The Tonic as Triad: Key Profiles as Pitch Salience Profiles of Tonic Triads

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MAJOR AND MINOR TRIADS EMERGED IN WESTERN music in the 13th to 15th centuries. From the 15th to the 17th centuries, they increasingly appeared as final sonorities. In the 17th century, music-theoretical concepts of sonority, root, and inversion emerged. I propose that since then, the primary perceptual reference in tonal music has been the tonic triad sonority (not the tonic tone or chroma) in an experiential (not physical or notational) representation. This thesis is consistent with the correlation between the key profiles of Krumhansl and Kessler (1982; here called *chroma stability profiles*) and the *chroma salience profiles* of tonic triads (after Parncutt, 1988). Chroma stability profiles also correlate with *chroma prevalence profiles* (of notes in the score), suggesting an implication-realization relationship between the chroma prevalence profile of a passage and the chroma salience profile of its tonic triad. Convergent evidence from psychoacoustics, music psychology, the history of composition, and the history of music theory suggests that the chroma salience profile of the tonic triad guided the historical emergence of major-minor tonality and continues to influence its perception today.

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Since **Krumhansl and Kessler (1982)** consolidated their key profiles (illustrated in Figure 1), the *K-K profiles* have maintained a central position in music psychology research. A tone in a tonal context is perceived to be *stable* if listeners perceive it to be a goal of melodic or harmonic motion, or a point of rest. The K-K profiles quantify the music-theoretic intuition that the most stable pitch in the chromatic scale is $\hat{1}$, followed by the other tones of the tonic triad ($\hat{5}$ and $\hat{3}$), other diatonic tones ($\hat{2}$, $\hat{4}$, and $\hat{6}$), the leading tone ($\hat{7}$), and finally the non-diatonic tones (cf. Lerdahl, 1988).

To facilitate comparison with other chroma[1] profiles considered in the present paper, the K-K profiles will be referred to as *stability profiles*. This term is not entirely satisfactory because Krumhansl's method is not a *direct* measure of stability (the word "stability" does not appear in the instructions to participants). But her method may be considered an empirical operationalization of the concept of tonal stability, and as such an important achievement of late 20th century music psychology. Initially criticized as a trivial, uncritical quantification of conservative tonal music theory, the K-K profiles came to be regarded as the most concise, robust and parsimonious psychological representations of *major-minor tonality* (henceforth *MmT*—also known as *common-practice tonality* or *harmonic tonality*)—even though they explicitly represent only the static harmonic aspect and explicitly exclude information about dynamic aspects such as chord progressions and voice leadings (Butler, 1989).

Krumhansl and Shepard (1979) presented major and minor scales followed by probe tones and asked listeners to rate goodness of fit. Krumhansl and Kessler (1982) presented chords and chord progressions instead of scales. The results showed that stability profiles do not necessarily depend on the acoustical or perceptual properties of preceding sounds in short-term memory. Nor is their origin physiological—they are not ultimately based on universal peripheral or central structures. Krumhansl and Kessler concluded that the profiles depend primarily on the prevalence of chromatic scale steps in the music to which listeners have been exposed—a kind of long-term musical memory. Consistent with this explanation, Russo, Cuddy, Galembo, and Thompson (2007) found that sensitivity to tonality is greater in the central musical range. The thesis that the profiles are learned from music is also consistent with the diversity of world musics.

[1]A *chroma* is a pitch category or scale degree within the 12-tone chromatic scale, without regard for octave register. For example, the pitch categories C4 (middle C), C5 and C6 are all examples of chroma C. The term chroma is commonly used in music psychology and is essentially the same as the term *pitch class* in music theory. A *chroma profile* comprises 12 (positive real) numbers, one for each chroma; the word *profile* refers to a graph of these numbers against chroma.

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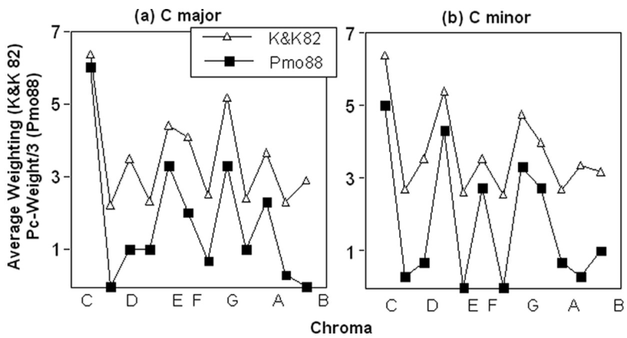

FIGURE 1. Comparison of (a) major and (b) minor K-K profiles (open triangles) with calculated chroma salience within the tonic triad (Parncutt, 1988, with root-support weights P1/P8 = 10, P5 = 5, M3 = 3, m7 = 2, M2/M9 = 1, m3 = 0) (filled squares). The vertical axis represents either mean experimental goodness-of-fit rating on a 7-point scale (for Krumhansl), or calculated chroma weight, divided by 3 for ease of comparison (for Parncutt).

The K-K profiles correlate strongly with the chroma prevalence profiles of Aarden (2003), which are based on thousands of melodies in major and minor keys. The correlation is not perfect, however. A striking difference is that is $\hat{1}$ is generally more stable, but not more prevalent, than $\hat{5}$. Scale degree $\hat{5}$ is more prevalent than $\hat{1}$ in the major key, and the two scale degrees are about equally prevalent in the minor. A possible explanation is that $\hat{1}$ is typically more salient than $\hat{5}$ within the tonic triad, suggesting that the profiles depend in some way on pitch perception. It has also been shown repeatedly that the K-K profiles depend on short-term memory for the sounds immediately preceding the probe tone (Butler, 1989; Huron & Parncutt, 1993; Leman, 2000; Parncutt, 1989). One aim of the present paper is to reconcile these contrasting findings and viewpoints, and to bring them together on a higher conceptual level.

