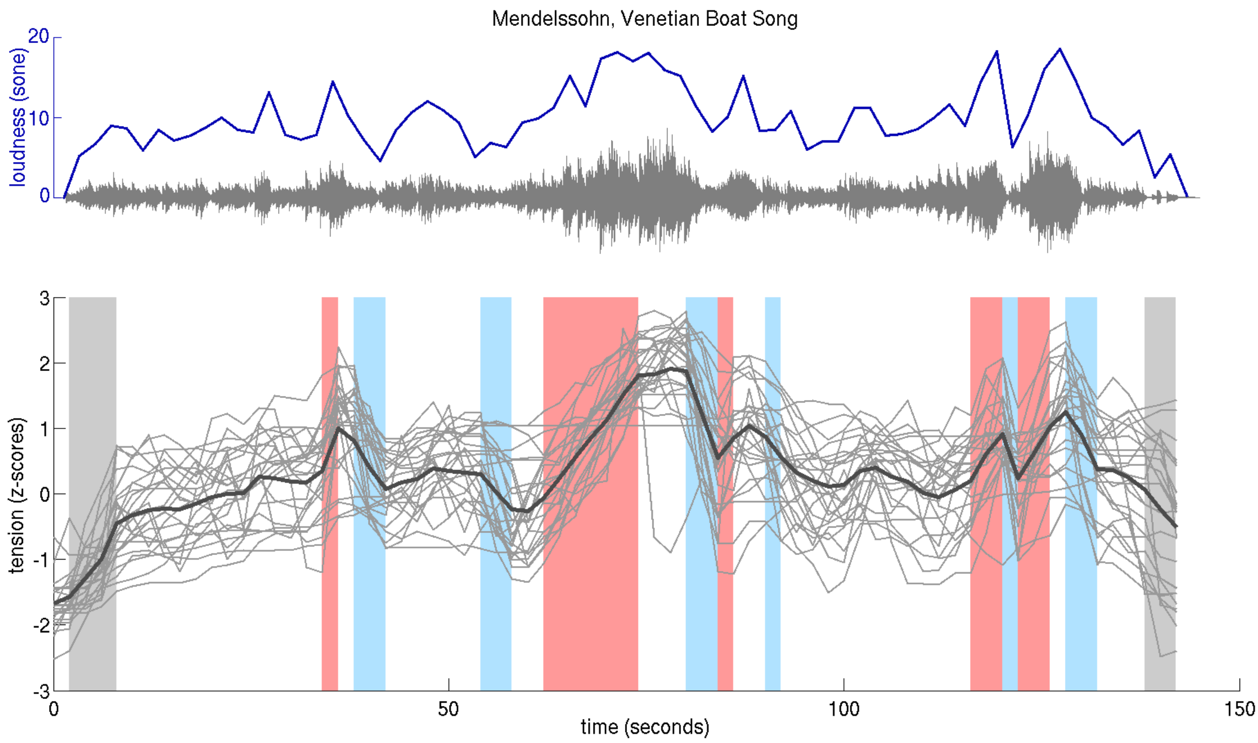

Figure 3.1. Top: Audio waveform (gray) and loudness (blue) of the Mendelssohn piece. Bottom: Individual (gray lines) and average (black line) tension ratings (N = 25). Shaded areas highlight time intervals that were modeled as increasing (red) and decreasing (blue) tension (gray shaded areas were excluded from data analysis because tension effects are confounded by music onset or ending). Loudness and tension ratings were downsampled to 1/2 Hz to match the time intervals of image acquisition. Note the similarity of loudness and the tension profile, and that, therefore, loudness was controlled by including it as regressor in the model used for data evaluation.

3.3 Results

3.3.1 Behavioral data

Figure 3.1 shows individual and average tension ratings for the Mendelssohn piece (version with dynamics). Pearson product-moment correlation coefficients between individual and average tension ratings of the different stimuli were high (M = .70; SD = .20). Overall, average tension profiles thus were in good correspondence with individual tension ratings.

Likewise, within-participant correlations assessed by comparing tension ratings before and after scanning were high (Mendelssohn: M = .76; SD = .12; Mozart: M = .62; SD = .28) indicating that the subjective experience of musical tension remained relatively stable over time.

Mean valence ratings of the pieces (measured on a five-point scale) ranged between 3.47 and 4.38 (M = 4.00; SD = 0.34) showing that participants enjoyed listening to the pieces. Mean arousal ratings for the different pieces were moderate, ranging from 2.00 to 2.98 (M = 2.41, SD = 0.31).

Except for one participant who missed one of the four sine tones that had to be detected, all participants correctly detected the tones indicating that they attentively listened to the music stimuli during scanning.

3.3.2 Functional MRI data

Statistical parametric maps (SPMs) for the different contrasts and regressors are shown in Figure 3.2 (for details see also Table 3.1). The contrast *music > rating* (Figure 3.2a) showed activation of bilateral supratemporal cortices. In each hemisphere, the maximum of this activation was located on Heschl's gyrus in the primary auditory cortex (right: 90% probability for Te1.0, left: 60% probability for Te1.0 according to Morosan et al., 2001), extending posteriorly along the lateral fissure into the planum temporale as well as anteriorly into the planum polare. Moreover, this contrast showed bilateral activation of the cornu ammonis (CA) of the hippocampal formation (right: 80% probability for CA, left: 70% probability for CA according to Amunts et al., 2005). Smaller clusters of activation for this contrast were found in the right central sulcus, left subgenual cingulate cortex, left caudate, and left superior temporal sulcus (STS).

Results of the loudness regressor (which, in contrast to the global *music > rating* contrast, specifically captured brain responses to loudness variations within music pieces) are shown in Figure 3.2b. This regressor revealed activations of Heschl's gyrus bilaterally (primary auditory cortices, right: 80% probability for Te1.0, left: 50% probability for Te1.0 according to Morosan et al., 2001) extending into adjacent auditory association cortex.

Figure 3.2c shows results of the tension regressor (pooled over versions with and without dynamics), that is, of the analysis indicating structures in which activity correlates with felt musical tension. (Note that loudness was controlled for by including the loudness regressor in the model, and that, therefore, loudness did not contribute to the results of this tension analysis.) The tension regressor indicated a positive correlation with blood oxygen level-dependent (BOLD) signal changes in the left pars orbitalis of the inferior frontal gyrus. No significant negative correlations were observed. To test whether the activation of the tension regressor differed between versions with and without dynamics, we also contrasted the tension regressor of original versions with versions with equalized MIDI velocity values (see Methods). For this contrast, i.e., *tension (versions with dynamics) > tension (versions without dynamics)*, activations were found in left caudate nucleus (see Figure 3.2d). The region of interest analysis for the tension regressor in left and right amygdalae (guided by our hypotheses, see Section 3.1) did not result in any significant activations.

To investigate structures in which activity correlates specifically with the rise and decline of tension, we also compared epochs of increasing and decreasing tension (see blue and red areas in Figure 3.1). Figure 3.2e shows results of the contrast *tension increase > tension decrease.* This contrast yielded significant activations of Heschl's gyrus bilaterally (primary auditory cortices, right: 70% Te1.0, left: 70% Te1.1) extending in both hemispheres posteriorly into the planum temporale. Smaller foci of activation for this contrast were also found in right anterior middle frontal gyrus (MFG), right thalamus, right precentral sulcus and right cerebellum. The opposite contrast (*tension decrease > tension increase*) did not reveal any significant activations. A region of interest analysis for the contrast *tension increase > tension decrease* in left and right amygdala indicated a significant activation of the right amygdala (MNI peak coordinate: 21 -4 -11; 80% probability for superficial group according to Amunts et al., 2005; p < .05, FWE-corrected on the peak level; cluster extent: 6 voxels; see Figure 3.2f).

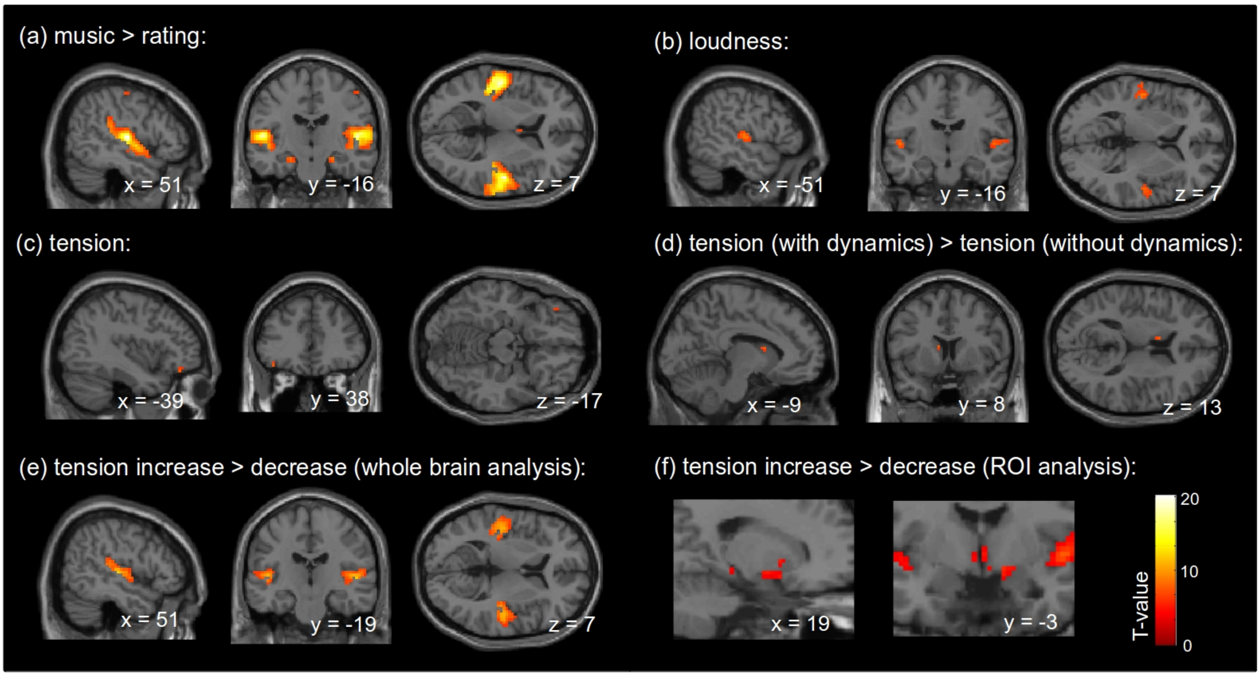

Figure 3.2. Statistical parametric maps of different contrasts and regressors, (a)-(e) whole-brain analyses (p < .05, FWE-corrected) for the contrasts *music* > *rating* (a), *loudness* (b), *tension* (c), *tension (versions with dynamics)* > *tension (versions without dynamics*) (d), and *tension increase* > *tension decrease* (e); (f) shows the region of interest analysis for left and right amygdala for the contrast *tension increase* > *tension decrease* (p < .05, small-volume FWE-corrected). All images are shown in neurological convention.

Table 3.1. Anatomical locations, MNI coordinates and *t*-values of significant local maxima for the different contrasts and regressors investigated in the whole-brain analysis ($p < .05$, FWE-corrected; cluster sizes in voxels). CA: cornu ammonis; MFG: middle frontal gyrus; STS: superior temporal sulcus.

anatomical location	X (mm)	Y (mm)	Z (mm)	T-value	cluster size
music > rating					
right primary auditory cortex	51	-13	7	19.67	768
left primary auditory cortex	-51	-19	7	19.13	586
right hippocampus (CA)	24	-13	-17	9.42	12
left hippocampus (CA)	-21	-16	-17	8.13	10
fornix	0	-1	13	8.60	20
left subgenual cingulate cortex	-3	26	-5	6.81	2
left subgenual cingulate cortex	-6	29	-8	6.28	1
right central sulcus	51	-16	55	6.63	3
left caudate nucleus	-6	11	1	6.40	1
left anterior STS	-42	5	-23	6.23	3
loudness					
left primary auditory cortex	-51	-13	4	8.33	46
right primary auditory cortex	51	-4	-2	8.21	44
tension					
left pars orbitalis	-39	38	-17	7.11	3
tension (versions with dynamics) > tension (versions without dynamics)					
left caudate nucleus	-9	8	13	7.22	3
left caudate nucleus	-6	11	7	5.89	1
tension increase > tension decrease					
right primary auditory cortex	51	-19	4	11.58	220
left primary auditory cortex	-39	-28	10	10.66	217
right MFG	42	47	13	9.47	12
right thalamus	12	-28	-5	7.67	3
right precentral sulcus	36	2	61	6.96	4
right cerebellum	6	-37	-8	6.65	2
right cerebellum	6	-70	-20	6.14	1

3.3.3 Functional connectivity / psychophysiological interactions (PPI)

To investigate whether there is a functional link between the brain regions associated with tension (in particular, the pars orbitalis and the amygdala), we also performed a post-hoc functional connectivity / PPI analysis (Friston et al., 1997) in which we tested (a) which brain areas correlate with activity in the peak voxels of the pars orbitalis and amygdala activations reported above (irrespective of subjectively experienced tension) and (b) whether there is a psychophysiological interaction with increasing or decreasing tension, i.e., in which brain areas the functional connectivity is modulated by tension (increasing vs. decreasing).

The seed voxel in the left pars orbitalis (MNI coordinate: -39 38 -17) showed, among others, a significant functional connectivity ($p < .05$, FWE-corrected) with bilateral hippocampal and amygdalar regions (see Figure 3.3). Conversely, the seed voxel in the right amygdala (MNI coordinate: 21 -4 -11) was functionally connected to the left pars orbitalis (for a complete list of significant activations from the functional connectivity analysis, see Table 3.2). The PPI analysis investigating in which regions functional connectivity is modulated by tension did not yield any significant results.

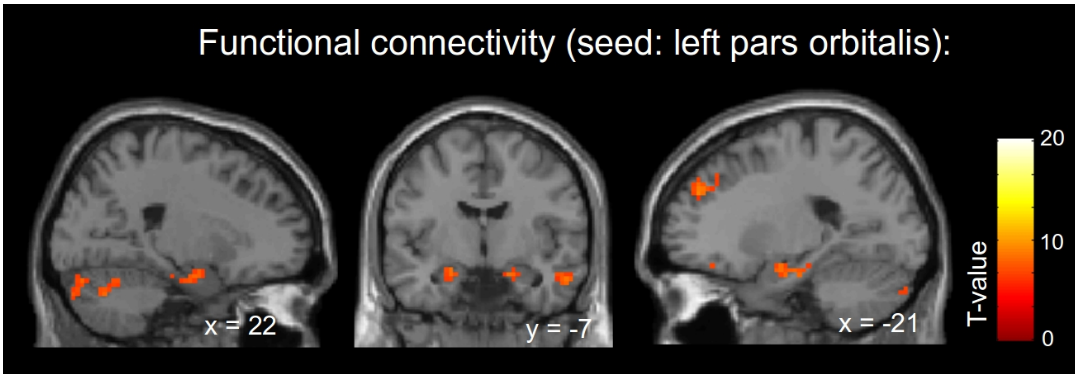

Figure 3.3. Statistical parametric maps ($p < .05$, FWE-corrected) for the functional connectivity analysis with the peak voxel of the left pars orbitalis used as seed region (MNI coordinate: -39 38 -17). The maps show functional connectivity with bilateral hippocampal and amygdalar regions.

Table 3.2. Results of the functional connectivity analysis. Anatomical locations, MNI coordinates and *t*-values of significant local maxima that are functionally connected to seed voxels in the pars orbitalis and the amygdala ($P < .05$, FWE-corrected; cluster size threshold: 10 voxels). Hippocampal and amygdalar activations form one continuous cluster. CA: cornu ammonis; MTG: middle temporal gyrus; MFG: middle frontal gyrus; IFG: inferior frontal gyrus; ITG: inferior temporal gyrus; STG: superior temporal gyrus.

anatomical location	X (mm)	Y (mm)	Z (mm)	t-value	cluster size
seed voxel: left pars orbitalis (-39 38 -17)					
left superior medial gyrus	3	53	19	12.35	321
right IFG (pars orbitalis)	33	29	-17	10.62	126
right hippocampus (subiculum)	30	-13	-26	9.85	58
right amygdala	18	-7	-20	8.17	
right hippocampus (CA)	33	-31	-14	9.49	15
left MTG	-51	-16	-23	9.31	54
right cerebellum	12	-85	-26	9.27	93
left orbital gyrus	-6	35	-14	9.14	65
right MTG	66	-43	-5	8.80	37
right MTG	48	-10	-20	8.49	22
left hippocampus (subiculum)	-18	-13	-23	8.40	62
left amygdala	-21	-7	-17	8.20	
right cerebellum	24	-67	-32	8.31	60
left MTG	-60	-52	-5	8.27	61
left MTG	-48	26	13	8.02	30
left cerebellum	-24	-88	-32	7.92	12
left MTG	-51	-61	22	7.85	43
left inferior parietal lobule	-51	-55	43	7.69	44
right angular gyrus	39	-61	52	7.61	47
right angular gyrus	51	-67	31	7.53	45
left inferior parietal lobule	-33	-67	46	7.42	47
left cerebellum	-6	-85	-32	7.39	21
right cerebellum	33	-76	-41	7.30	15
right MFG	33	59	7	7.19	14
right superior medial gyrus	9	65	22	7.14	12

left posterior cingulate cortex	-3	-46	28	6.93	29
left IFG (BA 44)	-45	14	34	6.91	19
right ITG	54	-61	-14	6.79	11
seed voxel: right amygdala (21 -4 -11)					
left hippocampus (CA)	-33	-31	-17	12.73	876
left IFG (pars orbitalis)	-39	26	-8	12.66	518
right ITG	45	-55	-11	10.31	92
right thalamus	9	-22	7	9.74	80
left cerebellum	-6	-43	1	9.47	16
left STG	-51	-25	13	9.19	112
right orbital gyrus	9	53	-2	9.16	118
left posterior cingulate cortex	-6	-49	31	8.89	462
right MTG	66	-34	1	8.87	30
right STG	54	-10	-11	8.84	91
right lingual gyrus	15	-55	4	8.19	24
right rolandic operculum	42	-13	19	7.82	11
right insula	39	-28	19	7.81	21
right precentral gyrus (BA 6)	27	-13	55	7.18	23
right fusiform gyrus	39	-43	-20	7.13	18

3.4 Discussion

The neural correlates of tension as subjectively experienced over the course of a music piece have not been previously investigated. In the present study, we identified brain areas correlating with continuous tension ratings of ecologically valid music stimuli. We found that tension correlates with BOLD signal increases in the left pars orbitalis of the inferior frontal gyrus (IFG). Moreover, a region of interest analysis in bilateral amygdala showed signal increases in the right superficial amygdala during periods of tension increase (compared with periods of tension decrease). A connectivity analysis showed functional connections between the pars orbitalis and bilateral amygdalar regions.