I will assume that chroma stability profiles can only be adequately explained and understood in an interdisciplinary approach that brings together relevant knowledge and epistemologies from all relevant humanities (e.g., history) and sciences (e.g., psychology). Progress in this and many other areas has been impeded by the institutional and infrastructural separation of humanities and sciences, both generally and within music research (Parncutt, 2007). Since human behavior and experience are strongly influenced by culture, psychology is culture dependent (Berry, Poortinga, Segall, & Dasen, 2002); conversely, anthropology depends on psychology: "cultural things . . . are . . . ecological patterns of psychological things" (Sperber, 1985, p. 73). And since culture depends on history, human behavior and experience also have a strong historical dimension (Mos, 1998): for example, theories of social behavior tend to reflect contemporary history because their theoretical premises are based on acquired dispositions (Gergen, 1973). Conversely, psychology contributes to an understanding of history (Runyan, 1988). More interaction is desirable between music psychology and cultural studies (Allesch & Krakauer, 2005–2006), music psychology and ethnomusicology (Huron, 2006a), and—as I will argue here—music psychology and music history.

The assumption that chroma stability depends on chroma prevalence links the perception of tonality with its historical development. How was Western music perceived before the emergence[2] of MmT in the 15th, 16th, and 17th centuries? One of the few things that we can claim with any certainty is that the tone-to-tone expectations of historical listeners were influenced by the statistical properties of contemporary musical styles—consistent with Meyer's (1956) statistical concept of musical style. But new styles do not suddenly appear; they emerge gradually in an extended historical process, during which pitch-time patterns gradually change. These patterns exist not only on paper in musical manuscripts, but also in the minds and brains of listeners. If the perception and cognition of musical syntax is founded in music history, a complete explanation of the K-K profiles must address the historical emergence of MmT.

The perception of tonal stability depends on both the individual history of the listener and the history of musical style. Consider the role of expertise in probe-tone experiments. If, as Krumhansl and others have argued, listeners' responses in such experiments are influenced by an activated tonal schema, their responses ultimately depend on the personal and cultural history of that schema. In our empirical studies on pitch salience profiles (Parncutt, 1989, 1993; Reichweger & Parncutt, 2009), which involved rating how well a probe tone went with a preceding sonority, experimental participants were primarily musicians with several years of experience practicing and performing a Western musical instrument. Nonmusicians were generally unable to perform the experimental task: their data often did not correlate with the presence or absence of tones in the sonorities. Musical experience was evidently less critical in Krumhansl's key profile experiments, because more tonal context was provided and the pitch-time structure of the context was more familiar. However, as a general rule both salience and stability profiles become more robust (less noisy, more replicable) when listeners have more musical experience and have actively interacted

[2] In this article, I use the word "emerge" in the neutral sense of the German *entstehen*. The presentist sense of inevitability that is inherent in the word "emerge" is unavoidable and unintended.

with similar sounds over an extended period. The K-K profiles thus represent not only an aspect of common Western cultural knowledge, but also the (more exact) knowledge of musical experts. This knowledge may be either sonically superficial (e.g., when listeners give fast, spontaneous responses), or it may involve music-theoretical constructs (when trained listeners are allowed time to think), but we may usually assume that listeners did not recognize relevant music-theoretic structures (they did not think to themselves, for example, that "the probe tone corresponds to a perfect fourth above the tonic or root"). Thus, we may neglect the contribution of explicit music-theoretic knowledge to the K-K profiles.

In this paper, I will relate Krumhansl's key profiles to the emergence of MmT in the 15th to 17th centuries, and the major and minor triads that came to function as tonal centers during that period. My central claim is that the tonic of MmT is a triad rather than a tone—consistent with the work of music theorists such as Rameau (1721/1971), Riemann (1893), and Schenker (1906/1954). Krumhansl and Kessler (1982) observed that the tone profiles of isolated triads correlate with tone profiles of cadential progressions ending on those triads, but did not consider the far-reaching implications of that observation.

The perception of tonality depends to some extent on the octave register of each tone. For example, the sense of closure at authentic cadences in the music of the classical period is reinforced by sounding the tonic $\hat{1}$ in both soprano and bass (Caplin, 1998). Other things being equal, outer voices are more likely to be perceived as roots or tonics than other tones because they are subject to less masking by other tones (Parncutt, 1997). For example, the root of a supertonic minor seventh is $\hat{2}$, but the root of an added sixth chord on the subdominant—a chord comprising the same four chromas—is $\hat{4}$. Another interesting example is the cadential six-four chord—a second-inversion tonic triad that is immediately followed by a dominant triad in root position. In a linear or Schenkerian approach, the root of the cadential six-four is $\hat{5}$ (Beach, 1967), but the long history of theorizing about this chord suggests a more ambiguous interpretation. The chord is either a non-final dominant that anticipates the dominant (as in the Schenkerian approach) or a non-final tonic that anticipates the final tonic (since it comprises the same chromas as the tonic triad). Perhaps it is both at once. In this paper, I assume that effects of octave register on tonality are relatively small and separable from effects of chroma. In octave-generalized music theory, the terms "major triad" and "minor triad" are implicitly understood to include all possible voicings (transpositions, inversions, doublings, spacings); a tone can function as a root or tonic in any register, and a triad as a tonic in any voicing.

The major and minor triads are regarded by music theorists as the basis for most other sonorities used in tonal music. For example, seventh chords are conceived of as major or minor triads with an added tone at a seventh interval above the root. The historical emergence of major and minor triads began with improvised, orally transmitted, and written contrapuntal styles in three or more voices in 13th century Europe. The prevalence of triads gradually increased during the 14th-16th centuries. Since about the 15th century, major and minor triads have been the most prevalent sonorities in polyphonic Western music. At the start of the 21st century, they still dominate most music, in spite of the extensive tonal and atonal experimentation during the 20th century.

Why are major and minor triads so central to MmT? One approach to this question is to study their perception in isolation. In Parncutt (1993), I measured the pitch salience profiles of individual chords. In each trial, one of five different chords—one of which was a major triad and one a minor triad—was presented. The triads were built from octave-complex tones (Shepard tones with a flat amplitude envelope) and each was transposed to a random position on the chroma circle. The triad was followed by a reference tone, which was also octave-complex. The listener was asked how well the tone went with the preceding chord. The results are shown in Figure 2.

The data can be explained by Terhardt's (1972) theory of pitch perception. Most pitches that we experience in everyday life including music are *virtual pitches* that correspond approximately to the fundamental of a harmonic series of audible partials (*spectral pitches*). The salience of a virtual pitch depends on the number of spectral pitches at or above it that correspond approximately to

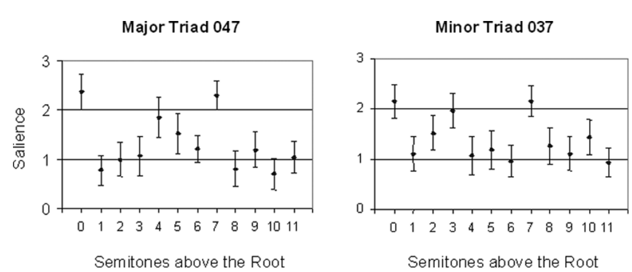

FIGURE 2. Experimental and calculated chroma salience profiles of (a) a major triad and (b) a minor triad (from Parncutt, 1993). Twenty-seven listeners (mainly musicians) rated how well a probe tone went with a preceding chord. Three other chords were tested in the same experiment: dom7, half-dim7, and dim7. Both chords and probe tones were constructed from octave-complex tones. Trials were shuffled and rotated randomly around the chroma cycle. The filled diamonds are mean experimental ratings and the error bars are 95% confidence intervals about those means.

its harmonics. It also depends on their individual saliences and the corresponding harmonic numbers.

These basic principles are consistent with the theory and data of different schools of pitch perception, and they hold regardless of whether the underlying physiology is dominated by time-domain or frequency-domain processes. The auditory system takes advantage of both temporal and spectral information to separate voices in harmonic and contrapuntal contexts (Moore, 2003), as do automatic transcription procedures in music information retrieval (e.g., Bello, Daudet, & Sandler, 2006). Terhardt's (1972) pitch model is often regarded as a frequency-domain model, but in fact makes no explicit assumptions about time- versus frequency-domain processing or underlying brain physiology. Both spectral and virtual pitches are regarded as purely experiential (cf. World 2 of Popper & Eccles, 1977)—not physical or physiological (World 1). The algorithm by which virtual pitches are extracted from spectral pitches is confined to World 2. The question of whether spectral and virtual pitches ultimately correspond to frequencies or periodicities is entirely avoided.

For the present purpose, the quantitative predictions of Terhardt et al. (1982) are hardly different from those of temporal models such as Meddis and Hewitt (1991). But only Terhardt's model estimates the perceptual salience of each predicted pitch, enabling an exploration of the relationship between calculated pitch salience and the relative stability of scale steps (the K-K profiles). A systematic analysis of pitch and pitch salience in musical chords reveals pitches at the missing fundamentals of incomplete, approximately harmonic series of spectral frequencies. Such pitches can explain which tones go well with a chord, or which scale/s it implies—raising the question of whether implied scales are learned from music experience or are psychoacoustically predetermined. I will assume here that both answers are correct, and analyze the underlying historical process.

The relationship between Krumhansl's key profiles and the pitch salience profiles of major and minor triads has both a quantitative and a qualitative aspect. Quantitatively, the correlation is high (about .95, see Figure 1). But correlation alone is not a convincing argument, because other models (described below) achieve similarly high correlations, and correlation does not imply causality. The qualitative aspect of the relationship is equally important, and involves the prevalence and function of major and minor triads in tonal Western music. Since I am adopting an interdisciplinary approach that aims to balance humanities and sciences, I take seriously the intuitive claims of music theorists that major and minor triads act as references to which other sonorities in a tonal progression psychologically refer (e.g., Riemann, 1893) and that passages of tonal music are prolongations of their tonic triad (Schenker, 1906/1954). I regard these various quantitative and qualitative findings and claims as convergent evidence for my thesis that the pitch salience profiles of major and minor triads represent the ultimate origin of Krumhansl's key profiles. This in turn is evidence for my central thesis that the tonic in MmT is a triad, not a tone.

The remainder of this paper is structured as follows. First, I review literature on the concept of tonality, addressing a range of relevant disciplinary approaches and problems. I then compare a number of different models of the K-K profiles, evaluating them both quantitatively (for goodness of fit between predictions and data) and qualitatively (for explanatory power and interdisciplinary consistency). Turning to the history of major and minor triads and MmT, I compare developments in the syntax of written music with developments in musical thought, as documented in theoretical treatises from the 12th to the 17th century. Finally, I consider implications of the tonic-as-triad model for music psychology, music theory, and music history.

Tonality

Before proceeding, I will attempt to clarify some central issues. How is the concept of tonality understood in music theory, music history, and music psychology? How has the concept changed historically? What is the relevance of mathematics (frequency ratios) and notation (enharmonic spelling) for MmT? How robust are the K-K profiles? What aspects of MmT do they represent? What aspects do they neglect?