In accordance with previous findings (Fredrickson, 2000; Krumhansl, 1996), our behavioral data show that the experience of musical tension was consistent both across and within participants. Correlations between tension ratings before and after scanning were high, indicating that the subjective experience of tension remained stable over time and that ratings acquired before the scanning session were in concordance with the tension experience during scanning. Likewise, the high correlations between individual and average tension ratings showed that the experience of musical tension of individual participants was well captured by the average tension rating which we used for the fMRI data analysis.

For the fMRI data, contrasting music periods with rating periods (i.e., periods of silence) showed, as expected, activations in typical regions of auditory processing in primary auditory cortex and surrounding auditory areas. In addition, this contrast revealed bilateral activation of the hippocampus. Hippocampal activation has regularly been observed in previous neuroimaging experiments using music stimuli (e.g., Blood & Zatorre, 2001; Brown et al., 2004; Koelsch et al., 2006; Mueller et al., 2011) and is taken to reflect memory and emotional processes related to music listening (Koelsch, 2012). Loudness also correlated with primary auditory cortex activations, consistent with previous studies that report BOLD signal increases dependent on the sound pressure level of auditory stimuli (Hall et al., 2001; Langers et al., 2007).

For musical tension, we observed activation in the left pars orbitalis (Brodmann area 47). BA 47 is part of the five-layered orbitofrontal paleocortex, and cyto- as well as receptorarchitectonically only distantly related to neighboring Brodmann areas 44 and 45 of the IFG (Amunts et al., 2010; Petrides & Pandya, 2002). BA 47 thus appears to be functionally more related to the orbitofrontal cortex (OFC) than to the IFG, suggesting a possible involvement in emotional processes. In the music domain, activation of orbito-frontolateral cortex has been related to emotive processing of unexpected harmonic functions (Koelsch et al., 2005; Tillmann et al., 2006). Similarly, Nobre et al. (1999) reported activations in orbito-frontolateral cortex for breaches of expectancy in the visual modality. In music, such breaches of expectancy are closely associated with the subjective experience of tension: unexpected events (for example, chords that are only distantly related to the current key context, thus creating an urge to return to the established tonal context) are usually accompanied by an experience of tension whereas expected events (e.g., a tonic chord after a dominant chord) tend to evoke feelings of relaxation or repose (Bigand et al., 1996). These musical expectations have been proposed to be the primary mechanism underlying music-evoked emotions (Meyer, 1956; Vuust & Frith, 2008), and psychologically, the subjective experience of tension may thus be taken to reflect the affective response to breaches of expectancy (but note that other phenomena can also give rise to musical tension, for reviews see Huron, 2006; Koelsch, 2012; Chapter 4 of this dissertation). In light of previous research that has proposed a functional role of orbitofrontal cortex in representing affective value of sensory stimuli (Rolls & Grabenhorst, 2008) and linking sensory input to hedonic experience (Kringelbach, 2005), the pars orbitalis activation observed for musical tension may therefore reflect neural processes integrating expectancy and prediction processes with affective experience. This is supported by the results of our connectivity analysis, showing that the pars orbitalis is functionally connected to bilateral hippocampal and amygdalar regions (however, this functional connectivity was not modulated by tension). Given the link between tension and processes of expectancy and prediction, the pars orbitalis activation and its functional connections to bilateral regions of the amygdala further corroborate the role of expectancy as a mediator of music-evoked emotions (Huron, 2006; Juslin & Västfjäll, 2008; Koelsch, 2012; Meyer, 1956). Importantly, the activation for musical tension in the pars orbitalis did not depend on the dynamics (i.e., the varying degrees of loudness) of the pieces because no activation differences in this region were observed when comparing tension for versions with and without dynamics.

The region of interest analysis for bilateral amygdalae revealed increased activations in right (superficial) amygdala for periods of increasing tension compared with periods of decreasing tension. This extends previous findings by showing that the amygdala does not only respond to irregular chord functions in simple chord sequences (Koelsch et al., 2008a) but is also related to subjectively experienced tension increases in real music pieces. Note that the amygdala is not a single functional unit: different subregions of the amygdala show distinctive activation patterns for auditory stimuli (with predominantly positive signal changes in the laterobasal group and negative signal changes in the superficial and centromedial groups, see Ball et al., 2007), and core regions of the amygdala respond to both positive and negative emotional stimuli (Ball et al., 2009). Interestingly, in both the present study and the study by Koelsch et al. (2008a), which investigated brain activations in response to unexpected chords, signal differences were maximal in the superficial nuclei group of the amygdala (SF). Although not much is known about this nuclei group, connectivity studies showed that the SF is functionally connected to limbic structures such as anterior cingulate cortex, ventral striatum and hippocampus, thus underscoring its relevance for affective processes (Bzdok et al. 2012; Roy et al., 2009). In neuroimaging studies using music, SF activations have been found for joyful music stimuli as opposed to experimentally manipulated dissonant counterparts (Mueller et al., 2011) and joyful as opposed to fearful music (Koelsch et al., 2013), suggesting a relation between SF and positive emotion. Considering a possible role of the SF in positive emotion and its functional connection to the nucleus accumbens (Bzdok et al., 2012), the SF activations reported here may also point to a possible relation between musical tension and so-called chill experiences (i.e., intensely pleasurable responses to music, see Grewe et al., 2009; Panksepp, 2005). Such chill experiences are typically evoked by new or unexpected harmonies (Sloboda, 1991), and have been found to be associated with dopaminergic activity in the ventral striatum (Salimpoor et al., 2011). The close relation between the amygdala and the reward processing of the striatum associated with musical pleasure gains further support from a recent fMRI study showing that the reward value of a music stimulus is predicted by the functional connectivity between the amygdala and the nucleus accumbens (Salimpoor et al., 2013). Thus, the SF may play a functional role in mediating pleasurable affective responses such as chills related to breaches of expectancy in music. Finally, a study by Goossens et al. (2009) suggests that the SF is particularly sensitive to social stimuli (in that study, SF responses were stronger in response to faces compared to houses), and a meta-analysis by Bzdok et al. (2011) revealed activation likelihood maxima in the SF for social judgments of trustworthiness and attractiveness, indicating a possible role in the processing of social signals. Thus, the present data perhaps reflect that irregular harmonies are taken by perceivers as significant communicative signals (see also Cross & Morley, 2008; Steinbeis & Koelsch, 2009), but this remains to be investigated in more detail.

Note that amygdala activations were only observed when comparing periods of increasing and decreasing tension; the continuous ratings of musical tension did not show amygdala activation. This points to an important limitation of one-dimensional tension measures (and continuous emotion measures in general) that do not distinguish between increases and decreases of rating values: although a point of rising tension can have the same absolute value as a point of falling tension, they probably reflect different cognitive and affective processes. Whereas the former is associated with a build-up of emotional intensity, the latter reflects a process of relaxation or resolution. In the present study, we accounted for this by explicitly modeling tension increases and decreases in a block-wise fashion. For future research, it may be promising to break the phenomenon of musical tension even further down into different sub-processes like the build-up of a musical structure, breaches of expectancy, anticipation of resolution, and resolution (see also Koelsch, 2012).

Finally, it has to be considered that musical tension involves both cognitive and affective processes, and brain activations related to musical tension can, in principle, be attributed to either of the two (or both). Although our results favor an affective interpretation (based on the observed brain regions as well as the nature of the experimental task, in which participants rated felt musical tension, not perceived tension), the contribution of affective versus purely cognitive processes of prediction and expectation to the observed activations remains to be explored more closely. For example, future research could disentangle cognitive and affective aspects of tension by comparing prediction and expectation processes in musical contexts that are largely devoid of emotional responses and are primarily based on the statistical properties of the stimulus (e.g., using computer-generated single-note sequences) with ones that involve emotion (such as the paradigm used in the present study). Furthermore, it may be promising to correlate BOLD responses with predictions of theoretical models of musical tension (Farbood, 2012; Lerdahl & Krumhansl, 2007) and compare resulting activations with the ones related to subjective ratings of tension. Cognitive and affective processes might also be disentangled in time (using methods with high temporal resolution such as EEG or MEG), assuming that brain areas reflecting cognitive processes of expectancy and anticipation precede the ones related to the emotional reaction.

3.5 Conclusion

The results of this music study show that the subjective experience of tension is related to neuronal activity in the pars orbitalis (BA 47) and the amygdala. Our results are the first to show that time-varying changes of emotional experience captured by musical tension involve brain activity in key areas of affective processing. The results also underscore the close connection between breaches of expectancy and emotive processing, thus pointing to a possible functional role of the orbitofrontal cortex and amygdala in linking processes of expectancy and prediction to affective experience.

4 Tension-resolution patterns as a key element of aesthetic experience: psychological principles and underlying brain mechanisms[1]

Abstract

In a wide variety of art forms (especially in temporal art such as music, film, or literature), the aesthetic emotional experience of perceivers is orchestrated by patterns of tension and resolution. Studying these tension-resolution patterns promises new insights into aesthetic emotions and emotional experience in general. This chapter explores general psychological principles by which tension-resolution patterns evoke aesthetic emotions. In particular, processes of expectancy, prediction, and anticipation are identified as key factors mediating experiences of tension and resolution. The special case of musical tension is considered in more detail and possible brain mechanisms underlying tension experiences in music are discussed.

[1] This chapter will be published as a book chapter: Lehne, M., & Koelsch, S. (in press). Tension-resolution patterns as a key element of aesthetic experience: psychological principles and underlying brain mechanisms. In J. P. Huston, M. Nadal, F. Mora, L. Agnati & C. J. Cela-Conde (Eds.), *Art, Aesthetics and the Brain*. New York: Oxford University Press.

"The creation and destruction of harmonic and 'statistical' tensions is essential to the maintenance of compositional drama. Any composition (or improvisation) which remains consonant and 'regular' throughout is, for me, equivalent to watching a movie with only 'good guys' in it, or eating cottage cheese."

— Frank Zappa

4.1 Introduction

Art forms like music, film, or literature play a major role in our cultural lives. But what exactly motivates humans to spend large amounts of their time listening to music, watching movies, or reading novels? One major incentive for "consuming" art is without a doubt its power to elicit strong emotions. A piece of music can move us to tears[1], a painting can induce feelings of awe and fascination, a poem can evoke feelings of melancholy, elation, or joy, and a suspenseful movie can make our hearts race in excitement. However, the emotional power of art leads to another conundrum: How can a piece of art evoke any emotion at all? Assuming that emotions are elicited by events that have some intrinsic significance (either favorable or harmful) to our individual concerns, or—in biological terms—some kind of survival value, the aesthetic emotions evoked by works of art remain largely mysterious. Unlike the imminent threat posed by the hungry grizzly bear one might accidentally run into on a hiking trip, or the feelings of excitement after having hit the lottery jackpot, the imaginary events of *Romeo and Juliet*, the brush strokes of Munch's *The Scream*, or the musical events of Mozart's *Requiem* seem to lack any relevance to our lives as biological organisms. So how can aesthetic emotions be integrated into a theoretical framework of human affect? What are their underlying psychological principles? And how do they relate to

[1] Note that seemingly negative emotions such as fear or sadness are often experienced as positive when encountered in works of art.

neuronal processes in the brain? In this chapter, we propose that studying *patterns of tension and resolution* in works of art can help to answer these questions and advance the understanding of aesthetic experience in art (and of emotions in general).

Tension-resolution patterns refer to the opposite poles of tension—a state of instability or dissonance associated with feelings of hopeful (or fearful) expectation—and its counterpart, resolution, relaxation, release, or repose. In music, for example, a sequence of dissonant chords may gradually build up tension that is finally resolved by a consonant and stable chord at the end of sequence. In literature, tension—and its close relative suspense—can be created on the level of the plot (e.g., the protagonist of a novel being threatened by impending peril) as well as on more micro-structural levels of the text (e.g., a single sentence creating tension via its elaborate syntactic composition). Although tension-resolution patterns are most apparent in art forms that unfold in time (e.g., music, literature, film, or dance), they can also be observed in non-temporal visual arts such as painting, sculpture, or architecture, because even in "static" pieces of art, the process of aesthetic experience and appreciation requires time to unfold (cf. Fitch, 2009). An abstract painting, for example, can create tension by triggering a process of interpretation—a drive for understanding—that is resolved when a satisfying interpretation is found. This omnipresence of tension-resolution patterns in a wide variety of different art forms suggests that they play a central role in the aesthetic experience of art, motivating a closer investigation of underlying psychological principles and possible brain mechanisms.

Although the opposite poles of tension and resolution were already proposed by Wilhelm Wundt as a key component of affective experience in his three-dimensional theory of emotion (Wundt, 1896; 1911), for the decades to come, psychological research has largely neglected the role of tension and resolution in emotion (for rather recent remediations see Schimmack & Reisenzein, 2002; Thayer, 1989; Watson et al., 1999). One of our aims in this chapter is to re-awaken the interest in tension and resolution phenomena as a valuable tool that may help to unravel the psychological and neuronal mechanisms underlying aesthetic emotions, and emotions in general. To some extent, many pieces of art can be regarded as a form of "applied psychology", and Zeki (1999) even suggests considering artists as "neurologists", who creatively explore the processing characteristics of the human brain. Accordingly, tension and resolution patterns constitute an important artistic device, by which artists take advantage of general principles of human cognition to evoke emotional responses. Thus, studying tension-resolution patterns in works of art—apart from promising new insights into the psychological mechanisms of aesthetic experience—can also inform psychological and neuroscientific research on emotions evoked in non-artistic contexts. In particular, the time-varying nature of tension-resolution patterns opens new research opportunities for investigating the dynamic, temporal aspects of emotional experience, thus complementing extant emotion research, which mostly focuses on static aspects of brief emotional episodes.

In this chapter, we explore tension-resolution patterns and their relation to aesthetic experience from a psychological and neuroscientific perspective. We begin the chapter with a discussion of general psychological principles underlying tension and resolution phenomena which are relevant to a wide variety of art forms. We will argue that experiences of tension are closely related to processes of expectancy, prediction, and anticipation, and reflect a general urge to resolve dissonances or uncertainty and reach a stable state of equilibrium. We will mainly focus on temporal art such as music, film, or literature, in which tension-resolution patterns are most apparent (interestingly, these art forms also happen to have the biggest "mass appeal", suggesting that they address very basic aspects of human emotion). However, many of the principles discussed also transfer to static visual art forms (e.g., painting, sculpture, or architecture). Following the general discussion of tension-resolution patterns, we consider the special case of music in more detail and discuss theoretical and empirical research on musical tension. We close the chapter with considerations on possible brain mechanisms mediating experiences of tension and resolution. Again, we mainly focus on evidence from music research, however, we refer to other work where elucidating.

4.2 Tension-resolution patterns: psychological principles

For a long time, writers, playwrights, choreographers, film directors, and composers have known the importance of creating tension and suspense[1] to capture the attention of their audiences and excite emotional responses. Western classical music, for example, can be understood as a continuous flow of consonance and dissonance, stability and instability—patterns of tension and resolution that orchestrate the emotional response of the listener. Likewise, tension and resolution phenomena play a key role in film and literature, and the appeal of many popular books and movies seems to directly derive from their power to evoke feelings of tension and suspense. Famous suspense movies like *Psycho*, *Jaws*, or *The Silence of the Lambs* have attracted millions of moviegoers, and suspenseful novels have hit bestseller lists around the world. Similarly, an abstract piece of visual art can create tension by putting the spectator in a state of non-understanding that is resolved when a meaningful interpretation has been found. Apart from works of art, various other instances, in which tension and resolution phenomena play a role and potentially evoke strong emotions, can be identified. In many forms of play and games, experiences of tension and resolution are important (in sports events, for example, the collective emotional reactions of spectators are often framed by episodes of tension and resolution), and also in everyday life tension and resolution phenomena are omnipresent: The fearful or hopeful expectation experienced before significant life events with uncertain outcomes, or the relaxation and contentment experienced after a desired goal has been reached can all be conceived of as feelings of tension and resolution. Although these examples at first glance appear to describe very different phenomena, the common occurrence of tension-resolution patterns—not only in art but in

[1] The words *tension* and *suspense* will be largely used synonymously, and the following paragraphs will try to show that both concepts build on similar psychological mechanisms.

virtually all aspects of human life—suggests very basic underlying psychological principles, which we will explore in the following sections.

4.2.1 Uncertainty

Previously, we described tension as a state of dissonance, instability, or fearful/hopeful expectation that is associated with a yearning for resolution, i.e., an urge for consonance, stability, harmony, or equilibrium. When dissecting the mechanisms by which feelings of tension or suspense are evoked, one major factor that can be identified as a mediator of tension is *uncertainty*, and many art forms systematically use uncertainty to evoke feelings of tension or suspense. Obvious examples are films or novels, in which uncertainty about events of the narrative plot creates suspense. In narrative plots, this uncertainty often takes the form of an explicit or implicit question in the mind of the reader or viewer ("Where was the purloined letter hidden?", "Who killed Laura Palmer?", etc.). Such questions arouse curiosity and create "the force that draws us through a narrative" (Rabkin, 1973). The eventual resolution of uncertainty then results in a state of understanding and provides a sense of closure that is associated with a positive affective response. The great effectiveness of so-called cliffhangers in television series provides a vivid example of the potential power of using uncertainty as a plot device: Ending an episode in a moment of high uncertainty, e.g., by putting the main character in a life threatening situation without resolving whether he survives or not, can create a strong, almost pathological desire to watch the next episode, in which the uncertainty and the associated suspense is hopefully resolved.

Uncertainty in narrative plots comes in different forms: there can be uncertainty about *what* will happen, *when* it will happen, *how* it will happen, or *if* it will happen. When Gabriel García Márquez starts his novella *Chronicle of a Death Foretold* with the sentence "On the day they were going to kill him, Santiago Nasar got up at five-thirty in the morning to wait for the boat the bishop was coming on.", there is high certainty about what will eventually happen (i.e., the murder of Santiago Nasar), however, suspense is created because the exact circumstances leading to the murder (i.e., how it will happen) remain unclear, thus capturing the interest and curiosity of the reader.

It may be argued that suspense in narrative plots is a very special case of tension that is only relevant to representational art forms such as films or novels, which usually refer to (hypothetical) events in the real world. In contrast, tension-resolution phenomena in more abstract nonrepresentational art may be based on entirely different principles. However, investigating tension-resolution patterns in music (which is arguably less representational than a movie or a novel) reveals strikingly similar mechanisms. Referring to suspense in music, music philosopher Leonard Meyer states that "[s]uspense is essentially a product of ignorance as to the future course of events" (Meyer, 1956, p. 27). Note that in music, uncertainty about *when* a certain event will happen is often more important than *what* will happen. For example, in most pieces it is very likely that harmonic tension is eventually resolved by returning to the tonic, however, it is not clear when this resolution occurs, and many music pieces are sophisticated examples of skillfully delaying the anticipated resolution. Likewise, abstract nonrepresentational pieces of visual art can use uncertainty to evoke feelings of tension and resolution by putting the spectator in a psychological state of non-understanding that triggers a process of interpretation which may culminate in a rewarding state of resolution as soon as a sensible interpretation has been found. As noted by Fitch (2009), some artworks leave the tension partly unresolved, thus motivating repeated viewings. Uncertainty thus works as a mediator of tension, whereas the reduction of uncertainty resolves tension.