In this paper, *tonality* refers only to perceived structure in musical *pitch*—not in rhythm or form (temporal structure). The clarity or complexity of musical pitch structure can be almost independent of the clarity or complexity of its temporal structure: a piece can have a clear or simple tonal pitch structure and an unclear or complex temporal structure—or vice-versa. Tonality depends on temporal structure only insofar as the temporal order, duration and repetition of tonal events affect it (e.g., Huron & Parncutt, 1993; Parncutt & Bregman, 2000).

Tonality refers to the tendency for some tones to act as psychological reference points for other tones. Music theorists and psychologists generally assume a simple one-to-one relationship between referentiality and stability: the more stable a tone is perceived to be, the more likely it is to act as a point of reference for other, less stable tones.

Tonality may be defined either broadly or narrowly (Norton, 1984; Thomson, 1958). In a narrow definition, it is about the hierarchical structure of pitch relationships in MmT. Broadly, it is about relationships, both successive and simultaneous, between and among any scale tones or pitches in any style in any culture (Fétis, 1840; Simms, 1975). In the West, the broad definition applies as well to medieval modality as it does to the diverse products of 20th-century modernism. According to Stravinsky (as cited in Thomson, 1958), "All music is nothing more than a succession of impulses that converge toward a definite point of repose. That is as true of medieval plainchant as it is of a Bach fugue, as true of Brahms' music as it is of Debussy's. The general law of attraction is satisfied in only a limited way by the traditional diatonic system, for that system possesses no absolute value" (pp. 35–56).

Fétis (1840) regarded tonality as a "metaphysical principle, a fact not of the inner structure or formal properties of music but of human consciousness, which imposes a certain cognitive organization—a certain set of dynamic tendencies—on the musical material" (Hyer, 2001, p. 592). Norton (1984) similarly emphasized the subjective nature of tonality:

> To turn tonality into an adjective with relation to consciousness is an attempt to restore the subjective ego to its proper relationship with the object it both creates and cognizes. The chief fault of mainstream scholarship has been to ignore (even fail to recognize) this relationship. There can be no ontology of tonality as a human endeavor until this relationship is brought into proper perspective—through physics and neurophysics, through psychology and sociology, through acoustics and psychoacoustics, and through politics and economics. Until this project is actively taken up by the musicological community there can be no progress toward the historical definition of our tonal consciousness (pp. 10–11).

Norton also urged that "the hearing subject and its processes of aural cognition are to be restored to their proper relationship with the tonal object that it creates" (1989, p. 125). After all, the major and minor modes "were born not through theoretical formulation but through the selectivity of the creative ear in discovering the processes of projecting organic tonal structure" (Novack, 1977, p. 86). The present paper takes up the challenge set by Norton and Novack by combining research in the humanities on the history of tonal harmonic syntax with scientific research on psychoacoustics and cognition to create a new theoretic synthesis.

Many musicologists have chronicled the history of MmT in the broader context of the history of Western musical syntax. Few (e.g., Eberlein, 1994) have systematically addressed corresponding historical changes in the *perception* of musical structure. Music perception depends on the structure of the music with which listeners are familiar; changes in music perception in turn affect how music is composed and performed, which again affects musical structure. Thus, the relationship between music perception and music structure is dynamic and bidirectional. Is it possible to describe and investigate historical changes in music perception from a modern, music-psychological viewpoint? On that basis, is it possible to ask how perceptual factors influenced the history of Western musical syntax? These are interesting questions for both historical musicologists and music psychologists.

These considerations suggest that three contrasting disciplines—music history, music theory, and music psychology—are necessary for a complete understanding of the nature and origins of tonality. Of the three, music theory is most directly concerned with questions of tonality. Music history is important because tonal syntax has always been in a state of flux—no more so than during the past thousand years in Europe. During this time, the perception of tonality—in the sense, for example, of the continuations that listeners expect if a piece of music suddenly stops—was also changing. Perception of today's tonal music depends on today's tonal syntax, which is the result of a long period of evolution that was influenced by a mixture of historical (political, sociological, compositional) and psychological (perceptual, cognitive, emotional) factors. Unfortunately for music psychology, the music listeners of the 19th and earlier centuries are no longer available for psychological testing, and the compositional treatises of the Middle Ages tend to focus primarily on principles of composition rather than what the listener hears. They do not include a CD in the back cover.

The Role of Mathematics, Acoustics, Psychoacoustics and Enharmonics

Some academic approaches to the nature and origins of MmT are problematic and should be avoided. Consider the Pythagorean-Platonic tradition of theories based on whole-number ratios between fundamental frequencies of musical tones or (equivalently) between the lengths of vibrating strings, such as 1:2 for the perfect octave (henceforth P8) and 2:3 for the perfect fifth (henceforth P5). A problem that haunts all such approaches is the lack of an unequivocal causal relationship among ratios, intonation, and enharmonic spelling. Pitch intervals in performed music often deviate systematically from the frequency ratios of both pure and Pythagorean tuning

(Duke, 1985; Loosen, 1993; Rakowski, 1990; Sundberg, 1982), casting doubt on the relationship between such ratios and the perceptual, cognitive, or musical properties of the resultant pitch-time patterns. Intonation depends on a host of factors including temporal context (Fyk, 1995) and emotional expression (Juslin, 2005). Its variation in typical performances typically exceeds the difference between theoretical tunings of specific intervals, e.g., 386 cents (pure, just) versus 408 cents (Pythagorean) for the major third (Burns, 1999).

One might equally criticize psychoacoustical attempts to explain MmT, if psychoacoustics is about fixed properties of the acoustical signal and the ear. MmT is a culture-specific artistic phenomenon with a long and complex history. How can such a phenomenon depend on something fixed and universal? Terhardt (1976) addressed this problem by using the term "psychoacoustics" in a relatively broad way to refer to any relationship between physical parameters and the real-time experience of sound. Given that auditory perception always depends on past auditory experience, and auditory experience has universal and culture-specific elements, psychoacoustics must also involve both universal and culture-specific relationships. The perception of virtual pitch is assumed to depend on past experience of the harmonic series as it occurs audibly in harmonic complex tones in speech, music, and other environmental sounds. We might therefore expect differences in pitch perception between listeners who have been regularly exposed to different pitch structures within complex tones in music (e.g., Western versus Indonesian musicians; Parncutt, 1989).

In my attempt to explain MmT, I will side not with Pythagoras and Plato, who emphasized the role of mathematical relationships, but with Aristotle and Aristoxenus, who emphasized the role of perception, observation, and empiricism in acquiring knowledge (Dyer, 2007; Litchfield, 1988). My approach is similar to Krumhansl's in that it relies neither on mathematical abstractions (integer ratios) nor on notational conventions (enharmonic spellings). Instead, I will consider only empirically observable phenomena. I will focus on the perception of pitch patterns in the chromatic scale, regarding scale steps as pitch categories rather than specific frequencies.

My theory involves frequency ratios, but only *indirectly* and *approximately*. The harmonic series is perceived within voiced speech sounds and other musical or environmental complex tones, but its perception is affected by pitch shifts due to masking and loudness (Terhardt, Stoll, & Seewann, 1982) as well as physical inharmonicities (e.g., in freely vibrating strings), so its cognitive correlate is slightly distorted. Moreover, I assume that the tuning of the chromatic scale in real music corresponds only approximately to equal temperament (cf. Aristoxenus' "diatonic" division of the octave into five tones and two semitones; Winnington-Ingram, 1932). Approximate equal temperament was in widespread use in instrumental music long before the first volume of Bach's *Wohltemperiertes Clavier* appeared in 1722—for example in the tuning of fretted instruments in the 16th century (Lowinsky, 1961, p. 46)—and is still the main form of tuning in Western music. Despite the widespread use of keyboards, most music is still performed on instruments whose tuning can be varied in performance, including the singing voice.

The K-K Profiles: Robust or Context Dependent?

The robustness of the K-K profiles has been demonstrated repeatedly by Lola Cuddy and collaborators. Under Cuddy's supervision, Thompson (1986) presented listeners with selected Bach chorales followed by octave-complex probe tones and asked listeners "how well probe tone fit the chorale in a musical sense on a scale from 1 to 7" (p. 69). He obtained major key profiles that were very close the major K-K profile (rank order or ratings for "exemplar 1": C, G, F, E, D, A, D#/A#, G#, B, F#, C#). Steinke and colleagues (1993, 1997/1998) presented a diatonic melody in a major key in piano timbre that was "characterized by simple elaborations of the tonic triad" (p. 85), a IV-V-I triadic progression in a major key composed of octave-complex tones, or a iv-V-i progression in a minor key; one hundred listeners rated on a scale of 1 to 10 how well the probe tone fit in with the preceding melody or progression. Results for listeners with low, moderate or high music training were strongly correlated; the main difference was that the range of mean responses was greater for musicians, reflecting their greater confidence. This finding is consistent with Krumhansl's assumption that, regardless of the music training of the participants, the profiles are determined primarily by passive exposure to tonal music (implicit memory)—not learned music theory (explicit memory). The rank order of mean responses for all subjects for the triadic C-major melody was C, G, E, D, F, A, D#, C#, F#, G#, B, A#; for the C-major progression, C, G, E, F, A, D#, D, A#, C#, G#, B, F#; and for the C-minor progression, C, Eb, G, Ab, F, D, Bb, C#, A, B, F#, E (cf. Figure 1).

The K-K profiles are determined by a combination of short-term memory for the specific stimulus and long-term memory for tonal music. Their exact shape depends on the specific stimuli used to establish a major or minor key, as well as musical experience of the listeners. Stimulus effects involve tone type (pure, harmonic complex, octave complex) and musical texture (melodic or harmonic). The method of Krumhansl and Shepard (1979) was similar to that of Krumhansl and Kessler (1982) in that octave-complex tones were used, but different in the use of a melodic rather than a harmonic stimulus (a rising scale), which can explain the differences in the profiles. The music-theoretically surprising finding of Krumhansl and Kessler that $\hat{3}$ is more stable than $\hat{5}$ in a minor key (see Figure 1) may be limited to tonal contexts constructed from octave-complex tones; the finding was replicated by Steinke et al. (1993; 1997/1998), who also used octave-complex tones, but not by Budrys and Ambrazevičius (2008), whose tonal contexts were constructed from chords of harmonic complex tones. A possible explanation is that the dominant and tonic triads presented by Budrys and Ambrazevičius were in root position, which increased the stability of $\hat{5}$ and reduced the stability of $\hat{3}$.

Modeling the K-K Profiles

The K-K profiles have inspired a number of explanatory models that have enjoyed various degrees of success. In this section, I evaluate and compare a number of models and model candidates.