4.2.2 Expectancy, prediction, and anticipation

Despite its importance for mediating tension, uncertainty alone is not sufficient for evoking feelings of tension (otherwise, tension would be highest for random sequences of events that are completely unpredictable). Another key element of tension are processes of expectancy, prediction, and anticipation[1]. As events unfold in time (e.g., in a piece of music, or in a narrative plot), they are constantly evaluated against a background of expectancies that are continuously updated during the temporal evolution of events. Events generating strong expectancies are then potential triggers of tension because they create an urge to be resolved. To allow the build-up of tension, there is usually some temporal distance between the event generating the expectancy and the event fulfilling the expectancy, and the most effective tension-resolution patterns often span large structures (e.g., the plot of a novel, or the music of an entire symphony).

Importantly, to create tension, expected events must have some kind of significance. If the outcome of an expected event is irrelevant, i.e., if it does not matter whether expectancies are fulfilled or violated, tension fails to build up. This means that expected events usually have either positive or negative valence. In narrative plots, impending danger conjures images of death or physical harm to the protagonist, which are hoped to resolve with a seemingly unlikely, but highly desired happy ending. In music, tension can be driven by a yearning for consonant and stable sounds that are experienced as pleasurable.

In its most elementary form, tension can thus be conceptualized as a divergence between a desired goal state and the actual state of the world. This divergence between the present state and the desired goal state creates a psychological discomfort that is experienced as tension. (The apparent paradox between the psychological discomfort and the feelings of pleasure derived from tension-resolution experiences will be addressed in a subsequent section of the chapter.)

To make the formation of predictions possible, some kind of information or formal structure is necessary on which predictive inferences can be based. In music, the generation of predictions is largely based on the "rules" of a given musical system (e.g., Western tonal

[1] Note that there are subtle conceptual differences between the terms *expectancy*, *expectation*, *prediction*, and *anticipation* (for accounts on terminology, see Bubic et al,, 2010; Rohrmeier & Koelsch, 2012). However, there is no consensus regarding the definition of the terms, and they are often used interchangeably in the literature.

music). For example, certain chords bear strong implications (e.g., a dominant seventh chord tends to be followed by a tonic chord), thus creating expectancies against which subsequent events are evaluated (for an overview of predictive processing in music, see Rohrmeier & Koelsch, 2012). Musical events with a strong implicative function generating clear expectancies about subsequent events then give rise to an experience of tension. In narrative plots, expectancies can be based on genre-specific conventions (e.g., the expected happy ending of a Hollywood movie) or rules of everyday life that activate specific cognitive schemata or scripts (Bartlett, 1932; Rumelhart, 1984; Schank & Abelson, 1977). Of course, expectancies need not always be fulfilled but can be violated to generate surprise and make a piece of art more interesting. In fact, the right "mix" between fulfillment and violation of expectancies is essential: if an artwork is too predictable (i.e., if it always fulfills expectancies) it runs the risk of being boring, whereas a piece of art that is completely unpredictable can easily lead to frustration by overcharging the perceiver's cognitive capacities (of course, in some artworks, this may be what the artist intended).

The predictive processes relevant for generating tension and resolution in works of art build on very basic aspects of human cognition. The philosopher Daniel Dennett stated: "A mind is fundamentally an anticipator, an expectation-generator" (Dennett, 1996), and anticipation has been suggested as a basic emotion category (Plutchik, 1980). Furthermore, the ability to form predictions has been proposed as a fundamental principle of human brain functioning (Bar, 2007; Bubic et al., 2010; Friston, 2010), which will be discussed in more detail in the last part of this chapter. The importance of anticipation processes as a general feature of human cognition is also plausible from an evolutionary perspective because the ability to make accurate predictions about the future promotes fast and adequate behavioral responses, and increases survival chances. Similarly, the urge to resolve uncertainties discussed previously has biological advantages because behavioral responses in a state of certainty and understanding usually lead more directly to a specific goal than in an uncertain environment. Thus, any art work that triggers predictions and creates expectancies takes advantage of this general feature of human cognition. Likewise, the episodes of uncertainty and non-understanding that are deliberately employed in works of art to create tension address a basic psychological need for uncertainty reduction and understanding. Similar to the concept of homeostasis in biology (i.e., the tendency of biological organisms to maintain a stable state in a constantly changing environment), feelings of tension and resolution thus seem to reflect a kind of "psychological homeostasis"—a general tendency to resolve dissonances, conflicts, and uncertainty, and strive towards a stable state of equilibrium.[1]

Interestingly, the fact that art takes advantage of these basic features of human cognition to arouse emotions indicates that these "aesthetic" emotions are not qualitatively different from the emotional experiences of everyday life (for an opposing view distinguishing aesthetic emotions from utilitarian emotions see Scherer, 2004). Instead, the omnipresence of tension-resolution phenomena suggests that the concomitant emotions build on general psychological principles that apply to a wide variety of seemingly different modalities.

4.2.3 The emotional valence of tension

If tension is associated with dissonance, instability, and uncertainty, i.e., emotional states that are usually associated with psychological discomfort, unease, and negative emotional valence, this raises an obvious question: Why would anyone deliberately seek out experiences that are associated with tension? Works of art potentially evoke feelings of tension, yet their popularity apparently contradicts the hypothesis that tension causes psychological discomfort and should therefore be avoided. To solve this contradiction, it is helpful to distinguish between tension experiences in art and tension in everyday life. Unlike tension experiences in real life that are usually considered as negative because they are associated with physiological or psychological strain, art provides an environment in which tension can be experienced

[1] Note the parallels to Festinger's theory of cognitive dissonance (Festinger, 1957), which states that humans have a strong urge to resolve psychological dissonances and strive towards cognitive states in which beliefs and behavior are consistent (even if this involves entertaining irrational beliefs).

without compromising one's physical or psychological health. While tension in everyday life often induces negative emotions and is therefore generally avoided, looking for tension experiences in works of art thus provides a safeguard against potential physical or psychological harm (for a similar discussion focusing on the excitement aroused by sport events see Elias & Dunning, 1986). However, even in art, tension is often only positively valued because it is tacitly assumed that it will eventually resolve. Not resolving tension (e.g., in a movie or a piece of music) is usually experienced as unsatisfying. The pleasure derived from tension-resolution experiences thus appears to be a function of the ratio between the discomfort associated with the tension and the comfort experienced during resolution: the higher the discomfort during the tension phase, the higher the pleasure in the moment of resolution. This view is also expressed in Berlyne's “arousal jag” theory (Berlyne, 1960), which postulates that a drop from unusually high levels of arousal (that are experienced as unpleasant) to a low level of arousal is associated with feelings of pleasure (however, see Zillmann, 1980, for an alternative account). Thus, the pleasure derived from this arousal jag is a motivator for engaging in activities that are associated with unusually high levels of arousal, such as fairground attractions or extreme sports. In a more moderate form, similar mechanisms appear to underlie the emotional reactions evoked by tension-resolution patterns in works of art.

4.2.4 The paradox of repeated exposure

Previously, we discussed uncertainty and processes of expectancy, prediction, and anticipation as key factors mediating experiences of tension and resolution. This raises the question as to how it is possible that tension can be experienced over repeated exposures to a piece of art. Assuming that uncertainty is resolved after the first exposure, and expectations during subsequent exposures are largely accurate—thus rendering the expectancy violations or fulfillments experienced during the first exposure ineffective—experiencing a piece of art more than once should make it dull and uninteresting. However, this contradicts common experience: The film philosopher Noël Carroll states that after having seen *King Kong* at least 50 times, he still feels “the irresistible tug of suspense” (Carroll, 1996a, p. 71), and a piece of music can be listened to hundreds of times while still conveying feelings of tension and resolution.

Various theories accounting for this “paradox of suspense”, “anomalous suspense”, or “resilience of suspense” have been proposed (for the special case of narrative plots, see Brewer, 1996). These include the postulation of a willing suspension of memory, or a shift of motivation (repeated readings of a literary text, for example, are often not motivated by evoking a state of suspense but may have other reasons such as focusing on more subtle details of the story, the writing style of the author, etc.). Partly, the paradox of repeated exposure may also be accounted for by imperfect memory because second exposures often occur after a period of time when considerable parts of the information of the first exposure may have been lost. Furthermore, even if the expectancy violations and the uncertainty of the first exposure are less effective during subsequent exposures, some aspects of an artwork can create tension because they are intrinsically associated with psychological discomfort (e.g., due to sensory dissonance in a piece of music or an unpleasant image in a piece of visual art) that is resistant against repeated exposures.

In music, the paradox that unexpected musical events can maintain their quality of “unexpectedness” even after repeated exposures has been referred to as Wittgenstein's paradox (Dowling & Harwood, 1986; Huron, 2006). To solve this paradox, Bharucha (1994) distinguishes between *veridical* and *schematic* expectations. Whereas veridical expectations refer to the expectations concerning actual events in a familiar piece of music (for example, a wrong note during the performance of a familiar piece violates a veridical expectation), schematic expectations are driven by the rules of a musical system (e.g., a dominant seventh chord followed by a chord that is not the tonic violates a schematic expectation). Although veridical and schematic expectations often coincide, they can diverge in familiar pieces, in which a musical event can be veridically expected but schematically unexpected, thus accounting for the remaining experience of unexpectedness over repeated exposures.

Finally, repeated exposure increases the predictive power of a listener, which might be experienced as pleasurable, and various studies have shown that repeated exposure to a musical piece increases liking (Lieberman & Walters, 1968; Peretz et al., 1998; Verveer et al., 1933). This effect of "mere exposure" (Zajonc, 1968) may to a certain degree compensate for the lower effectiveness of expectancy violations after repeated exposures.

4.2.5 Tension-resolution patterns and the aesthetic trajectory

The aesthetic experience associated with patterns of tension and resolution can be conceived of as a trajectory that unfolds in time and comprises different temporal stages. Fitch (2009) proposed a minimum of three stages for this *aesthetic trajectory*: "an initial stage of familiarity, recognition, or stability; a second stage of surprise, ambiguity, or tension; and a third stage of integration, resolution, or synthesis" (p. 61). These three stages closely correspond to the mechanisms mediating experiences of tension and resolution described above. Previously we stated that the expectation and anticipation processes related to tension experiences require a formal structure that makes it possible to form predictions, i.e., they presuppose some kind of familiarity and recognition reflecting the initial stage of Fitch's aesthetic trajectory. Second, the initial stage of familiarity is challenged by expectancy violations generating surprise, ambiguity, or tension. Finally, during the last stage, tension is resolved by integration and synthesis.

Similar to Fitch's aesthetic trajectory, the expectation processes generating tension can also be related to different stages of the *tension-arc* proposed by Koelsch (2012): During the initial build-up of expectancy, tension is created; this tension may be modulated by the harmonic stability and the extent of the established structure, and further increased by breaches of expectancy generating an anticipation for resolution; when the resolution is finally reached, tension is released, giving rise to an experience of pleasure and reward. Usually, several of such tension-arcs are superimposed and intertwined on different time scales (such as a phrase embedded in a part of a movement of a sonata). Koelsch's tension arc specifically refers to musical tension. However, considering the relevance of expectation processes as a general feature of human cognition, the different stages of the tension-arc may also be generalizable to other tension and resolution experiences.

4.3 Musical tension

The continuous ebb and flow of tension and resolution—a waxing and waning of episodes of dissonance and instability versus passages of consonance and stability—is one of the hallmarks of Western tonal music, and constitutes a major aspect of emotional experience during music listening. Tension and resolution are related to various features of the music: Different notes of a musical scale are associated with different degrees of stability and instability, different chords, or combinations of chords, convey different degrees of consonance or dissonance, metrical features like syncopation can delay or anticipate certain musical events, and expressive features such as dynamics and agogics create fluctuations in loudness or tempo, thus contributing to experiences of tension and resolution. Tension and resolution can be related to purely acoustic features (e.g., loudness or sensory dissonance being associated with an increase in experienced tension; Farbood, 2012; Pressnitzer et al., 2000), or they can involve higher cognitive processes (e.g., expectation processes building on the rules of a musical system; Lerdahl & Krumhansl, 2007). As mentioned above, tension-resolution patterns occur at different levels: they can be small-scale changing from one musical event to the next as well as large-scale, encompassing, for example, the global structure of an entire symphony. These global and local tension-resolution patterns possibly interact with one another, thus maximizing the emotional effect of the aesthetic experience.

As discussed previously, expectancy and anticipation processes as well as a general striving for consonance, stability, and resolution play a key role for inducing experiences of tension. The important contribution of expectation processes as a mediator of music-evoked emotions has prominently been put forward in the seminal work "Emotion and meaning in music" by Leonard Meyer (1956), in which expectation and the associated experiences of tension and resolution were proposed as a key mechanism for creating musical meaning and emotion. According to Meyer, the continuous play with expectations in music (i.e., the fulfillment or violation of expectancies) is paramount to the associated affective and aesthetic response. Similarly, Huron (2006) proposes a general psychological theory of expectation illustrated for the special case of music. Like Meyer, he stresses the important role of expectation for generating tension, which he defines as a physiological reaction "that arises from changes in arousal and attention, in preparation for some expected event" (Huron, 2006, p. 305).

Expectation processes in music build on the implicative structure of musical events (a dominant seventh chord, for example, is implicative of the subsequent tonic chord). For the special case of melodic expectations, Narmour (1990) devised a theory, identifying a set of general principles mediating expectation processes in melodies (summarized in Krumhansl, 1995), which have been largely confirmed by experimental research (Cuddy & Lunney, 1995). Subsequent research (Schellenberg, 1997) has shown that the principles postulated by Narmour for melodic expectations can be reduced to two basic predictor variables, namely *pitch proximit*y and *pitch reversal*. The pitch proximity principle states that listeners expect a melodic sequence to continue on a note that is proximate in pitch to the last note. Extending the pitch proximity principle, the pitch reversal principle claims that listeners expect the next note to be close in pitch to the note before the last note. For example, when a melody features a large leap (violating the pitch proximity principle), listeners expect the melody to return to a note close to the note before the leap.

According to Narmour (1990), melodic expectation is governed by innate bottom-up as well as learned top-down processes. This view has been challenged by computational modeling approaches showing that melodic expectation can be accurately modeled based on general learning mechanisms without assuming innate representational rules (Pearce & Wiggins, 2012). The learning mechanisms built into the model distinguish between long-term and short-term learning processes. Whereas long-term learning reflects listeners' experiences acquired over previously encountered musical pieces, short-term learning reflects the learning that occurs during exposure of the current piece. Interestingly, the model has begun to be extended to harmony (Whorley, Wiggins, Rhodes, & Pearce, 2010) and even language (Wiggins, 2011), indicating that it reflects general modality-independent cognitive processes rather than music-specific rules or principles.

Although musical expectancies have mostly been investigated in tonal contexts (i.e., in melodies or chord progressions), expectation processes are equally important in the processing of musical rhythm. Studying rhythms of the “Black Atlantic” diaspora (the rhythms underlying popular music genres such as jazz, blues, reggae, funk, rock, or hip-hop), Pressing (2002) argues that the emotional effect of these rhythms crucially relies on prediction and expectation processes.

Importantly, the expectation processes relevant to mediating musical tension can happen on different cognitive levels and involve different degrees of previously acquired knowledge. They can be knowledge-free (i.e., not relying on long-term knowledge) or they can be based on information stored in long-term memory. For example, expectation generation related to small-scale structures (e.g., the grouping of notes) may depend exclusively on auditory sensory memory and the processing according to Gestalt principles. On the other hand, the formation of expectations can be informed by (implicit) knowledge of music-syntactic structures stored in long-term memory (see Koelsch, 2012, for a more detailed discussion of different levels of music processing). It remains to be investigated whether the different levels of cognitive processing involved in the generation of expectancies are associated with tension experiences that are qualitatively different from each other.

4.3.1 Empirical research

Various experimental studies have tapped into the subjective experience of tension. Most research investigating musical tension employs continuous self-report methods (Schubert, 2010) to measure the subjective experience of tension. In studies using continuous self-report methods, the tension experience of participants is tracked online during the actual listening experience. In the first empirical study of musical tension, for example, Nielsen (1983, cited in Krumhansl, 1996) used a set of spring-loaded tongs that participants pressed together according to their degree of experienced tension while listening to excerpts from Joseph Haydn's *Symphony No. 104* and Richard Strauss' *Also sprach Zarathustra*. The deflection of the tongs was recorded and put into relation to different structural features of the music (see below). The tension profiles obtained by Nielsen were replicated by Madsen and Fredrickson (1993) using the so-called continuous response digital interface (CRDI), a potentiometer that records dial-movements of participants while they listen to a piece of music. An alternative method for acquiring tension ratings is to play music to participants until a certain event of interest is reached, then stop the music and ask participant to rate how much tension they experienced or how conclusive the last musical event felt to them (e.g., Bigand et al., 1996; Bigand & Parncutt, 1999; Lerdahl & Krumhansl, 2007). Other studies use sliders depicted on a screen that can be adjusted with the computer mouse depending on the degree of experienced tension (e.g., Farbood, 2012; Krumhansl, 1996; see also Chapters 2 and 3). In a web-based survey by Farbood (2012), tension of short musical excerpts was rated by selecting graphical representations that best corresponded to short music excerpt (e.g., an upward-rising line symbolizing an increase in tension). Note that when acquiring subjective tension ratings (and emotion ratings in general) one has to distinguish between the tension that is subjectively experienced by participants (*felt* musical tension) and the tension that participants think that the music expresses (*perceived* musical tension). This distinction is important because felt and perceived emotion in music do not necessarily coincide (Gabrielsson, 2002).

Musical expectancies have been studied using *priming paradigms* and the *probe tone technique*. In priming experiments, participants are presented with a musical event (the prime) that is followed by a target event. When the target is expected, it is processed faster than when it is unexpected. By having participants perform a simple decision task (e.g., deciding whether the target is in- or out-of-tune), response times can be recorded indicating how expected a specific musical event is in relation to a preceding prime (see, for example, Bharucha & Stoeckig, 1986). In probe tone paradigms, a musical context is played to participants that is followed by a tone, for which participants have to judge how well it fits the preceding musical context. Using this procedure, it is possible to construct a "tonal hierarchy" that ranks different pitches according to their perceived stability in a given context (see Krumhansl & Shepard, 1979; Krumhansl & Kessler, 1982). For example, notes of a musical scale are perceived as more or less stable, with the first note of the scale (the tonic) usually being experienced as most stable.

Experimental studies also investigated how different musical features influence the subjective experience of tension. The previously mentioned study by Nielsen (1983) found dynamics, tonal aspects (melodic contour and harmony), timbral features, and repetition to influence ratings of musical tension. Other features that were found to affect tension ratings are phrase structure, note density (Krumhansl, 1996), pitch height, loudness, onset frequency, and tempo (Farbood, 2012). Discarding expressive features of the music (i.e., dynamics and agogics) appears to preserve the overall tension-resolution patterns of a musical piece (Krumhansl, 1996; see also Chapter 2 of this dissertation), however, expressive features can enhance the experience of tension, and the contribution of different musical features depends on their relative importance in the specific musical piece (Farbood, 2012; see also Chapter 2). Moreover, tension ratings correlate highly within individuals over different exposures (Krumhansl, 1996) as well as between different groups of persons such as musicians and non-musicians or school children of different ages (Fredrickson, 1997, 1999, 2000), suggesting relatively consistent and stable underlying cognitive and affective processes. Tension ratings also have been found to correlate with ratings of discrete emotions (happiness, sadness, and fear) and psychophysiological measures such as finger pulse amplitude, respiration rate, blood pressure, skin conductance, and temperature (Krumhansl, 1997), thus supporting its role in affective processing.

Musical tension has been modeled based on the tonal structure of a musical piece (Lerdahl, 1996; Lerdahl & Krumhansl, 2007). In these models, tension is estimated by calculating the psychological "distance" between chords of a musical piece (chords that are "further away" from the tonal center of a piece are associated with higher tension values) based on the theory of tonal pitch space (Lerdahl, 2004) and the hierarchical syntactic structure as described by Lerdahl & Jackendoff (1983). A more recent model of musical tension (Farbood, 2012) includes other musical parameters such as loudness, melodic expectation, onset frequency, and pitch height, and also accounts for dynamic cognitive processes (memory and attention) that affect the experience of tension.

Altogether, the empirical studies of musical tension indicate that a plethora of features affects the experience of tension, ranging from purely acoustic features such as sensory dissonance or loudness to aspects that require more complex cognitive processing (e.g., the processing of musical syntax). To gain a better understanding of musical tension, future research may profit from a closer investigation of the underlying mechanisms by which different musical features create tension. In particular, it may be useful to investigate to what extent the influence of different features on musical tension can be accounted for by the processes of expectation and prediction discussed above, and to what degree other mechanisms (e.g., sensory dissonance) play a role.

4.3.2 Musical tension and emotion

How do the tension-resolution patterns of a musical piece relate to the listener's subjective emotional experience? First, emotional qualities of musical events mediating tension and resolution experiences may partly depend on their specific psycho-acoustic properties. For example, musical chords conveying tension are often more dissonant than chords associated with resolution (regardless of the musical context). The experience of dissonance is, at least partly, determined by the sensory processing of sound in the ear: Chords perceived as dissonant often feature frequencies that are close together causing interferences between the auditory sensory receptors of the basilar membrane in the inner ear, which are perceptually experienced as roughness (Helmholtz, 1877). Due to this roughness, chords associated with tension may thus intrinsically be experienced as more unpleasant than consonant chords.[1]

Apart from the intrinsic emotional quality of isolated musical events, expectation processes again play a key role in inducing emotional experiences related to tension and resolution during music listening. Previously, we referred to the works by Meyer (1956) and Huron (2006) who proposed expectation processes as the driving force behind music-evoked emotions. Likewise, Juslin and Västfjäll (2008) identify musical expectancy as one of six mechanisms by which music can induce emotions (the other five are brain stem reflexes, evaluative conditioning, emotional contagion, visual imagery, and episodic memory). The power of expectation processes as a mediator of music-evoked emotions is further corroborated by empirical research on so-called chill experiences during music listening. Chills (also referred to as thrills, shivers, or frisson) are intensely pleasurable responses to

[1] In addition to sensory processes, the experience of dissonance is also influenced by listening habits and can change over time. For example, some chords that may have been regarded as relatively dissonant a century ago, are nowadays perceived as more consonant (e.g., major seventh chords).

music that are often associated with specific physical sensations such as shivers down the spine or goose bumps (for an overview see Panksepp, 1995). Sloboda (1991) found that these chill experiences are often evoked by new or unexpected harmonies, thus supporting the close connection between expectancy violations and emotional responses.

4.3.3 Underlying brain mechanisms

The advent of modern neuroimaging methods, in particular functional magnetic resonance imaging (fMRI), has opened new avenues for investigating brain processes related to aesthetic experience by providing a non-invasive method for studying cognitive and affective processes in the human brain. Although neuroscientific research that directly investigates the neural correlates of tension-resolution patterns is scarce, various studies investigating expectancy violations in music, as well as studies investigating chill experiences point to brain areas relevant for mediating feelings of tension. Furthermore, there is evidence that the pleasure derived from music listening is driven by neural mechanisms of prediction and expectation associated with dopaminergic neuronal activity in the midbrain.

A large body of research has investigated predictive processing in music (reviewed in Rohrmeier & Koelsch, 2012), and neuroscientific studies have begun to identify underlying brain mechanisms. In particular, cognitive processing of expectancy violations in music appears to be associated with specific signatures in the electroencephalogram (EEG). These signatures differ with regard to the level of cognitive processing involved. At a relatively low level of cognitive processing, for example, occasional deviants in a sequence of tones give rise to the so-called mismatch negativity (MMN), a characteristic negativity of event-related scalp potentials (ERPs) peaking around 150-250 ms after the deviating event (for a review, see Näätänen et al., 2007). On a higher level of music-syntactic processing, expectancy violations in short chord sequences manifest in an "Early Right Anterior Negativity" (ERAN), which peaks around 150-200 ms after an unexpected chord function (Koelsch et al., 2000). In a study using magnetoencephalography (MEG), the neural source of this brain potential was localized in the inferior frontal gyrus (IFG, Brodmann area 44; Maess et al., 2001). This finding has been corroborated by subsequent fMRI studies (e.g., Koelsch et al., 2005, Tillmann et al., 2006), indicating a functional role of the IFG in music-syntactic processing. Importantly, however, apart from activating cortical areas involved in syntactic processing, expectancy violations have also been found to activate areas related to emotive processing in the orbitofrontal cortex (Koelsch et al., 2005; Tillmann et al., 2006), as well as the amygdala (Koelsch et al., 2008a). The amygdala activations in response to irregular musical events are consistent with the observation that expectancy violations in music also evoke autonomic responses such as increases in electrodermal activity (Koelsch et al., 2008b; Steinbeis et al., 2006), which are mediated by the central nucleus of the amygdala (LeDoux, 2000).

A recent fMRI study of our own group (see Chapter 3) investigated neural correlates of musical tension more directly by relating fMRI data to behavioral tension ratings of four piano pieces by Mendelssohn, Mozart, Schubert, and Tchaikovsky. It was found that tension (as rated by the participants) was related to signal increases in the orbitofrontal cortex (Brodmann area 47) and the amygdala (consistent with the fMRI studies mentioned above; Koelsch et al., 2005; Tillmann et al., 2006; Koelsch et al., 2008a).

There are also hints that certain brain areas are related to the different stages of the tension-arc proposed by Koelsch (2012). Studying neural correlates of chill responses, Salimpoor et al. (2011) found that the anticipation of a chill response and the actual chill response itself were related to different brain areas. Whereas actual chill responses were related to neuronal activity in the ventral striatum, presumably the nucleus accumbens (a structure involved in reward processing), the anticipation of chill responses activated more dorsal parts of the striatum. Activations in the same compartment of the dorsal striatum were also evoked by unexpected chords in short chord sequences (Koelsch et al., 2008a). Assuming that irregular chords evoke an anticipation for resolution and that the resolution is experienced as pleasurable, it appears that two distinct stages of the aesthetic trajectory, *anticipation* and *resolution*, map to specific brain areas in the striatum. However, to disentangle the brain mechanisms underlying the different phases of the aesthetic trajectory, in particular the different stages of the tension-arc proposed by Koelsch (2012), further research is required.

In previous sections we mentioned that the predictive processes related to experiences of tension and resolution constitute a fundamental aspect of human cognition and brain functioning. In this regard, the theory of predictive coding (Friston, 2010) is especially relevant. This theory has been proposed as a unified brain theory, according to which action, perception, and learning can be accounted for by a basic principle: the minimization of prediction errors (i.e., the minimization of surprise). Considering the role of predictive processes in tension-resolution phenomena, it seems likely that their appeal and emotional power, at least partly, derive from the fact that they tap into this basic principle of brain functioning. For music, the close relation between the predictive coding theory and music-evoked emotions has been put forward in a recent article by Gebauer et al. (2012), suggesting that the fulfillment or violation of musical expectancies is associated with activity of the brain's dopaminergic reward system. According to this view, musical expectancies activate dopaminergic neurons in the midbrain, coding information about a listener's expectations concerning upcoming musical events. If these expectations are violated, a prediction error ensues that is associated with emotional experiences. Although the exact neuronal mechanisms by which prediction processes trigger affective responses during music processing remain largely unclear, the theory of predictive coding provides a promising framework, from which new insights into the neural mechanisms underlying music-evoked emotions and affective experience in general can be expected.

4.4 Summary

Tension-resolution patterns are an important artistic device that drives emotional experience in a variety of different art forms (especially in temporal art forms such as music, film, or literature). In this chapter, we discussed general psychological mechanisms underlying tension and resolution phenomena. In particular, we argued that experiences of tension build on processes of expectation and anticipation as well as a general urge to resolve uncertainty, dissonance and instability and strive towards a stable state of equilibrium. We discussed emotional aspects of tension and resolution phenomena and highlighted their important role in the aesthetic experience of art and their relation to different stages of an "aesthetic trajectory". The special case of musical tension was considered in more detail, giving an overview of empirical research that has identified various features mediating experiences of tension and resolution. Finally, we discussed neuroimaging research that has identified limbic and paralimbic structures of the brain related to expectancy violations and "chill" experiences (and their anticipation), thus pointing to possible neural correlates of tension and resolution experiences.

5 On first looking into Hoffmann's “The Sandman”: Neural correlates of suspense during the first reading of a literary text[1]

Abstract

Stories are omnipresent in human culture; they can elicit powerful emotions. A key emotion evoked by narrative plots (e.g., novels, movies, etc.) is suspense. Suspense appears to build on basic aspects of human cognition such as prediction and theory-of-mind processing; however, the neural processes underlying emotional experiences of suspense have not been previously investigated. We acquired functional magnetic resonance imaging (fMRI) data while participants read a suspenseful literary text (E.T.A. Hoffmann's “The Sandman”) subdivided into short text passages. Individual ratings of experienced suspense obtained after each text passage were found to be related to activation in the medial frontal cortex, bilateral frontal regions (along the inferior frontal sulcus), lateral premotor cortex, as well as posterior temporal and temporo-parietal areas. The results indicate that the emotional experience of suspense depends on brain areas associated with mentalizing and predictive inference.

[1] This chapter is currently under review at *Brain & Language* as Lehne, M., Engel, P., Menninghaus, W., Jacobs, A. M., & Koelsch, S., On first looking into Hoffmann's “The Sandman”: Neural correlates of suspense during the first reading of a literary text.

"I could a tale unfold whose lightest word
Would harrow up thy soul, freeze thy young blood,
Make thy two eyes, like stars, start from their spheres,
Thy knotted and combined locks to part
And each particular hair to stand on end,
Like quills upon the fretful porpentine."

— William Shakespeare, *Hamlet*, Act I, scene 5, line 15.

5.1 Introduction

Spoken or written words can evoke powerful emotions. A prime example of this are stories. For millennia, generations of humans around the world have been moved, fascinated and entertained by stories, and oral traditions of storytelling may be as old as human language itself. Stories—factual or fictional—are omnipresent in human culture: Apart from their artfully refined role in literature (e.g., in novels, short stories, and many forms of poetry and drama), stories are told in a variety of other contexts, and the appeal of movies, songs, speeches, jokes, newspaper articles—and perhaps even scientific papers—often depends on their capacity "to tell a good story". The human ability to understand, tell, and enjoy stories involves a multitude of cognitive and affective mechanisms including perception, attention, memory, reasoning, simulation of actions, emotion, and, naturally, language. Investigating story processing with modern neuroimaging methods can therefore provide insights into the neural signature of these mechanisms.

Various neuroimaging studies have begun to tap into the brain mechanisms associated with story processing (for meta-analyses of story and text comprehension studies see Ferstl et al., 2008; Mar et al., 2011). Most of these studies have focused on cognitive aspects of story processing, investigating, for example, neural activations in response to coherent narratives as opposed to unrelated sentences or words (Ferstl & von Cramon, 2001; Hasson et al., 2007; Mazoyer et al., 1993; Xu et al., 2005; Yarkoni et al., 2008), comparing neural responses to written and auditory text presentations (Lindenberg & Scheef, 2007), or probing memory encoding during story processing (Hasson et al., 2007).

Neuroscientific research on emotional responses to stories, however, is scarce, and only a few studies have specifically investigated the neuroaffective processes underlying story processing. An fMRI study by Wallentin et al. (2012) found that the emotional intensity experienced during auditory presentation of a story correlates with heart rate variability, activation of temporal cortices, the thalamus, as well as the amygdala, and that passages associated with positive valence are related to orbitofrontal cortex activations. Investigating emotional valence for short narratives, Altmann et al. (2012) showed that negative story valence is associated with increased activation of theory-of-mind-related brain regions (such as the medial frontal cortex and the temporo-parietal junction). These studies provide first evidence that investigating emotions evoked by narrative plots can offer new insights into neuroaffective brain processes.

One component of emotional experience that is particularly relevant to story processing is suspense. Suspense plays an important role in many forms of media entertainment (e.g., film, television, literature, or music) and accordingly has been discussed by scholars from different disciplines such as literary science, film studies, or media psychology (for introductions, see Brewer & Lichtenstein, 1982; Carroll, 1996b; Fill, 2007; Löker, 1976; Vorderer et al., 1996; Zillmann, 1980). Creating “the force that draws us through a narrative” (Rabkin, 1973), suspense is the predominant emotion in many types of literary genres (e.g., thrillers, detective stories, spy novels, etc.), and the broad popularity of these genres illustrates the power of suspense to attract audiences and excite emotional responses. Suspense in narrative plots is closely intertwined with processes of prediction and anticipation which are triggered by explicit or implicit questions in the minds of the audience (Carroll, 1996b), and which arise from the uncertainty of the outcome of events of the plot (cf. Comisky & Bryant, 1982; Gerrig & Bernardo, 1994). The plots of suspenseful novels or movies, for example, often involve conflicts and obstacles that the protagonists have to overcome, making the audience ponder over possible solutions to these conflicts and anticipate their eventual resolution. Predictive inferences during story processing have been found to be related to activation in inferior frontal and posterior temporal regions (Chow et al., 2008; Jin et al., 2009; Virtue et al., 2008), and more generally, action and event prediction have been proposed to be supported by motor-related regions of the brain, in particular the lateral premotor cortex (Schubotz, 2007). Apart from adding to research on affective mechanisms involved in story processing, investigating neural responses to suspenseful narrative plots thus also promises insights into the brain structures associated with predictive inference.

Moreover[1], suspense is closely related to processes of immersion, transportation, or absorption in media reception, such as reading (Appel & Richter, 2010) or computer games (Jennett et al., 2008), which can be explained by the neurocognitive poetics model of literary reading (Jacobs, 2011; 2014; see Jacobs, 2013, for a sketch of the model). At the text level, a suspense discourse organization involves an initiating event or situation, i.e., an event which potentially leads to significant consequences (either good or bad) for one of the characters in the narrative. The structural-affect theory of stories by Brewer and Lichtenstein (1982) states that the event structure must also contain the outcome of the initiating event, allowing to resolve the reader's suspense. According to the model by Jacobs, the core affect systems "FEAR", "ANGER", or "CARE" described in Panksepp's emotion theory (1998) are likely to be involved in this suspense building process, e.g., when a reader experiences suspense through vicarious fear, because a protagonist is in danger (especially when this danger is only

[1] The following two paragraphs were primarily written by Arthur M. Jacobs.

known to the reader), which is mediated by processes of empathy and sympathy. The study by Altmann et al. (2012) supports this assumption, indicating that short narratives with negative content induce more affective empathy with the described characters in readers than neutral stories, as evidenced by increased brain activity in theory-of-mind and empathy-related areas (i.e., the medial frontal cortex, superior temporal sulcus, and temporo-parietal junction).

Although suspense can be measured at both the subjective (through questionnaires) and more objective behavioral and physiological levels, such as facial expressions, heart rate, or skin temperature (Zillmann et al., 1975), at present, there are no neuroimaging results speaking directly to the issue of suspense in literary reading contexts.

In the current study, we investigated the neural correlates of suspense experienced by readers during their first reading of a literary text. For this, we acquired fMRI data while participants read a coherent story (E.T.A. Hoffmann's “The Sandman”) subdivided into short text segments. After each segment, participants rated the level of suspense they had experienced while reading the segment. We then identified brain areas in which activation was related to the level of subjectively experienced suspense. Due to the dearth of previous research on neural correlates of subjectively experienced suspense, it was difficult to make specific predictions about brain regions involved in the experience of suspense. However, we were particularly interested in neuroaffective responses to suspenseful text segments. Previous fMRI research from the music domain has found ratings of musical tension—the musical equivalent of narrative suspense (cf. Chapters 4 and 6)—to be associated with activity changes in the lateral orbitofrontal cortex and the amygdala (see Chapter 3), and the violation, anticipation, and fulfillment of musical expectancies that mediate feelings of tension have been associated with amygdala (Koelsch et al., 2008) as well as dorsal and ventral striatum activations (Salimpoor et al., 2011). We expected suspense to be related to increased activity in similar brain structures associated with affective processing. In addition, based on the results reported by Altmann et al. (2012, see above), we explored whether suspense is related to activation in areas associated with theory-of-mind processing and mentalizing, i.e. the medial frontal cortex and the temporo-parietal junction (Amodio & Frith, 2006; Li et al., 2014; Saxe & Kanwisher, 2003; Van Overwalle, 2009). Furthermore, based on the connection between suspense and predictive processes discussed above, we expected suspense to correlate with activation in brain areas associated with prediction (e.g., lateral premotor regions).

5.2 Methods

5.2.1 Participants

Right-handed German native speakers who were unfamiliar with the story and who enjoyed reading literature (according to self-reports) were recruited as participants for the experiment. Data from 23 participants (12 female, age range: 19 – 32 years, $M = 24.1$, $SD = 3.9$) were included in the analysis. Data from five additional participants were excluded because they did not finish reading within scanning time (four participants) or answered fewer than two of five control questions that were asked after the experiment correctly (one participant). All participants gave written consent and were compensated with 15 euros or course credit. The study was approved by the ethics committee of the Department for Educational Sciences and Psychology of the Freie Universität Berlin.