Chroma Prevalence

The K-K profiles are widely assumed to represent listeners' familiarity with tonal Western music, based on passive exposure to that music. Specifically, the profiles are assumed to reflect *chroma prevalence*—the relative frequency of occurrence of the 12 chromas in a musical performance or score. According to Krumhansl and Kessler (1982), "In music certain tones are emphasized by their prevalence, particularly at phrase beginnings and endings, and these tones typically have longer duration and are given greater rhythmic stress" (p. 363). Krumhansl (1990) showed that chroma prevalence profiles of European vocal works from the 18th and 19th centuries, as determined by Youngblood (1958) and by Knopoff and Hutchinson (1983), correlated with the corresponding K-K profiles. Her analysis was based on frequency of occurrence of onsets, whereas Lantz and Cuddy (as cited in Smith & Schmuckler, 2004) found that the dependency of tonal stability on prevalence primarily involved duration. Järvinen (1995) replicated Krumhansl's finding on the basis of transcriptions of melodic jazz improvisations. Huron (1993) demonstrated that the more stable pitches in the K-K profiles are more likely to be doubled than less stable pitches (e.g., in four-part voicings of triads). Oram and Cuddy (1995) determined tone profiles following non-diatonic sequences in which chroma prevalence had been carefully controlled; consistent with the theory that the profiles arise from passive exposure to music, tone profiles from musically trained listeners could be accounted for by a combination of chroma prevalence (bottom up) and chroma stability in major and minor tonalities according to the K-K profiles (top down) (see also Cuddy, 1997). Krumhansl, Louhivuori, Toiviainen, Järvinen, and Eerola (1999) demonstrated that listeners were sensitive to prevalence distributions of tones and tone transitions in Finnish spiritual folk hymns. More generally, Eberlein and Fricke (1992) and Eberlein (1993) observed that listeners were sensitive to the prevalence of specific harmonic-melodic patterns (e.g., chord progressions) in tonal music. Listeners' general sensitivity to chroma prevalence in tonal music is analogous to sensitivity to prevalence in other domains such as language (e.g., Saffran, Aslin, & Newport, 1996), suggesting a similar underlying mechanism (self-organizing neural networks; Tillmann, Bharucha, & Bigand, 2000).

Roughness

How did acoustical factors influence the history of MmT? Krumhansl and Kessler (1982) recognized that "the role played by the factors of overtone structure and frequency ratios in the initial construction of the tonal hierarchy, at least that found in Western music, cannot be ruled out" (p. 364), but did not further explore that possibility. Realizing the greater potential of *psycho*-acoustic considerations to explain the K-K profiles, Krumhansl (1990, Chapter 3) systematically compared the profiles with existing data on and models of the consonance of harmonic intervals (Helmholtz, 1863/1954; Hutchinson & Knopoff, 1978; Kameoka & Kuriyagawa, 1969; Malmberg, 1918). Consonance has been defined in many different ways (Tenney, 1988); in harmonic intervals, it may be considered after Terhardt (1976) as a combination of fusion (Stumpf, 1911) and lack of roughness (Helmholtz, 1863/1954). While many of Krumhansl's comparisons were moderately successful, with correlation coefficients between the K-K profiles and predictions of six models (each for major and minor keys) ranging from .38 to .83 (mean .61; $df = 10$), doubts may be raised regarding the conceptual validity of such an approach, because it mixes arguments about intervals with arguments about scale-steps. From a music-theoretical or music-perceptual standpoint, one would not expect the consonance of an isolated interval to be directly related to the stability of the scale degree at that interval above the tonic (as pointed out by Larson, 1997).

TABLE 1. Comparison of the K-K Profiles with Four Predictors.

(a) Major key

chroma	K-K	Smith	Lerdahl	Butler	Parn89	Parn88
0	6.35	11.0	5	8	11.5	18
1	2.23	0.5	1	0	0.2	0
2	3.48	7.0	2	4	3.7	3
3	2.33	0.5	1	0	0.5	3
4	4.38	9.0	3	7	4.5	10
5	4.09	5.5	2	2	3.9	6
6	2.52	2.5	1	0	0.1	2
7	5.19	10.0	4	9	8.3	10
8	2.39	4.0	1	0	0.5	3
9	3.66	8.0	2	3	3.7	7
10	2.29	2.5	1	0	0.7	1
11	2.88	5.5	2	3	1.7	0

Pearson correlation coefficients (all p < .01):

	K-K	Smith	Lerdahl	Butler	Parn89
Smith	.91				
Lerdahl	.98	.90			
Butler	.91	.93	.95		
Parn89	.99	.89	.98	.91	
Parn88	.94	.82	.91	.82	.93

(b) Minor key

Chroma	K-K	Smith	Lerdahl	Butler	Parn89	Parn88
0	6.33	11.0	5	8	9.6	15
1	2.68	2.5	1	0	1.1	1
2	3.52	5.5	2	4	2.8	2
3	5.38	9.0	3	7	7.1	13
4	2.6	0.5	1	0	0.8	0
5	3.53	7.0	2	2	4.3	8
6	2.54	0.5	1	0	0	0
7	4.75	10.0	4	9	9.4	10
8	3.98	5.5	2	3	5.6	8
9	2.69	2.5	1	0	0.3	2
10	3.34	8.0	1	0	1.3	1
11	3.17	4.0	2	3	2.1	3

Pearson correlation coefficients (all p < .01):

	K-K	Smith	Lerdahl	Butler	Parn89
Smith	.89				
Lerdahl	.94	.82			
Butler	.90	.81	.95		
Parn89	.94	.86	.95	.94	
Parn88	.95	.83	.90	.86	.94

Abbreviations: **chroma** = chromatic scale step in semitones above the tonic, **K-K** = K-K profiles (Krumhansl & Kessler, 1982; Krumhansl, 1990, p. 30), **Smith** = inverse (12-x) of *rank of cumulative consonance* (Smith, 1997), **Lerdahl** = inverse (5-x) of *pitch-class embedding distance* (Lerdahl, 1988), **Butler** = prevalence of notated pitches in K-K's stimuli (cf. Butler, 1989), **Parn89** = like Butler, but weighted by a model of pitch salience (Parncutt, 1989), **Parn88** = calculated chroma salience profile of tonic triad (*pitch weights* of Parncutt, 1988) with root support weights P1/P8 = 10, P5 = 5, M3 = 3, m7 = 2, M2/M9 = 1 (all other intervals including m3 = 0)

There is presumably an indirect, historically and perceptually mediated relationship between the two, but that relationship is complex and unclear. At any rate, a clear relationship between interval consonance and scale-step stability would be inconsistent with the separate existence of major and minor keys. For example, the M3 is a relatively consonant interval, but the corresponding chromatic scale degree is of course unstable in a minor key. And the fact that a harmonic P5 is perceived as consonant by Western listeners and treated as such by composers cannot explain why $\hat{1}$ is more stable than $\hat{5}$ in a major or minor key. The "smoothness" (i.e., lack of "roughness") of the P5 is not directional; it does not apply to one tone of the interval more than it does to the other.