5.2.2 Stimuli

The story “Der Sandmann” (“The Sandman”) by E.T.A. Hoffmann was used as stimulus material. A prominent example of the German Romanticist narratives devoted to the darker sides of emotional life, the story relates events in the life of the student Nathaniel who—traumatized by the early death of his father—is haunted since childhood by the mysterious Sandman. The story was chosen because of its suspenseful character and uncanny atmosphere (famously discussed in Sigmund Freud's essay ”The Uncanny”; Freud, 1919). Importantly, the story features text passages inducing high as well as low suspense (as determined in a preceding pilot rating study), thus ensuring sufficient variability in the suspense ratings to use them as parametric regressor in the fMRI data analysis (see Section 5.2.5). The story was presented in German. To make it suitable for the experiment, the text was shortened (from 12,232 to 6,859 words) and some words that are now out of use and hence unfamiliar were replaced by more common ones to guarantee that participants comprehended the text. Special care was taken to ensure that the shortening of the text did not modify the plot or make the story less intelligible. For the presentation in the MRI scanner, the story was partitioned into 65 segments of approximately equal length ($M = 105.5$ words per segment; $SD = 26.1$ words). Segmentation was done in such a way that the level of suspense remained relatively constant within one text segment.

5.2.3 Experimental procedure

Participants read the story, segment by segment, while functional imaging data were recorded. The text was presented on a screen above participants' head via a magnet-compatible projection mirror system (the text was shown in a black font against a gray background). To make the reading experience as natural as possible, reading time was self-paced, i.e., participants decided how long each text segment was presented by pressing a button whenever they wanted to proceed (however, to avoid fatigue, scanning was stopped after a maximum of 60 minutes, and four participants who had not finished reading within this time were excluded from the analysis). After each text segment, participants rated how much suspense they had experienced during the preceding segment on a 10-point scale (ranging from “not suspenseful” to “very suspenseful”) using two buttons of an MRI-compatible response box (at the initial presentation of each rating screen, a random rating value was selected that had to be adjusted according to the experienced suspense using the two buttons). Using a third button, participants confirmed the rating and proceeded to the next text segment (the same button was used to proceed from the text segment to the rating; see Figure 5.1).

Participants were explicitly instructed to rate the suspense they subjectively experienced (not the suspense they thought the segment was supposed to evoke). To become familiar with the experimental task, participants completed a short practice trial (with a different text) before the actual experiment. Due to the self-paced reading times, the scanning duration varied between 28:05 and 53:52 min across participants (*M* = 42:55 min; *SD* = 7:33 min).

To assess whether participants had read the text attentively, five multiple-choice control questions were asked after the experiment (in order not to influence the natural reading process, participants were not informed about this before the experiment). We also assessed participants' general reading habits (e.g., how many books they usually read per year, and what type of literature genres).

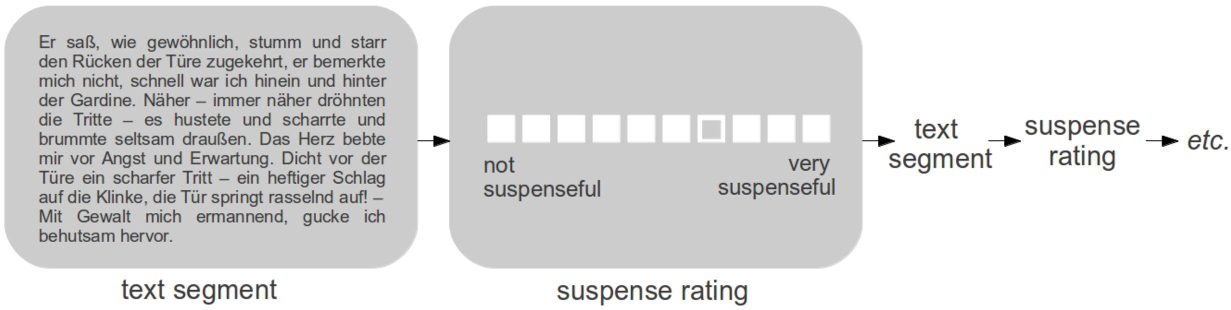

Figure 5.1. One trial of the experiment: A segment of the text was presented, followed by a rating screen on which the suspense experienced while reading the text segment was selected on a 10-point scale using two buttons (for moving the selected point on the rating scale to the left or right). Timing was self-paced, i.e., participants pressed a button in order to proceed to the next text segment / rating screen. A total of 65 text segments was presented during the experiment.

5.2.4 Image acquisition

MRI data were acquired at the Dahlem Institute for Neuroimaging of Emotion at the Freie Universität Berlin using a 3 Tesla Siemens Magnetom TrioTim MRI scanner (Siemens

AG, Erlangen, Germany). Before functional scanning, a high-resolution (1x1x1 mm) T1-weighted anatomical reference image was obtained using a rapid acquisition gradient echo (MP-RAGE) sequence. For the acquisition of functional data, a continuous echo planar imaging (EPI) sequence was used (37 slices; slice thickness: 3 mm; interslice gap: 0.6 mm; echo time: 30 ms; repetition time: 2 s; flip angle: 70°; 64x64 voxel matrix; field of view: 192x192 mm) with slice acquisition interleaved within the TR interval. To reduce susceptibility-induced image distortions and signal losses in areas such as the orbitofrontal cortex and the temporal lobes, the acquisition window was tilted at an angle of 30° to the intercommissural (AC-PC) line (Deichmann et al., 2003; Weiskopf et al., 2007).

5.2.5 Image processing and statistical analysis

Data were analyzed using Matlab (MathWorks, Natick, USA) and SPM8 (Wellcome Trust Centre for Neuroimaging, London, UK). Before statistical analysis, functional images were realigned using a 6-parameter rigid body transformation, co-registered to the anatomical reference image, normalized to standard Montreal Neurological Institute (MNI) stereotaxic space using a 12-parameter affine transformation, and spatially smoothed with a Gaussian kernel of 6 mm full-width at half-maximum. Low-frequency noise and signal drifts were removed using a high-pass filter with a cut-off frequency of 1/256 Hz. Serial correlations between scans were accounted for using an autoregressive AR(1) model.

A standard general linear model (GLM) approach was used for statistical analysis. Potential confounding factors were added as control variables to the model. The control variables included were “action”, “imageability”, arousal, valence, and average sentence length of each text segment. To determine the amount of action described in the text segments we acquired additional ratings from a different group of participants (N = 20, 13 female, age range: 20–33 years, M = 23.5, SD = 3.8) asking how eventful each segment was experienced during reading (ratings were given on a 7-point scale). The Berlin Affective Word List

(BAWL-R; Võ et al., 2009) was used to estimate imageability, arousal, and valence based on values of single words which were then averaged over all words from one text segment. Average sentence length (in words) of each text segment was added to control effects of working memory during reading of the text, assuming that longer sentences generally impose higher demands on working memory. Thus, the model included the following regressors: reading periods were modeled as block regressor; control variables (action, imageability, arousal, valence, and average sentence length) and individual suspense ratings were modeled as a parametric modulator (Büchel et al., 1998; Wood et al., 2008) of the reading periods (suspense ratings were orthogonalized to the control variables); rating periods were modeled as block regressor; estimates of the motion correction parameters obtained during the realignment were added as regressors of no interest. Model parameters were estimated using the restricted maximum likelihood approach implemented in SPM8. After model estimation, whole-brain statistical parametric maps (SPMs) were calculated for the contrasts *reading* > *rating* and the parametric regressor *suspense* (and its inverse *–suspense*). To obtain group level results, the contrast images of individual participants were entered into a second-level random effects analysis. Activations with a p-value smaller than .05 corrected for family-wise errors (FWE) at the cluster level (with a cluster-forming threshold of $p < .005$) were considered significant (FWE-corrected cluster extent threshold: 210 voxels).

5.3 Results

5.3.1 Behavioral data

Figure 5.2 shows average suspense ratings for the story. Pearson's product-moment correlation coefficients between individual suspense profiles, averaged over all possible pairs of participants, revealed a moderate inter-participant agreement ($r = .31$, $p < .05$; because Pearson's correlation coefficients are not additive, a Fisher z-transformation was applied before averaging over correlation coefficients and the resulting z-value was then converted back into a correlation coefficient). Average reading time for one text segment was 29.98 s (*SD* = 12.04 s). No correlation between reading speed and suspense ratings (averaged over participants) was observed ($r = .08$, $p = .55$). Moreover, suspense ratings did not correlate with the lengths of the text segments ($r = –.04$, $p = .74$).

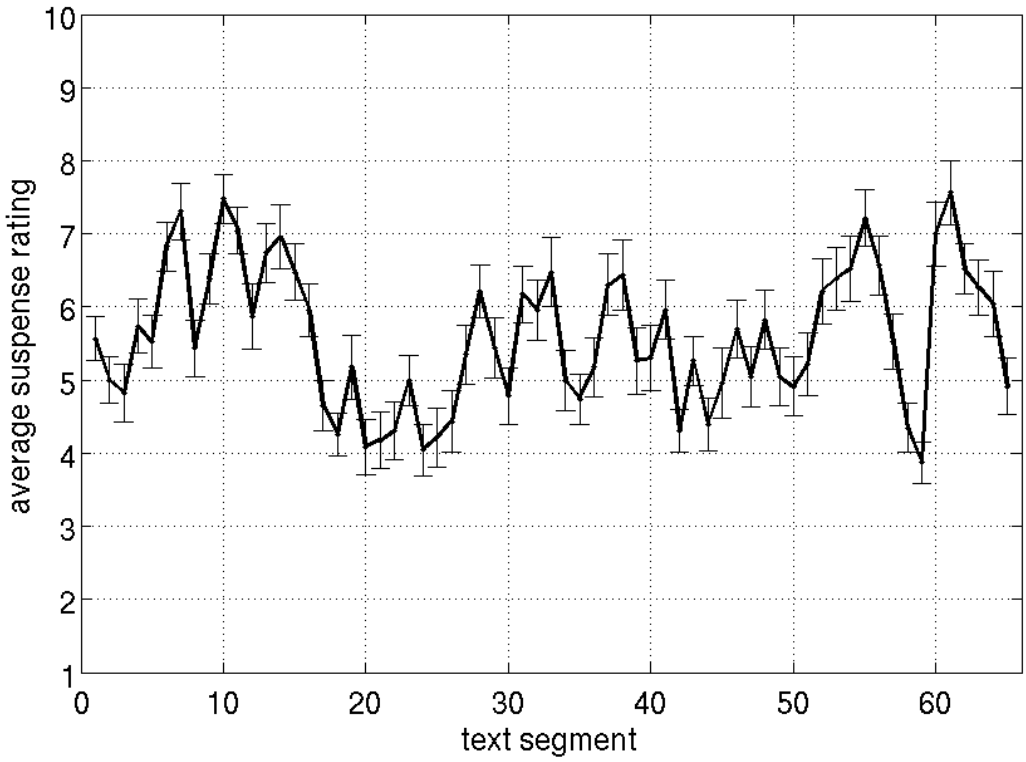

Figure 5.2. Average suspense ratings ($N = 23$) and standard errors for each segment of the text.

5.3.2 Functional MRI data

Comparing reading periods with rating periods (*reading* > *rating*, Figure 5.3A) revealed bilateral activations in visual cortices, the entire superior temporal sulcus (with left hemispheric dominance), and anterior hippocampus (cornu ammonis). Moreover, left-hemispheric activations were observed in the precentral gyrus and fusiform gyrus.

The suspense regressor (reflecting participants' individual experience of suspense) showed a medial frontal activation cluster, as well as, in each hemisphere, a lateral frontal and a posterior temporal cluster of activation (Figure 5.3B). More specifically, the lateral frontal activation clusters extended anteriorly along the IFS into the inferior frontal gyrus (IFG), and posterior-superiorly into the precentral sulcus and precentral gyrus (lateral premotor cortex). The temporal clusters covered the posterior part of the superior temporal sulcus (STS), extending into the temporo-parietal junction (TPJ). These temporal and temporo-parietal activations were more pronounced in the left than in the right hemisphere. No negative correlations with suspense were observed, and none of the analyses showed activity changes in the amygdala, nor the orbitofrontal cortex. For a complete list of activations see Table 5.1.

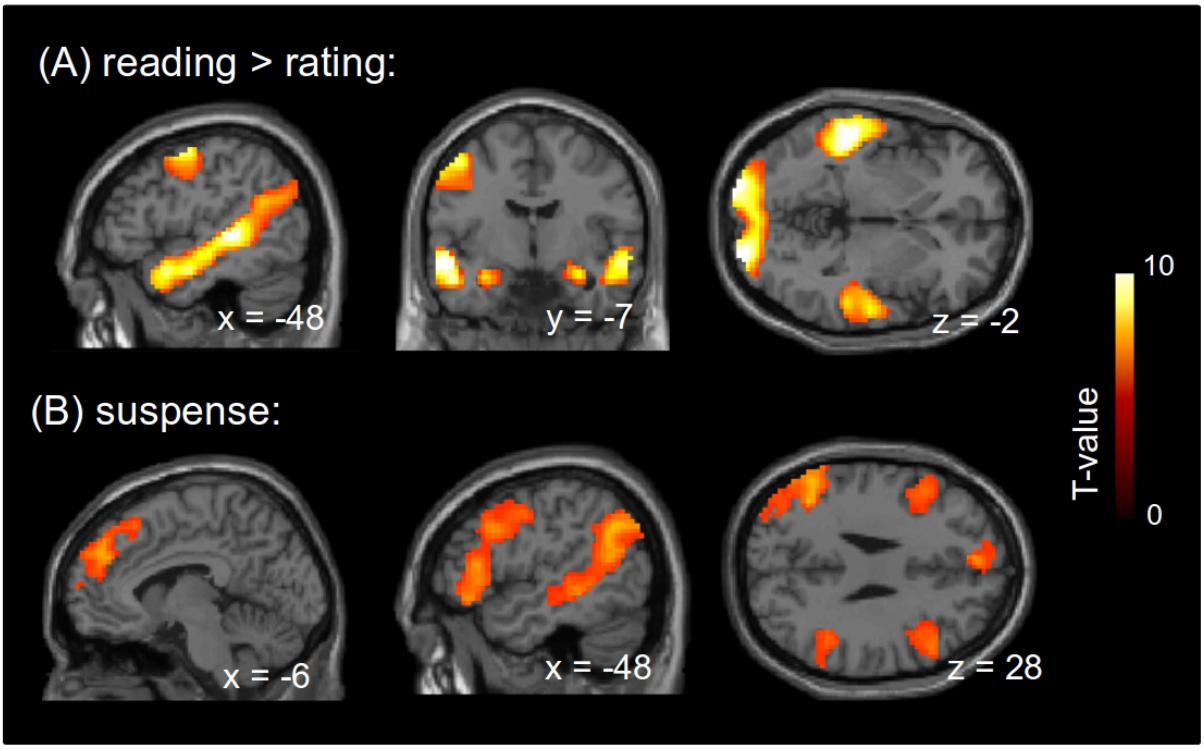

Figure 5.3. Statistical parametric maps ($p < .05$, cluster-level FWE-corrected, shown in neurological convention) for (A) the contrast *reading* > *rating* and (B) the parametric *suspense* regressor capturing participants' experience of suspense during reading.

Table 5.1. GLM analysis: anatomical locations, peak MNI coordinates, T-values, and cluster sizes (number of voxels) of significant clusters for the *reading* > *rating* contrast and the parametric *suspense* regressor (p < .05, cluster-level FWE-corrected; indented regions are part of one continuous cluster). CA: cornu ammonis; FFG: fusiform gyrus; IFS: inferior frontal sulcus; MTG: middle temporal gyrus; MFC: medial frontal cortex; PMC: premotor cortex; STS: superior temporal sulcus; TPJ: temporo-parietal junction.

anatomical location	hemisphere	X (mm)	Y (mm)	Z (mm)	T-value	cluster size
reading > rating						
visual cortex	R & L	27	-97	-5	13.20	2417
superior temporal sulcus	L	-54	-10	-8	12.19	
hippocampus (CA)	L	-30	-13	-17	9.95	
FFG	L	-42	-46	-17	5.58	
superior temporal sulcus	R	57	-10	-11	10.02	648
hippocampus (CA)	R	30	-10	-17	7.69	
precentral gyrus (PMC)	L	-45	-4	52	8.05	288
suspense						
TPJ	L	-45	-58	31	5.73	1123
posterior STS	L	-48	-34	-8	4.52	
IFS	R	45	20	22	5.43	627
precentral gyrus (PMC)	R	45	-1	52	5.38	
IFG (pars orbitalis)	R	45	32	-5	3.57	
MFC	L	-6	50	34	5.22	371
IFG	L	-45	35	-8	5.20	717
IFS	L	-48	17	31	4.70	
precentral gyrus (PMC)	L	-42	-1	43	4.81	
posterior STS	R	54	-28	-11	4.09	297
TPJ	R	45	-46	31	3.88	

5.3.3 Psychophysiological interactions (PPI)

To investigate whether there is a relationship between suspense ratings and the functional connectivity patterns of brain areas associated with suspense, we also performed a *post hoc* PPI analysis (Friston et al., 1997). For this, we used the upper and lower quartiles of individual suspense ratings to dichotomize suspense ratings into high and low values which were used to test the interaction of suspense with the functional connectivity of voxels around the maxima of the five activation clusters reported above (i.e., left TPJ, right IFS, MFC, left IFG, and right posterior STS; for exact locations, see peak MNI coordinates in Table 5.1). The contrast high vs. low suspense was multiplied with the eigenvariate of the voxels within a sphere with the radius 3 mm around the peak activation voxel of each cluster to obtain the interaction term. We expected psychophysiological interactions of the regions related to suspense with limbic/paralimbic regions implicated in emotion (such as the amygdala and the orbitofrontal cortex, see Introduction). However, for the MFC seed region, the only significant cluster encompassed cerebellar and occipital visual areas. Moreover, suspense significantly modulated the functional connectivity between the left IFG and cerebellar and occipital regions, as well as the posterior inferior temporal gyrus and premotor cortex (see Table 5.2). For the other seed regions (left TPJ, right IFS, and right posterior STS), the PPI analysis did not yield significant results.

Table 5.2. PPI analysis: anatomical locations, peak MNI coordinates, T-values, and cluster sizes (number of voxels) of brain areas in which suspense (high vs. low) significantly modulated the functional connectivity to the seed region (*p* < .05, cluster-level FWE-corrected; indented regions are part of one continuous cluster). IFG: inferior frontal gyrus; ITG: inferior temporal gyrus; MFC: medial frontal cortex; PMC: premotor cortex.

anatomical location	hemisphere	X (mm)	Y (mm)	Z (mm)	T-value	cluster size
seed area: left IFG (MNI coordinate: -45 35 -8)						
cerebellum	L	-6	-76	-14	6.12	832
visual cortex	L	-9	-82	-5	5.26	
visual cortex	R	9	-82	-8	4.80	
superior occipital gyrus	R	24	-85	31	4.54	423
posterior ITG	L	-51	-55	-8	4.53	577
precentral gyrus (PMC)	L	-36	-19	64	4.14	525
seed area: MFC (MNI coordinate: -6 50 34)						
cerebellum	L	-18	-73	-14	4.34	465
visual cortex	R	12	-76	-8	4.01	

5.4 Discussion

In the present study, we investigated the neural correlates of suspense evoked by a literary text. For this, we acquired functional imaging data while participants read a coherent story subdivided into short text passages. After each text passage, a rating of subjectively experienced suspense was obtained. Suspense ratings correlated with blood oxygen level-dependent (BOLD) signal intensity in the medial frontal cortex, bilateral frontal regions along the inferior frontal sulcus (extending into the inferior frontal gyrus and premotor cortex) as well as posterior temporal and temporo-parietal regions bilaterally.