Short-Term Memory

Table 1 presents the results of various models of the K-K profiles. The first (and most parsimonious) model is the stimulus profile of Butler (1989)—a short-term memory model. He simply counted the number of times each notated chroma occurred in the experiments of Krumhansl and Kessler—like a long-time average spectrum (Jansson & Sundberg, 1975) applied to sonorities of octave-complex tones. Butler averaged over tone profiles following four different contexts: in C major, the diatonic chord progressions F-G-C, d-G-C, a-G-C and a C chord alone; in C minor, similarly (all progressions were presented in all 12 chromatic transpositions). In Table 1, the "Butler C-major profile" is obtained by counting how many times each chroma occurs in the hypothetical chord sequence F-G-C-d-G-C-a-G-C-C-C-C (cf. Leman, 2000; Parncutt, 1989). This procedure approximately models the prevalence of these chord functions in tonal music (tonic more prevalent than dominant, dominant more prevalent than other diatonic triads); the author has attempted to incorporate a more precise setting of these probabilities according to data of Budge (1943), but the correlation coefficients with the K-K profiles were not improved. Comparing the Butler profiles with the corresponding K-K profiles yields significant correlations of $r = .91$ for the major key and $r = .90$ for the minor, consistent with Butler's (1989) assertion that most of the information contained in the K-K profiles is already present in the notation of typical cadential progressions. Butler's approach does not, however, explain the profiles obtained by Krumhansl and Shepard (1979) following scales (rather than chord progressions), unless the scales are assumed to imply chord progressions or the perception of MmT is assumed to be based on learned properties of familiar chord progressions.

Consonance and History

The relative stability of scale steps may be indirectly influenced by variations in the consonance of individual sonorities. Smith (1997) suggested that "tonal consonance leads to the frequent use of certain tones, which in turn leads to the perceived differences in key context stability" (p. 186). In other words, consonance influences prevalence, which in turn influences stability. Smith attempted to account for the major-minor system and for the K-K profiles by considering the harmonic consonance of progressively more complex musical elements, as follows. The most consonant harmonic interval class is the P4/P5. This interval also has a clear root, corresponding to the upper tone of the P4 (or the lower of the P5). According to Terhardt (1976), that tone has greater perceptual salience or clarity. The root of the P5 interval corresponds to $\hat{1}$ in the major-minor system and the other tone to $\hat{5}$. This is the only step in Smith's model where a psychoacoustic parameter other than sensory consonance is invoked. The most consonant triads that may be obtained by adding one tone to P4/P5 dyad are the major and minor triads. The most consonant tetrads that may be obtained by adding one tone to the major and minor triads are the major added-sixth chord (e.g., C6 = CEGA) and the minor seventh chord (e.g., Cm7 = CEbGBb) respectively. In subsequent steps of Smith's model, the tones D, B, and F are added to the C6 chord and the tones F, Ab, and D to the Cm7 chord to produce the C major and C harmonic minor scales, respectively. As shown in Table 1, the order in which tones are added by Smith corresponds well to the K-K profiles ($r = .91$ for major, .89 for minor). This procedure is reminiscent of the historical procedures of *musica ficta*: favoring consonant intervals means that tritones against the tones of the tonic triad are avoided.

Tonal Pitch Space

Another approach to modeling the K-K profiles is to build a hierarchical, music-theoretical model of tonal stability. Lerdahl (1988) proposed a 5-level tonal pitch space in which the top level includes only $\hat{1}$, the second $\hat{1}$ and $\hat{5}$, the third $\hat{1}$, $\hat{3}$ and $\hat{5}$, the fourth the diatonic scale $\hat{1}\ \hat{2}\ \hat{3}\ \hat{4}\ \hat{5}\ \hat{6}\ \hat{7}$, and the fifth the chromatic scale. These levels correspond to stages in Smith's model: they follow in much the same order, and may be justified on the basis of similar historical and perceptual arguments. Comparing the first and second levels, the tonic lies at the root of a P5, which can be justified in terms of Terhardt's pitch theory. The third level is represented by the tonic triad, presumably for reasons of harmonic consonance (smoothness, fusion). The fourth level in Lerdahl's model corresponds to a series of steps in Smith's model, in which tones are successively added. A quantitative predictor of tonal stability may be constructed from Lerdahl's space simply by counting the number of levels to which each chromatic tone belongs: $\hat{1}$ belongs to five levels, $\hat{5}$ to four levels, and so on (Temperley, 1999, 2001). The resultant profiles, which are presented in Table 1, correlate strongly with the K-K profiles ($r = .98$ for the major key and .94 for the minor). The weaker correlation in the minor key is presumably because $\hat{5}$ is more stable in Lerdahl's model than $\hat{3}$ in both major and minor modes, but this relationship is reversed in the minor K-K profile (see Figure 2). This difference calls into question the psychological reality of Lerdahl's distinction between the second (dyad) and third (triad) levels. Apart from that, the model successfully combines conceptual and mathematical simplicity with predictive accuracy.