Comparing reading periods with rating periods yielded activations in the left (and to a lesser degree right) superior temporal sulcus. Activation of these areas has previously been associated with semantic processing of written and spoken language in general (see Price, 2012, for an overview) and story processing in particular (Lindenberg & Scheef, 2007; Mazoyer et al., 1993). Reading also activated the left fusiform gyrus or what has been termed the "visual word form area" which has previously been ascribed a specialized role in the processing of written words (Cohen et al., 2002; Dehaene et al., 2002). As could be expected, reading of the story thus evoked typical brain activations of a left-lateralized language and reading network. Moreover, reading was associated with increased activation in visual cortices, possibly reflecting the higher visual input during reading periods compared with rating periods.

Suspense—as subjectively experienced by participants—was related to bilateral clusters of activation in the medial and dorsolateral prefrontal cortex, in particular the inferior frontal sulcus, the inferior frontal gyrus, and the precentral gyrus (lateral premotor cortex), as well as posterior temporal areas extending into the TPJ. Activations of posterior temporal regions, particularly the TPJ, have previously been related to social cognitive tasks such as perspective taking (Ruby & Decety, 2003) or theory-of-mind processing (Saxe & Kanwisher, 2003; Saxe & Wexler, 2005). A meta-analysis investigating neural correlates of social cognition associated the TPJ with the inference of other people's goals and actions (Van Overwalle, 2009), and TPJ activations have been repeatedly observed for story processing (e.g., Altmann et al., 2012; for a meta-analysis, see Mar, 2011). Likewise, the medial frontal cortex, which also showed activation related to suspense, has been discussed as a key area associated with social cognition and theory-of-mind (Amodio & Frith, 2006). For example, a study comparing theory-of-mind processing in cartoon tasks and story tasks found overlapping activity for both tasks in the medial frontal cortex (Gallagher et al., 2000), coinciding with the activation found in the present study. Similarly, a study by Steinbeis and Koelsch (2009) reports medial frontal cortex activation during episodes when participants believed they were listening to music written by a composer as opposed to computer-generated music, underlining the role of the MFC in theory-of-mind processing and mental state attribution. As hypothesized in the aforementioned neurocognitive poetics model of literary reading (Jacobs, 2011; 2014), activation of temporo-parietal and medial frontal areas could thus be due to readers adopting the perspective and inferring the mental states of the main characters of the story during emotionally engaging and suspenseful text segments. Suspenseful parts of a narrative plot (in particular the suspenseful text segments of the current experiment) often involve situations in which a main character of the story is facing situations of potential danger or threat. Following Zillmann's definition “that the experience of suspense in dramatic presentations derives characteristically from the respondent's acute, fearful apprehension about deplorable events that threaten liked protagonists” (Zillmann, 1980, p. 140), activation of the TPJ and MFC may reflect these fearful anticipations of upcoming events that depend on the ability to infer the mental states, goals, and actions of characters of the story. This is in line with connectivity studies indicating that the MFC (in particular its dorsal parts) and its connectivity with the TPJ are associated with the understanding of others' mental states (Li et al., 2014). Furthermore, suspense has been proposed to build on a disparity between the knowledge of a character and the knowledge of the reader or viewer (most notably discussed by Alfred Hitchcock in Truffaut, 1967; see also Bae & Young, 2009). This disparity of knowledge is often based on theory-of-mind processing (e.g., knowing that the characters don't know what one oneself knows) and could therefore account for the activation of theory-of-mind-related brain areas during suspenseful texts (however, for the text used in the present experiment, the disparity of knowledge between characters and readers appears to be less relevant for inducing suspense).

The posterior temporal activations associated with suspense (particularly the ones in the left hemisphere) also suggest that neural activity in lower-level language areas is influenced by suspense, as these areas have been associated with the cognitive processing of written words and texts, e.g., word recognition (Cohen et al., 2002; Dehaene et al., 2002; Wandell, 2011), acoustic-phonetic processing (Caplan et al., 1995), mapping of orthographic to phonological representations (Joubert et al., 2004), and the integration of semantic information (Binder et al., 2009). However, whether suspense directly modulates lower-level language areas or whether suspenseful text segments tend to covary with linguistic features that could influence neural activation in lower-level language areas remains to be investigated more closely (see Section 5.4.1).

In addition to the MFC and TPJ activations, suspense was associated with bilateral activations in inferior frontal regions extending into lateral premotor cortex in the precentral gyrus. The activation of premotor areas during the experience of suspense suggests a connection between suspense and neural processes of prediction and anticipation. As described previously, premotor cortex activations (particularly in ventrolateral parts) have consistently been reported for tasks involving action and event prediction (for reviews, see Schubotz, 2007; Schubotz & von Cramon, 2003), which is corroborated by studies showing that predictive processing of sequential information is impaired in patients with premotor lesions (Schubotz et al., 2004), and that ventrolateral premotor activations are associated with the processing of biological as well as abstract non-biological stimulus sequences (Schubotz & von Cramon, 2004). Our results point to a possible role of the premotor cortex in predictive processes concerning upcoming events in a suspenseful narrative plot, thus supporting the conjecture that the premotor cortex is involved in general aspects of event prediction (regardless of whether these predictions require motor control or planning; see Schubotz, 2007). Moreover, predictive inferences in the context of story processing have been associated with inferior frontal and posterior temporal activation: In a study by Jin et al. (2009), short “mini-stories” provoking predictive inferences (compared with non-predictive counterparts) were related to left IFG activations, and Virtue et al. (2008) found story passages that required active inferences (based on previous information given in the story) to be associated with activation in the right posterior STG and bilateral IFG. The inferior frontal and posterior temporal activations observed for suspense could therefore reflect predictive processes associated with inferences about the unfolding of events of the story. The involvement of predictive processes during suspenseful text segments could also provide an alternative explanation to the MFC and TPJ activations discussed above: Decety and Lamm (2007) argue that TPJ activations are not specific to theory-of-mind processing but reflect more domain-general mechanisms "involved in generating, testing, and correcting internal predictions about external sensory events" (Decety & Lamm, 2007, p. 583), and similarly, MFC activations have been implicated in predictive inferences during text comprehension (Chow et al., 2008; Ferstl & von Cramon, 2001; Friese et al., 2008; Siebörger et al., 2007).

The close link between suspense and prediction is particularly interesting in light of Bayesian accounts of brain functioning such as predictive coding and free energy (Friston & Kiebel, 2009; Friston, 2010). From the perspective of these theories—which postulate that perception, action, learning, and emotion (Joffily & Coricelli, 2013) are essentially based on the minimization of prediction errors, surprise, and uncertainty—suspense can be viewed as the emotional component reflecting this urge for uncertainty reduction. Novels, movies, television series and various other forms of media entertainment appear to take advantage of this fundamental principle of human cognition, thus accounting for their general appeal and popularity. However, apart from reflecting an urge for uncertainty reduction, suspense may involve other (neuro-)cognitive mechanisms. If the emotional experience of suspense only resulted from its association with uncertainty, it should primarily be experienced as negative (and only the resolution of suspense should have a positive valence). Yet, suspense—in particular in forms of media entertainment such as film, music, or literature—is often experienced as positive, and the emotional "thrill" associated with suspense experiences may be enjoyed for its own sake (especially when the context in which suspense is elicited is devoid of potentially negative real-life consequences, as in literature, film, or music; cf. Levinson, 1997; Hanich et al., 2014).

The bilateral activation clusters of the inferior frontal sulcus included the so-called inferior frontal junction (IFJ, cf. Amunts et al., 2010; Clos et al., 2013). Located at the intersection of premotor, language, and memory areas, activations in this area have previously been reported in experiments involving cognitive control, task switching, or updating processes (Brass et al., 2005; Braver, 2012; Derrfuss et al., 2005; Miller, 2000; Clos et al., 2013). For example, a meta-analysis by Derrfuss et al. (2005) reports activation of the IFJ in experimental paradigms requiring the updating of task representations (e.g., task-switching paradigms, Stroop tasks, or n-back tasks). With regard to language processing, left inferior frontal regions have been associated with semantic encoding (Demb et al., 1995; Fletcher et al., 2000), semantic working memory (Gabrieli et al., 1998), semantic retrieval (Noppeney et al., 2004; Wagner et al., 2001), or selection of information from semantic memory (Thompson-Schill et al., 1997). On a more speculative note, the frontal activation clusters observed for suspense may therefore reflect the recruitment of cognitive control structures during suspenseful text segments, i.e., during passages when the reader's interest about the unfolding of events of the story is highest. Being “captured” by the story during episodes of high suspense may lead to the engagement of top-down control mechanisms that rely on the IFJ and that may optimize semantic processing of the content of the story. This is in line with dynamic causal modeling (DCM) studies showing that IFG regions coordinate temporal and parietal regions associated with lower-level language processing (Bitan et al., 2005, 2006; Chow et al., 2008).

5.4.1 Limitations and outlook

We also had expected suspense to be related to neural activity in limbic brain structures associated with emotional processing such as the amygdala or the striatum. This hypothesis was not confirmed. One aspect of our experiment that may have compromised the evocation of emotional responses was that participants had to shortly interrupt reading after each text segment to give the suspense ratings, which may have disrupted the immersive reading experience usually associated with natural reading of suspenseful texts. We had deliberately opted for these online suspense ratings to capture the suspense experience of each individual participant as accurately as possible (alternative methods acquiring suspense ratings retrospectively after participants have read the complete text without interruption or using average suspense ratings of a different group of participants might have reflected individual suspense experiences during reading less accurately, thus decreasing the sensitivity of the statistical analysis). However, it remains to be investigated whether uninterrupted reading of a suspenseful text engages limbic brain structures associated with emotional processing. Using "stronger" stimulus material—such as, for example, thriller movies—to induce suspense experiences may further facilitate the measurement of neural substrates of emotional responses.

Moreover, it may be objected that lower-level stimulus features may have confounded the brain activations observed for suspense. We accounted for possible confounds by including action, imageability, arousal, valence, and average sentence length of each text segment as control variables in the model. However, when investigating a high-level concept like suspense in a relatively naturalistic setting using a real text, controlling all possible low-level stimulus properties is unfeasible, and the possibility that results are influenced by these stimulus features can never be entirely excluded. For example, the IFG activations observed for suspenseful text segments could also be interpreted as reflecting effects of syntactic processing (cf. Makuuchi et al., 2009). We did not include syntactic complexity as as control variable because there is no straightforward measure quantifying syntactic complexity in natural language texts. However, increased syntactic processing during suspenseful text segments seems unlikely because the relationship between syntactic complexity and suspense in the text of the present experiment is rather negative, i.e., suspenseful text segments tended to feature more simple sentences (often a concatenation of simple main clauses with few embedded sentences) than less suspenseful segments. Nevertheless, controlling as many confounding variables as possible in future neuroimaging studies on suspense is highly desirable.

Finally, we used only one text as experimental stimulus. Whether the results reported here generalize to other texts and domains (e.g., film) remains to be clarified by future research.

5.5 Conclusion

Suspense is an important component of the emotional experience evoked by narrative plots (e.g., in literature, film, etc.). To our knowledge, this is the first study exploring the neural correlates of suspense during the reading of a literary text. Recording functional imaging data while participants read a suspenseful piece of literature, we found that individual ratings of suspense were related to activity in the medial frontal cortex, posterior temporal and temporo-parietal regions, as well as the dorsolateral prefrontal cortex along the inferior frontal sulcus including the IFG and premotor cortex. Our results indicate that text passages that are experienced as suspenseful engage brain areas associated with mentalizing, predictive inference, and possibly cognitive control.

6 Towards a general psychological model of tension and suspense[1]

Abstract

Tension and suspense are powerful emotional experiences that occur in a wide variety of contexts (e.g., in music, film, literature, sports, and everyday life). The omnipresence of these tension experiences suggests that they build on very basic cognitive and affective mechanisms. However, the psychological underpinnings of emotional experiences of tension remain largely unexplained. In this paper, we discuss key components of tension experiences and propose a general psychological model of tension and suspense. According to this model, tension experiences originate from states of conflict, instability, dissonance, or uncertainty that trigger predictive processes directed at future events of emotional significance. The model provides a theoretical framework that can inform future empirical research on tension phenomena.

[1] This chapter is currently under review at *Emotion Review* as Lehne, M., & Koelsch, S., Towards a general psychological model of tension and suspense.

6.1 Introduction

Experiences of tension are ubiquitous affective phenomena that pervade many aspects of our lives.[1] Ranging from everyday life events to many leisure activities, tension (and its close relative suspense) is experienced in a wide variety of contexts and constitutes an important ingredient of human emotion. In some contexts, experiences of tension are associated with negative emotions such as fear, concern, or distress, which are generally tried to be avoided; in other contexts, tension is experienced as positive, and can, in fact, be a major motivator to engage in certain activities. The appeal of many forms of media entertainment such as music, film, or literature, for example, often seems to directly derive from their power to evoke feelings of tension and suspense. Similarly, tension is experienced in a multitude of everyday life situations, most typically during the anticipation of uncertain but (potentially) significant events (e.g., medical diagnoses, exams, job interviews, etc.). The omnipresence and potential emotional impact of tension phenomena indicates that they tap into fundamental aspects of human cognition and emotion, and the idea that tension plays an important role in emotion dates back to at least as far as Wilhelm Wundt, who proposed the opposite poles of tension (*Spannung*) and resolution (*Lösung*) as one dimension of affective experience in his three-dimensional model of emotion (Wundt, 1896; 1911). However, recent emotion research has largely neglected the role of tension in emotion, and surprisingly little is known about the psychological mechanisms underlying experiences of tension. Our aim in this article is to re-awaken the interest in tension phenomena and highlight their relevance for psychological research of emotion. We discuss basic psychological principles as well as possible neural mechanisms underlying tension experiences, and propose a general, modality-independent psychological model of tension and suspense. We argue that studying tension phenomena can greatly advance our understanding of emotion by providing new insights into general psychological principles underlying human affect. More specifically, studying tension

[1] By experiences of tension we refer to psychological experiences of tension (in contrast to physiological tension such as muscular tension, although both kinds of tension can interact).

phenomena can shed light on the dynamic, time-varying aspects of emotions, elucidate the relation between emotions and predictive processes, and illuminate the mystery of aesthetic emotions.

Previous research on tension and suspense has mainly focused on specific modalities, in particular music (Bigand et al., 1996; Farbood, 2012; Krumhansl, 1996; Lerdahl & Krumhansl, 2007; Madsen & Fredrickson, 1993; Pressnitzer et al., 2000), literature (Anz, 1998; Auracher, 2007; Brewer & Lichtenstein, 1980; Fill, 2003; Gerrig & Bernardo, 1994; Jacobs, 2011; Rabkin, 1973), film (Carroll, 1996b; Comisky & Bryant, 1982; Greifenstein & Lehmann, 2013; Hubert & de Jong-Meyer, 1991; Löker, 1976; Mikos, 1996; Zillmann, 1980), and sports (Knobloch-Westerwick et al., 2009; Peterson & Raney, 2008). Though providing valuable insights, modality-specific accounts of tension and suspense run the risk of overestimating the importance of aspects that are idiosyncratic to the particular area of interest, thus losing general mechanisms out of sight.[1] To overcome this limitation, the present paper mainly focuses on modality-independent aspects of tension experiences, emphasizing general mechanisms that are relevant to tension phenomena in different contexts. Although many examples used to illustrate our points rely on types of media entertainment and art forms such as music, literature, or film, which are often characterized by patterns of tension and resolution (see also Chapter 4) and therefore lend themselves especially well to psychological investigations of tension, our points generalize to tension phenomena in a variety of contexts, thus covering a broad scope of affective experiences.

[1] For example, in theories of suspense in narrative plots (e.g., movies or novels), concern about the well-being of a sympathetic protagonist is often discussed as a key element of suspense (Skulsky, 1980; Zillmann, 1980). However, this aspect of suspense in narrative plots obviously does not generalize to tension phenomena in music or many tension experiences in everyday life. On the other hand, specific aspects of musical tension are irrelevant to film suspense. The contribution of modality-specific accounts to a better understanding of general principles underlying emotional experiences of tension is therefore limited.

6.2 Tension and suspense and their relevance for emotion research

What exactly do we mean by tension? And what can psychological research of emotion gain from studying tension phenomena? First, we define tension and suspense[1] as affective states that (a) are associated with conflict, dissonance, instability, or uncertainty, (b) create a yearning for resolution, (c) concern events of potential emotional significance, and (d) build on future-directed processes of expectation, anticipation, and prediction (Section 6.4 discusses the different aspects of tension experiences in detail). We believe that studying tension phenomena can provide new insights into the following areas of emotion research in particular:

(1) *Time-varying aspects of emotion.* Emotions are rarely static states and their dynamic, time-varying nature is in fact one of their defining features (Scherer, 2005). However, most experimental emotion research focuses on relatively static aspects during brief emotional episodes (using experimental stimuli that remain relatively constant over time, e.g., affective pictures, facial expressions, words, etc.). Because tension phenomena usually require time to unfold and thus predominantly reflect time-dependent aspects of affective experience, studying these phenomena can help to shift the focus of psychological emotion research to the more dynamic aspects of emotion that are underrepresented in current emotion research.

(2) *The relation of emotion and processes of prediction.* Tension and suspense are closely related to processes of prediction (see Section 6.4.3). These predictive processes have been proposed as a basic principle of human cognition (Dennett, 1996; Gregory, 1980) and brain functioning (Arnal & Giraud, 2012; Bar, 2007; Bubic et al., 2010; Clark, 2013; Friston, 2010), and may also play a central role in emotion. Being related to both predictive processes and emotion, tension phenomena could provide the “missing link” that may help to bridge the gap between the “cold” cognitive processes of prediction on the one hand and the “hot”

[1] Although tension and suspense are sometimes distinguished from one another (with tension generally referring to more stationary states, and suspense referring to states that depend more on processes that unfold over time), both terms are often used interchangeably, and we will focus on psychological mechanisms that are relevant to both concepts.

processes of emotion on the other hand, thus integrating predictive processes into a general theory of human affect. In this context, studying the brain mechanisms underlying tension experiences from the perspective of the theory of predictive coding (Friston, 2010) seems particularly promising (see Section 6.6).

(3) *Aesthetic emotions.* Ever since Fechner (1876), aesthetic emotions have attracted the curiosity of psychologists, and recent years have seen a growing interest in the psychology and neuroscience of aesthetic perception and emotional experience (Di Dio & Gallese, 2009; Fitch et al., 2009; Jacobsen, 2006; Leder et al., 2004; Nadal & Skov, 2013; Silvia, 2005; Zeki, 1999). However, aesthetic emotions (e.g., emotions evoked in artistic contexts such as music, painting, literature, etc.) remain largely mysterious. Assuming that emotions are generally elicited by events that have some intrinsic significance to the concerns of the individual or, in biological terms, some kind of survival value, aesthetic emotions are a conundrum: the musical events of a Mozart sonata, the brush strokes of a Rembrandt painting, or the fictitious events of a Shakespearean drama seem to lack any relevance to our lives as biological organisms.[1] Apart from other factors contributing to aesthetic experiences (e.g., stimulus complexity, symmetry, or familiarity), patterns of tension and resolution appear to be a key mediator of emotional responses to art forms such as music, literature, or film (cf. Chapter 4). A better understanding of the mechanisms underlying tension experiences can therefore shed light on the mystery of aesthetic emotions evoked by works of art.

6.3 Measuring tension

Experiences of tension are accessible to empirical research by means of subjective rating experiments in which participants give some form of rating reflecting the degree of tension they experience during exposure to an experimental stimulus (e.g., a piece of music). Tension

[1] However, starting with Darwin's *The Descent of Man, and Selection in Relation to Sex*, various biological accounts of aesthetic perception and emotion have been proposed (see Darwin, 1871; Dutton, 2009; Menninghaus, 2011).

ratings can be acquired continuously over the whole course of the stimulus or they can be collected in a discrete manner at specific time points of the stimulus (see Figure 6.1 for two examples). To acquire continuous tension ratings, various kinds of interfaces have been used including spring-loaded tongs (Nielsen, 1983), dial interfaces (Madsen & Fredrickson, 1993), or real or virtual sliders (Farbood, 2012; Krumhansl, 1996; Vines et al., 2006; see also Chapter 2 of this dissertation). However, experiments probing tension experiences in music (Madsen & Fredrickson, 1993; Lehne, unpublished data) indicate that different interfaces yield similar results. For discrete measures of tension experiences, the stimulus is usually interrupted several times (unless it is very short) and participants are asked to indicate the amount of tension experienced during the preceding stimulus segment on a rating scale (e.g., in Bigand & Parncutt, 1999; Lerdahl & Krumhansl, 2007). Although continuous tension measures may seem preferable to discrete ones, their acquisition is not always feasible because for some stimuli (e.g., written texts) the dual task of focusing attention on the stimulus while simultaneously giving continuous tension ratings can lead to unacceptable quality decreases of the rating data. Moreover, there usually is a temporal lag between the values of continuous tension ratings and the stimulus events they refer to, making it difficult to unequivocally relate stimulus events to exact rating values. The choice between discrete or continuous tension measures, therefore, ultimately depends on the stimuli being used in the experiment and the type of research question investigated.

Furthermore, music research has shown that there can be differences between perceived and felt emotion (Gabrielsson, 2002), and when instructing participants about tension ratings one should therefore make explicit whether they should rate the tension they perceive (i.e., the tension they assume the stimulus is supposed to express) or the tension they subjectively feel.

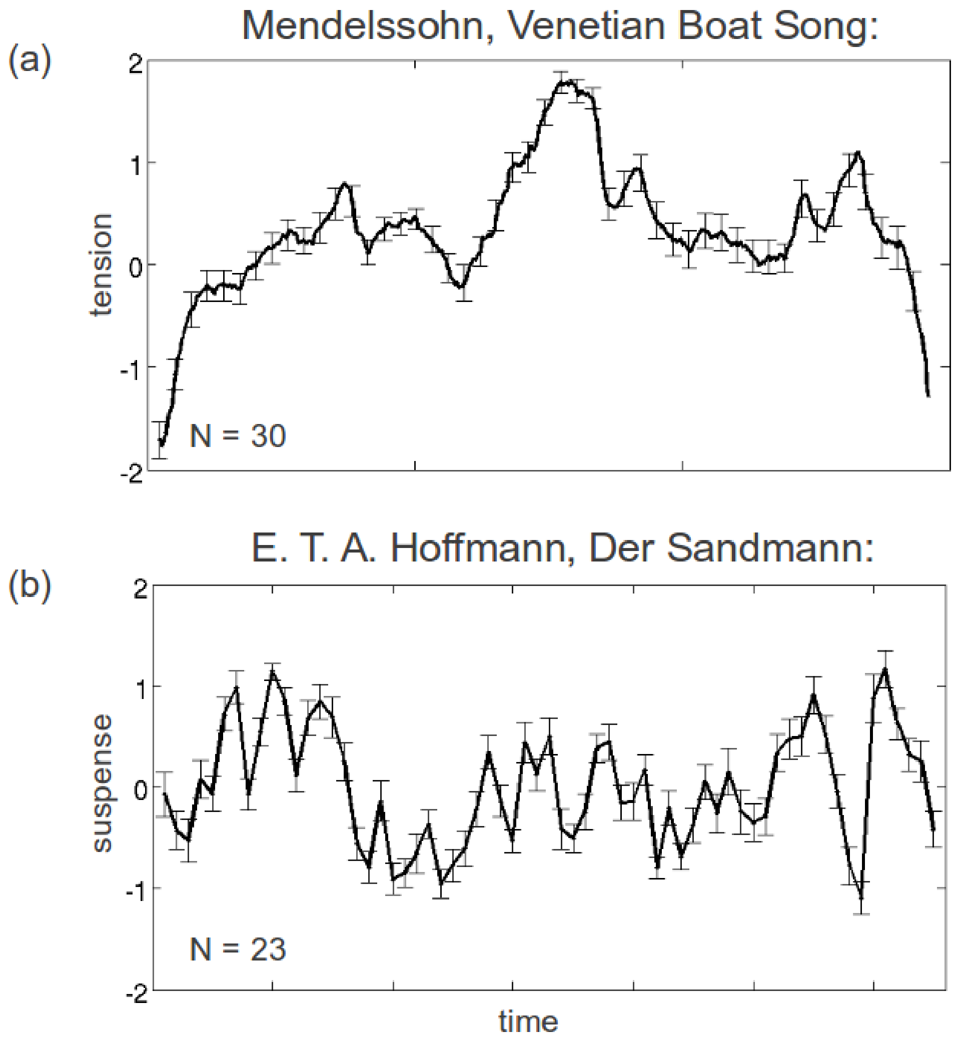

Figure 6.1. Average ratings of tension and suspense (standard scores with standard errors) experienced over the course of (a) a music piece (Mendelssohn's Venetian Boat Song) and (b) a literary text (E.T.A. Hoffmann, The Sandman). For the music piece, tension ratings were acquired using a virtual slider shown on a computer screen that participants continuously adjusted depending on their subjective experience of tension; for the literary text, suspense ratings were acquired at 65 time points during reading of the text (see also Chapters 2 and 5).

6.4 Key components of tension and suspense experiences

Previously, we defined tension as an affective state associated with conflict, dissonance, instability, or uncertainty concerning events of potential emotional significance that builds on processes of prediction and creates an urge for resolution. The following section examines the different components underlying tension and suspense experiences in more detail (some ideas presented in this section have previously been discussed in Chapter 4).

6.4.1 Conflict, dissonance, and instability

Tension experiences usually originate from events associated with conflict, complication, dissonance, or instability which create a yearning for more stable, or consonant states. This is, for example, illustrated by the way tension and suspense are created in narrative plots (e.g., in films, novels, theater plays, etc.) or in music. Reaching back to Aristotle's *Poetics*, in which complication is identified as an integral part of tragedy, a basic “suspense formula” employed by playwrights, fiction writers, and Hollywood directors until the present day is to put the protagonist of a story into a situation of conflict that has to be mastered. This creates tension and suspense experiences in the audience that persist until the conflict is resolved and replaced by a more stable state.

Although seemingly very different from suspense in narrative plots, tension experiences evoked by music appear to be governed by similar principles: musical events associated with dissonance or instability create experiences of tension whereas consonant stable events are associated with resolution and relaxation. For example, musical chords that do not belong to the underlying key context of a musical piece are perceived as less stable and accordingly are associated with higher degrees of experienced tension than chords belonging to the underlying key (Lerdahl & Krumhansl, 2007).

Similar to the biological homeostasis of an organism (i.e., its tendency to maintain a stable physiological state in a changing environment), tension experiences thus appear to build on a kind of “psychological homeostasis”—an urge to resolve psychological conflicts and dissonances and strive towards stable states of equilibrium (note the relation to Festinger's theory of cognitive dissonance according to which humans try to resolve psychological dissonances to achieve “consonant” cognitive states; Festinger, 1957).

However, this does not mean that stable states of equilibrium are always favored over states of tension. To the contrary, events associated with tension may sometimes be preferred because they promise excitement and intense emotional experiences that are usually not experienced in states of constant equilibrium. This is especially true in contexts such as music, film, or literature in which seemingly negative tension experiences can be experienced as positive and rewarding because they usually lack any negative real-life implications (cf. Levinson, 1997). Moreover, the state achieved after having gone through an experience of tension may be preferable to the one before the tension experience, thus sometimes justifying the deliberate exposure to negative tension experiences. For example, tension is often associated with situations in which an individual's model of the world (i.e., previous knowledge, expectations, see also Section 6.4.3) is challenged, providing an environment for learning in which the model of the world is expanded.

6.4.2 Uncertainty

Another important building block of tension experiences is uncertainty (although its exact role in mediating tension and suspense is a matter of debate, see Section 6.4.4). Obvious instances of uncertainty triggering experiences of tension are real life examples in which anticipated future events with uncertain but potentially highly significant outcomes can create strong tension experiences (e.g., a medical diagnosis, an important job interview, a rendezvous, etc.). Similarly, in narrative plots such as novels or movies, uncertainty about the unfolding of events of the plot creates suspense. The uncertainty associated with tension experiences—whether in real life or in narrative plots—often takes the form of an implicit or explicit question (e.g., the classic “Whodunit?” in a detective story), triggering an experience of tension that resolves when an answer to the question is provided. Note that uncertainty can take on different forms, for example, there can be uncertainty about *what* will happen, *how* it will happen, *when* it will happen, or *if* it will happen.

6.4.3 Expectation, prediction, anticipation

A key component underlying tension and suspense experiences are future-directed processes of expectation, prediction, and anticipation.[1] As events unfold in time (in real life, fictional worlds, or music), they are constantly evaluated against a background of predictions that is continuously updated during the temporal evolution of events. Anticipated events of emotional significance (see Section 6.4.5) can then generate experiences of tension or suspense. The resulting tension experiences are closely related to the emotions of hope and fear: anticipated events with positive valence elicit emotions of hope, whereas negative events create fear. In typical tension experiences, both emotions can co-occur because often both positive and negative outcomes are possible. In fact, the degree of experienced tension appears to be directly related to the range of anticipated events and their emotional valence That is, the experience of tension is more intense if the range of anticipated outcomes varies from highly positive to highly negative events, as opposed to, for example, slightly positive to neutral events (see Section 6.7).

The formation of predictions requires explicit or implicit knowledge such as learned concepts, categories, schemata, or scripts (Bartlett, 1932; Rosch et al., 1976; Rumelhart, 1984; Schank & Abelson, 1977). Furthermore, both long-term and short-term knowledge are relevant for the formation of predictions. Predictive processes in music, for example, build on long-term knowledge that is acquired over years of exposure to a musical system (e.g., Western tonal music) as well as short-term knowledge that is acquired during the exposure to a specific music piece (Pearce & Wiggins, 2012; Rohrmeier & Koelsch, 2012; Tillmann et al.,

[1] Although often used interchangeably, there are subtle conceptual differences between expectation, expectancy, prediction, and anticipation. We use the term “expectation” to refer to distinct instances of future events (i.e., expecting a specific event to happen), whereas the terms “expectancy” and “anticipation” are used to denote predictive processes that are more diffuse and less specific. “Prediction” is used to refer to all processes directed at future events, whether specific or unspecific (for accounts on terminology, see also Bubic et al., 2010; Rohrmeier & Koelsch, 2012).

2014). Musical events generating strong expectancies are then potential triggers of tension (notably, these expectancies need not necessarily be fulfilled but can be violated, thus generating surprise).

Expectation processes thus require some kind of information or structure on which predictive inferences can be based. During the formation of predictions, the probability of anticipated events also plays an important role and shapes the resulting experience of tension or suspense. However, the exact relation between anticipated probabilities of future events and experienced tension remains largely unclear (but for the special case of narrative plots and film suspense, see Carroll, 1996b; Comisky & Bryant, 1982; Gerrig & Bernardo, 1994).

6.4.4 The paradox of suspense

If tension experiences build on an urge for uncertainty reduction and processes of expectation, prediction, and anticipation, this raises the question as to how tension can be experienced over repeated exposures to a stimulus. Assuming that uncertainty is resolved after the first exposure, subsequent exposures should have lost their power to create tension or suspense. However, this does not always appear to be the case, and in some contexts, tension experiences seem to be resistant against the loss of uncertainty associated with repeated exposures. A piece of music can be listened to hundreds of times while still conveying feelings of tension and resolution, and—at least according to some authors (see Carroll, 1996a; Gerrig, 1989)—the narrative plots of novels or movies can be experienced as suspenseful even in the absence of uncertainty after several viewings or readings. Moreover, music pieces, novels, or movies often conform to genre-specific standards that make it possible to predict outcomes with high accuracy (in a typical Hollywood movie, the “good guys” usually win, a Beethoven sonata will end on a consonant stable chord, etc.), thus putting the role of uncertainty as a mediator of tension into question. This apparent contradiction known as the *paradox of suspense* has spurred much discussion, and conflicting accounts have been put forward as possible solutions.[1] While some authors question the possibility of experiencing suspense in the absence of uncertainty (Yanal, 1996), others have argued that the experience of suspense after repeated exposure to a narrative plot derives from the sympathy with the characters (who themselves are uncertain about future events, Skulsky, 1980), or that immersing into a suspenseful story for repeated times involves a game of make-believe, in which a kind of feigned uncertainty, not actual uncertainty, causes the experience of suspense (Walton, 1978). A related idea was proposed by Gerrig (1989) who postulated that external events automatically are processed with the "expectation of uniqueness", i.e., they are perceived as if they have never been encountered before. With regard to music, empirical evidence suggests that unexpected musical events are processed preattentively and automatically with regard to their music-syntactic function (Koelsch et al., 2002). Due to this automatic processing, a musical event can be experienced as music-syntactically unexpected, despite familiarity with the piece (which should render all musical events expected). This accounts in part for the experience of tension in the absence of uncertainty (see also the distinction between schematic and veridical expectations in music, Bharucha, 1994).

Despite the resilience of tension experiences over repeated exposures to some stimuli, we believe that in most cases the reduction of uncertainty, *ceteris paribus*, leads to a considerable decrease of tension or suspense. Watching a recording of the soccer World Cup finals is clearly less suspenseful when knowing the end result of the game, and a suspenseful movie is rarely watched twice in close succession, indicating that parts of the suspense experience do get lost after repeated exposure. Nevertheless, the paradox of suspense indicates that the exact role of uncertainty in creating experiences of tension and suspense is still not fully understood and remains to be investigated more closely.

[1] Note that for most real life tension experiences (i.e., the ones not pertaining to narrative plots or music), the paradox of suspense is less relevant because the impossibility of travelling back in time usually impedes the repeated exposure to real life events.

6.4.5 Emotional significance of anticipated events

Importantly, anticipated events need to be relevant to the concerns of the individual, i.e., they have to have some emotional significance, in order to generate tension or suspense. Apart from expecting specific events to happen, someone experiencing tension or suspense usually also *wants* a specific event to happen (or not to happen; cf. Anz, 1998). In fact, everything else being equal, the amount of tension experienced appears to depend directly on the significance or desirability of the anticipated outcome. Outcomes promising great rewards (e.g., winning the lottery) or portending great pain or suffering (e.g., a medical diagnosis) can elicit strong experiences of tension whereas events that are largely irrelevant to the concerns of the individual usually fail to create tension. Of course, the emotional significance of events can differ largely between individuals (a baseball fan may experience high levels of suspense during an important game of his team while his girlfriend sitting beside him may feel extremely bored).

Whereas the relevance of an event's emotional significance is relatively obvious for most real life examples of tension (job interviews, exams, etc.), this is not the case for the tension experiences created by many forms of media entertainment: the fictitious events of a movie or a novel, or the musical events of a Beethoven symphony appear to lack any direct relevance to our lives, yet they can trigger powerful experiences of tension. Nevertheless, even for fictitious events of a narrative plot, it is important that they become significant to the reader or viewer, and many writers or movie directors go through great lengths to make audiences care about the events of the plot (e.g., by portraying the protagonist as likable, addressing moral values of the reader or viewer etc.). However, it remains to be investigated more closely how seemingly irrelevant events can acquire emotional significance, thus becoming potential triggers of tension experiences. In some instances, a mere curiosity about how events will unfold in time may be sufficient for generating experiences of tension, although such experiences usually lack the emotional intensity associated with tension experiences in which something important is at stake.

6.4.6 Lack of control

Apart from the factors discussed above, a lack of control, i.e., an inability to influence the course of events, often contributes to experiences of tension. This lack of control is brought about by a temporal distance between the initiating event triggering the tension experience and the event that resolves the tension. During the time interval between these two events, there is usually not much that can be done except for waiting for the tension to resolve (in the best case the time of resolution can be influenced). This means that during the actual tension experience any action tendencies are rendered largely ineffective because the course of events cannot be changed, and this may induce a feeling of helplessness that can add to the experience of tension. This, of course, does not mean that tension experiences are devoid of action tendencies—to the contrary, tension experiences can evoke strong impulses to act and these impulses may prepare the organism for adequate behavioral responses in the moment when tension resolves.

6.4.7 Temporal aspects

Tension experiences can be observed at different temporal levels. They can span large time intervals encompassing, for example, the complete plot of a novel but they can also be observed at smaller, microstructural levels. In a written text, for example, a single sentence which is very long, and in which subject and verb are separated by various subordinate clauses or parenthetical statements (e.g., by making ample use of relative clauses, brackets, dashes, etc.), thus taxing the working memory load of the reader—longer sentences usually require more elements to be kept active in memory—and delaying syntactic integration necessary for understanding the sentence, can create tension. The different temporal levels (such as sentences, scenes, and entire plots) can interact, thus potentially amplifying the tension experience.

The previous example also illustrates that the temporal distance between the initiating event creating the tension and the moment in which tension resolves influences the tension experience. It has been proposed that delaying the resolution of the tension intensifies the tension experience (de Wied, 1995), however, there is a scarcity of empirical research investigating the relation between deferment of the resolution and experienced tension.

6.5 Tension and emotion

We already mentioned the relation between tension experiences and emotions of fear and hope (i.e., fear of an undesirable outcome and hope for a desired outcome). Because tension experiences usually are directed at future events of emotional significance, tension often precedes other emotions such as joy, pleasure, sadness, or disappointment and can thus be conceived of as a diffuse affective antecedent to more discrete emotional reactions. Generally, the more divergent the emotional valence of anticipated events is, the more diffuse and unspecific the associated tension experience tends to be. For example, in situations, in which both highly positive or negative outcomes are possible (e.g., betting a thousand dollars on the result of a coin flip), tension experiences may have neither a clear positive nor negative valence (although in this specific coin flip example, tension is probably experienced as more negative due to people's tendency for loss aversion, cf. Kahneman & Tversky, 1984). On the other hand, when the affective valence of possible outcomes is negative and the best outcome is just a preservation of the status quo, associated tension experiences also tend to be negative, whereas if a positive outcome is anticipated and the worst outcome is a preservation of a neutral status quo the tension experience also tends to be positive. The emotional valence of tension experiences is therefore often defined by the emotional valence of the anticipated resolution. However, there are also cases in which the emotional intensity and “thrill” of the tension experience is appreciated for its own sake (e.g., in extreme sports, fairground attractions, movies etc., see Berlyne's arousal-jag theory or Zillmann's excitation-transfer paradigm for accounts of these phenomena; Berlyne, 1960; Zillmann, 1980).

In its most diffuse form, tension can just arise from the expectancy that “something” significant will happen. Depending on what then actually happens, tension resolves into positive or negative emotions. If something completely unexpected happens, this can lead to surprise or amusement, e.g., when expecting something significant to happen that then instead resolves into something trivial (cf. the false-alarm-theory of humor and laughter; Ramachandran, 1995).

It also seems worthwhile to examine the relation of tension experiences and flow (Csíkszentmihályi, 1990)—the state of being completely absorbed in an activity (e.g., reading, watching a movie, listening to or performing music, sports, etc.). Tension and suspense, like flow, are associated with strong immersive experiences in which attention is highly focused (it is, for example, remarkable how long, especially in comparison to other stimuli, a suspenseful novel or movie can capture one's attention). A better understanding of the psychological mechanisms underlying tension and suspense could make it possible to deliberately create these experiences of minimal distraction and highly focused attention associated with flow. Furthermore, via their capacity to focus attention, tension and suspense may potentially emphasize and enhance other emotions (positive or negative) that manifest during the tension experience.

6.6 Neural correlates of tension and suspense

Investigating tension phenomena from a neuroscientific perspective can provide insights into general mechanisms of human brain functioning, in particular the ones associated with emotion and predictive processing. Vice versa, neuroscientific findings can inform psychological theories of tension.

First empirical research investigating brain processes underlying the experience of tension in music indicates that musical tension is associated with neural activity in the lateral orbitofrontal cortex, and that increases in experienced tension (in comparison with tension decreases) are related to activity in the (superficial) amygdala (see Chapter 3). This is consistent with studies showing that harmonic expectancy violations in music (which are highly relevant to experiences of tension, see Section 6.4.3) also activate the lateral orbitofrontal cortex (Koelsch et al., 2005; Tillmann et al., 2006) and the amygdala (Koelsch et al., 2008). In addition, other music studies indicate that expectation processes are associated with activity in the basal ganglia, particularly the striatum (Salimpoor et al., 2011; Seger et al., 2013). There is further evidence from a study investigating suspense during the reading of a literary text, indicating that the experience of suspense recruits brain areas associated with theory-of-mind processing such as the medial frontal cortex and temporo-parietal junction as well as areas in the premotor cortex (see Chapter 5). Such premotor cortex activations have been implicated with action and event prediction (Schubotz, 2007), underlining the connection between experiences of suspense and predictive processes. With regard to these predictive processes, the connection of psychological tension theories with Bayesian accounts of brain functioning such as predictive coding and the free energy principle (Friston & Kiebel, 2009; Friston, 2010) may prove useful. According to predictive coding theories, perception, action, and learning are essentially based on the minimization of prediction errors, surprise, and uncertainty, i.e., it is assumed that the brain constantly generates predictions at different levels of the processing hierarchy that are compared with input from lower levels of the hierarchy (e.g., sensory input). If there is a mismatch between (top-down) predictions and (bottom-up) input, this results in a prediction error. If such a prediction error occurs, predictions are updated or behavior is changed in such a way that predictions are fulfilled, thus minimizing future prediction errors, surprise, and uncertainty. Although these predictive processes most likely also have an emotional component, predictive coding and emotion are only beginning to be integrated into a common theoretical framework (Joffily & Coricelli, 2013). As discussed above, tension and suspense are closely connected with processes of expectation and anticipation and thus appear to rely on very basic brain mechanisms associated with predictive processing. At the same time, tension phenomena can evoke intense emotional responses. Studying neural correlates of tension and suspense can therefore help to develop a theory of human brain function integrating cognitive processes of prediction with affective emotional processes. For the special case of music, an integration of predictive processes, emotion, and underlying brain processes has recently been proposed by Gebauer et al. (2012), who relate music-evoked emotions to so-called “pleasure cycles” which are distinguished by different phases of wanting, liking, and learning (for details, see Georgiadis & Kringelbach, 2012; Kringelbach et al., 2012) and which depend on listeners' expectations and their fulfillment or violation. The different phases of these pleasure cycles are put into relation with neuronal processes of the dopaminergic reward system representing expectations and prediction errors according to the theory of predictive coding. Extending these considerations to more general aspects of expectation and anticipation, in particular to the ones associated with tension and suspense, could significantly advance our understanding of human emotion and the underlying brain mechanisms.

Tension experiences also share many of the components that are relevant to the perception of risk (e.g., in decision-making) such as uncertainty, predictive processing, and emotion. Brain regions associated with tension experiences may therefore overlap with regions that have been implicated in risk processing, for example, the anterior insula or dorsomedial and dorsolateral prefrontal cortex (Mohr et al., 2010).

Apart from providing insights into the neural mechanisms underlying tension experiences, neuroscientific methods may also open new perspectives for objectively quantifying the amount of tension or suspense evoked by an experimental stimulus (e.g., a movie excerpt, a piece of music, etc.). Studies by Hasson (for an overview, see Hasson et al., 2010) have shown that the intersubject synchronization of cortical activity, measuring to which degree brain activity correlates between different individuals, varies between different kinds of audiovisual stimuli (natural scenes or movies), with the highest synchronization observed for suspenseful movies (Hitchcock's “Bang! You're dead” or Leone's “The good, the bad and the ugly”). This suggests that the intersubject synchronization of brain activity can serve as an indicator of how much suspense a stimulus evokes on average over a group of participants.

6.7 Towards a psychological model of tension and suspense

Figure 6.2 shows a model of tension and suspense based on the points discussed in this article. According to this model, experiences of tension originate from the perception of an initiating event that is associated with conflict, instability, dissonance, or uncertainty which triggers future-directed processes of prediction, expectation and anticipation (modulated by previous knowledge, situational factors, or personality, see below). These predictive processes create a space of possible outcome events. A divergence between the affective values of these anticipated events (i.e., their desirability) then results in an experience of tension. More specifically, we propose that the intensity of tension experiences increases as the variability of the affective values of anticipated outcomes increases. That is, anticipated events whose affective values are highly variable (e.g., ranging from very positive to very negative events) are associated with higher degrees of experienced tension than events whose range of affective values is smaller. Note that the most positive or negative outcome event is often just the maintenance of the status quo whereas the others are more positive or negative events (for example, tension can be created by a mismatch between a desired goal state and the actual state of the world). Outcomes that have a negative affective value are associated with fear whereas positive outcomes can evoke feelings of hope. Furthermore, the perceived probabilities of anticipated events influence the tension experience (however, their contribution to the experience of tension remains to be determined by future research). Initiating and outcome events can coincide, i.e., an outcome event can be the initiating event of a new tension process, thus creating a succession of different tension experiences that give rise to a dynamic flow of tension and resolution (e.g., in a piece of music or a movie).

Importantly, the anticipated events of the outcome space as well as their affective values and perceived probabilities can largely differ between (and within) individuals because the predictive processes generating the outcome space depend on factors such as previous knowledge, personal values, mood, the context, in which events occur, attention, or personality (e.g., whether someone generally has a more optimistic or pessimistic outlook on the future).

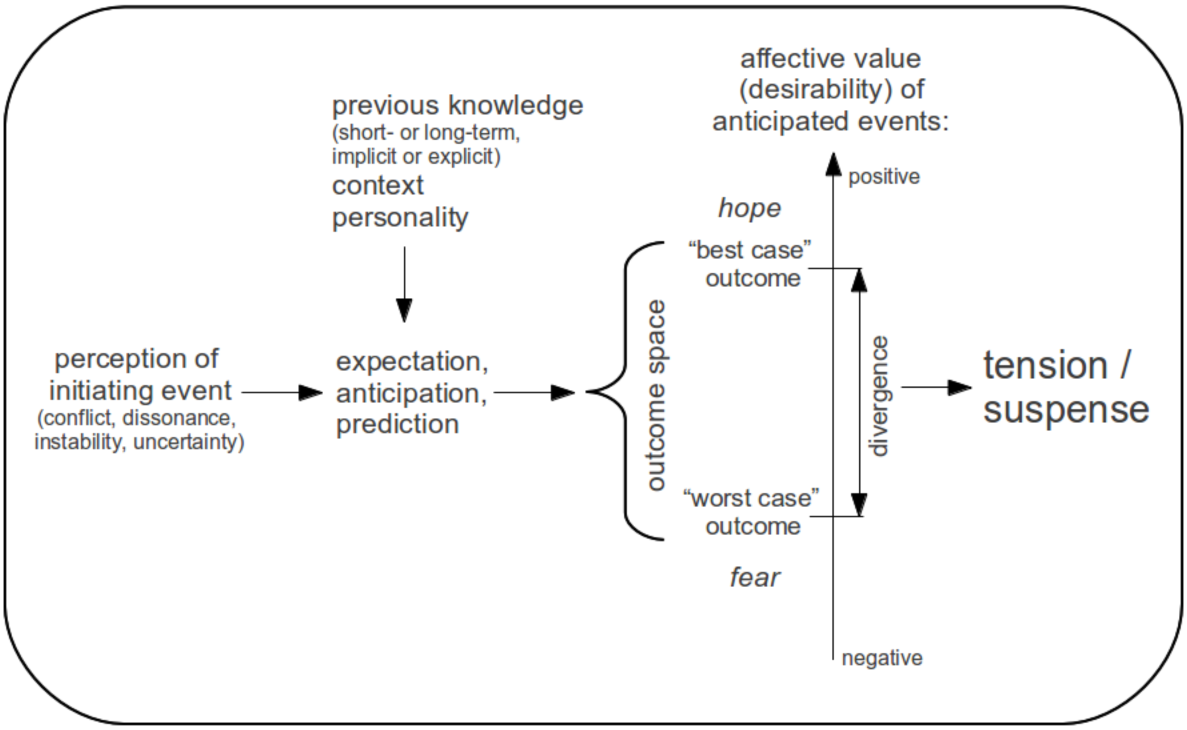

Figure 6.2. Tension model. The perception of an initiating event associated with conflict, dissonance, instability, or uncertainty triggers future-directed processes of expectation, anticipation and prediction (depending on previous knowledge, context, and personality factors) generating a space of anticipated outcome events that vary with regard to their affective values / desirability. A divergence between the affective values of anticipated outcomes (i.e., a differing desirability of outcome events) leads to the subjective experience of tension (with positive outcomes being associated with hope and negative outcomes with fear).

6.8 Future directions

The model proposed in the previous section should be regarded as a first step towards a psychological theory of tension and suspense. It provides a starting point from which experimental hypotheses can be generated and tested in empirical studies, which then may motivate further refinements of the model. In particular, future research is needed to specify how the perceived probabilities of anticipated events affect the subjective experience of tension. Furthermore, the role of uncertainty in generating experiences of tension and suspense is unclear and remains to be resolved by investigating how tension experiences change over repeated exposures to an experimental stimulus. Moreover, exploring how tension experiences change depending on the temporal distance between the event that triggers the tension experience and the event resolving tension (e.g., by investigating whether there is an "optimal" time interval between these two events to achieve a maximum of experienced tension, or how tension develops between these two events) may add to a better understanding of tension experiences.

We also mentioned that the factors determining the degree of experienced tension (such as the affective values of anticipated events and their perceived probabilities) are highly subjective and context-dependent. It is therefore worthwhile to explore how personality, mood, or situational factors shape experiences of tension. Related to that, it remains to be investigated more closely in which contexts tension is experienced as positive, and when as negative. Investigating neural mechanisms underlying tension experiences, in particular the ones related to predictive processes, could further add to a psychological theory of tension and suspense.

6.9 Conclusion

In the present paper, we explored the psychological mechanisms underlying experiences of tension and suspense. We discussed the relevance of tension phenomena for emotion research, identified key components of tension experiences and proposed a general psychological model of tension and suspense. According to the model, tension experiences originate from events associated with conflict, instability, dissonance, or uncertainty which trigger processes of prediction. The divergence between the affective values of anticipated events then results in experiences of tension. The model provides a starting point from which open questions concerning the psychological underpinnings of tension phenomena can be addressed. In particular, future research could investigate how the probability of anticipated events influences tension experiences, how situational and personality factors contribute to tension experiences, and how the temporal delay of resolution moments shapes tension. Furthermore, the paradox of experiencing tension and suspense over repeated exposure deserves a closer investigation. Last, integrating affective experiences of tension into neural theories of predictive coding offers promising avenues for future research.

7 General discussion and outlook

The aim of this dissertation project was to investigate emotional experiences of tension and suspense from empirical and theoretical perspectives. Three empirical studies investigated tension and suspense experiences evoked by music and literature using behavioral and neuroimaging methods (fMRI). Moreover, the psychological underpinnings of tension experiences were explored in two theoretical articles.

Results of a behavioral study investigating the contribution of different structural features to the experience of musical tension indicate that musical tension is largely mediated by the tonal features of a musical piece (e.g., harmonic or melodic features) and their relative importance in the piece but can be enhanced by expressive features such as dynamics. A subsequent fMRI study showed that music-evoked tension experiences are associated with neural activity in the orbitofrontal cortex (particularly the pars orbitalis of the inferior frontal gyrus) and the amygdala, underlining the close connection between musical tension and emotional responses of the listener. In analogy to this music study, a second fMRI study investigated the neural correlates of suspense evoked by a literary text. Text passages that participants rated as suspenseful were related to increased BOLD responses in bilateral inferior frontal, posterior temporal and temporo-parietal as well as medial prefrontal regions, suggesting a role of theory-of-mind and predictive inference processes. In the theory articles, the role of tension-resolution patterns as a mediator for emotions evoked by art forms such as music, literature, or film was explored in more detail, and general psychological mechanisms underlying tension experiences were discussed. Finally, a general psychological model of tension and suspense was proposed. According to this model, tension experiences—irrespective of the domain in which they are evoked—are based on expectation processes directed at future events of emotional significance.

Taken together, this dissertation presents work contributing to the understanding of psychological mechanisms and neural correlates of emotional experiences of tension and suspense. It includes the first neuroimaging studies investigating the brain processes associated with tension experiences and explores their psychological underpinnings, concluding with a general, domain-independent model of tension and suspense, which may guide subsequent empirical research. The dissertation should be regarded as a step towards a (neuro-)psychology of tension and suspense, providing a foundation that may inform future psychological and neuroscientific studies on tension phenomena. After all, many interesting questions concerning the psychological and neuronal processes generating tension experiences remain to be clarified. For example, the effect of repeated exposure to a stimulus on the experience of tension and suspense remains largely unclear (cf. paradox of suspense, see Chapters 4 and 6). Moreover, exploring the role of the statistical properties of a stimulus (e.g., its probability of occurrence) on the magnitude of experienced tension may add to a better understanding of emotional experiences of tension and may eventually make it possible to estimate the degree of subjectively experienced tension based on objective stimulus properties. Music appears to be particularly well-suited to investigate this question, as it provides the possibility to objectively quantify statistical stimulus properties (e.g., the conditional probability of a specific chord function occurring given a preceding harmonic context) and to put these into relation with subjective ratings of experienced tension. For example, using information theoretic measures of musical expectation as described in Pearce and Wiggins (2012) to predict subjective tension ratings seems promising and may help to extend and refine existing models of musical tension (e.g., Farbood, 2012; Lerdahl & Krumhansl, 2007). By emphasizing aspects relevant to different domains and reflecting general aspects of cognitive processing (e.g., the processing of event probabilities) instead of idiosyncratic factors only relevant to music (e.g., the sensory dissonance of a musical chord), an information theoretic model of musical tension may possibly be extended to other domains such as film or literature (however, in these domains, estimating event probabilities is more difficult than in music because the range of possible events is usually much larger).

Further research is also required to gain a better understanding of the brain mechanisms associated with the general cognitive processes underlying experiences of tension. The attentive reader may have noticed that the fMRI studies presented in this dissertation, probing tension experiences in music and literature, find different brain areas to be associated with musical tension in comparison with suspense evoked by a literary text. This contradicts the assumption that musical tension and suspense evoked by a literary text build on the same underlying cognitive processes. However, the existence of general cognitive mechanisms (e.g., expectation processes) generating tension experiences regardless of the domain in which they are evoked is highly plausible from a psychological point of view, as has been illustrated in the theoretical articles included in this dissertation (see Chapters 4 and 6). Future neuroimaging research should therefore aim to identify brain structures reflecting these domain-independent processes by comparing neural correlates of tension experiences more systematically over different domains, using more controlled experimental designs, in which as many stimulus features as possible are kept constant over the domains in question. For the fMRI studies presented here, such a comparison was not feasible because the stimuli used in the studies differed on many dimensions such as sensory modality (visual vs. auditory) or the time scale at which tension changes occurred (in the order of seconds for the music study whereas changes were slower for the literature study), making it difficult to draw meaningful conclusions from a comparison of obtained brain activations. Future research may also particularly benefit from using film clips as experimental stimulus material because suspenseful films can be assumed to evoke stronger experiences of tension and suspense than the stimuli used in the experiments presented here (music and literature). Generally, an interdisciplinary approach involving researchers from the fields of psychology, neuroscience, musicology as well as film and literature studies seems desirable.

Ultimately, a better understanding of the psychological mechanisms driving emotional experiences of tension and suspense may render it possible to actively shape these tension experiences, fostering positive emotional experiences (e.g., in entertainment contexts such as music, film, literature, or sports) and reducing negative ones (e.g., stressful tension experiences in real life situations).

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Appendix

Music pieces used in Study 1 ("The influence of different structural features on felt musical tension in two piano pieces by Mozart and Mendelssohn"):

Mendelssohn Bartholdy, Venetian Boat Song (Op. 30, No. 6):

2


31
dim.
pp
sfz
36
dim.
p
41
p
cresc.
f
46
dim.
p
cresc.
f
sfz dim.
51
sfz
p
dim.
pp

Mozart, Piano Sonata KV 280 (Second Movement):

Lebenslauf

[Aus Gründen des Datenschutzes ist der Lebenslauf in der Online-Version nicht enthalten.]

Eidesstattliche Erklärung

Hiermit erkläre ich, dass ich die vorliegende Arbeit selbständig und ohne unzulässige Hilfe verfasst habe. Für die im Rahmen der Promotion durchgeführten Studien und die Erstellung der Fachartikel war ich hauptverantwortlich. Die Arbeit ist in keinem früheren Promotionsverfahren angenommen oder abgelehnt worden.

Berlin, den 6. April 2014

Moritz Lehne