In the above discussion, differences between correlation coefficients are often not significant at the $p < .05$ level. I will assume that this problem is not serious. Examples of pairs of correlation coefficients over 12 cases whose difference is just significant ($p \approx .05$) using a two-tailed test are .99 and .94; .98 and .88; .95 and .72. But such calculations are misleading when the underlying assumption of 12 independent measures does not hold. Moreover, qualitative considerations are also relevant to this discussion: a theory may be preferred for its inherent psychological or music-theoretical logic, or for its consistency with the history of tonal syntax and theory.

Pitch Salience Models

The above methods mostly neglect variations in perceptual salience among chord tones, and all neglect the possible role of virtual pitches that do not correspond to musical notes (i.e., missing fundamentals of approximately harmonic series of spectral pitches). According to Terhardt (1972), a sonority or *Klang* (a complex tone or a musical chord) evokes a virtual pitch when a set of spectral pitches corresponds to lower elements of a harmonic series. The virtual pitch corresponds to the fundamental of the pattern, regardless of whether there is an audible pure tone component at that frequency or not. The salience of a virtual pitch (the pitch's perceptual strength) may be operationalized as the probability that a listener will be consciously aware of the pitch—a definition that applies equally well in pitch-matching experiments and music listening settings. The salience of a virtual pitch depends on the number and salience of spectral pitches forming a harmonic pattern above it, how well they are tuned to that pattern, and the harmonic numbers at which matches occur (spectral pitches corresponding to lower harmonics have more effect). Since a virtual pitch need not correspond to a spectral pitch, it need not correspond to a musical note, either. A familiar example is the missing root at $\hat{5}$ that is perceived under a diminished triad on $\hat{7}$ (e.g., the G that is perceived under a BDF-sonority in the key of C major or minor); for empirical confirmation see Parncutt (1993).

How perceptually (or musically) real (or important) are such missing fundamentals in musical contexts? Cook (1989) noted that music listeners "do not necessarily hear notes as separate entities and indeed they sometimes do not hear them at all, at least in a manner that directly corresponds to what is visible in the score" (p. 121). Empirical data of Hutsteiner (2000) suggest that the salience of pitches at missing fundamentals is not reduced by voice leading in chord progressions. The empirical data of Seither-Preisler et al. (2007) further suggest that musicians hear pitches at missing fundamentals more strongly or clearly than nonmusicians, which implies that they hear chord roots more clearly, even when they are missing (as for example in typical bebop jazz voicings). In a similar experiment, Schneider et al. (2005) found no difference between musicians and nonmusicians; both heard pitches at missing fundamentals.

Parncutt's (1989) model accounted for missing fundamentals and variations in pitch salience in the following way. First, all partials (pure tone components) in a sonority were assigned to chromatic scale steps (tuning variations smaller than plus/minus a quartertone and pitch shifts were neglected). The audibility of each partial was predicted by a simplified version of the masking algorithm of Terhardt et al. (1982). The salience of virtual pitches was predicted by a pattern matching procedure in which the pattern to be matched was the harmonic series, which had also been categorized into the chromatic scale (e.g., the interval between the fourth and seventh harmonics was ten semitones). The series was limited to the first ten harmonics on the assumption that higher harmonics are rarely separately audible, and the harmonics were weighted such that lower harmonics played a more important role than higher harmonics. To analyze a given sonority, the harmonic pattern was shifted in steps of one semitone across the entire audible range. At each position, the match between the pattern and the audible spectrum of the sonority was calculated. The result was a virtual pitch at the fundamental of the pattern whose predicted salience depended on the number of matching harmonics (i.e., the number of audible partials in the sound corresponding to harmonics of the virtual pitch), their salience, and the salience of the corresponding template elements. If there was no match, the predicted salience at the fundamental of the template was zero. Following Terhardt et al. (1982), Parncutt (1989) assumed that the pitch with the highest calculated salience was most likely to be noticed by a typical listener when the sonority was presented in isolation in a regular pitch-matching or probe-tone experiment. I also assumed that other pitches with relatively high salience would be noticed (*pitch ambiguity, pitch multiplicity*), and that calculated pitch salience was a measure of the probability of noticing a pitch.

In Parncutt (1989), I used this model to predict the K-K profiles. My approach was similar to Butler's stimulus profile: chroma salience profiles were calculated for each chord used in the experiments of Krumhansl and Kessler, and the profiles were added across time to predict the overall tone profile of the progression. The results, reproduced as "Parn89" in Table 1, were quantitatively more promising than those of Butler, with a correlation coefficient of .98 for the major key and .94 for the minor—consistent with the assertion that virtual pitches play a role in the perception of MmT. Moreover, the model appeared to solve the problem of the relative stability of $\hat{3}$ and $\hat{5}$ in minor keys: $\hat{3}$ was predicted to be weaker than $\hat{5}$ in major keys and stronger in minor, in agreement with the K-K profiles. Since this difference was neither expected and nor music-theoretically self-evident, it can be regarded as *surprising* in the sense of Honing (2006): a model's validity depends not only on the goodness of fit between predictions and empirical data, but also on the degree to which the model's (correct) predictions are "precise (constrained), nonsmooth, and relatively surprising" (p. 374).

In Parncutt (1994), I presented convergent evidence that missing fundamentals and variations in pitch salience contribute to chroma stability profiles. In Table 3 of that paper, the individual stimuli presented to listeners by Krumhansl and Kessler were psychoacoustically modeled. For each chord progression or single chord, I calculated a chroma salience profile (accounting for missing fundamentals and variations in pitch salience) and correlated it with both the corresponding stimulus profile and the mean goodness-of-fit ratings of the listeners in Krumhansl and Kessler's experiment. Correlation coefficients were consistently higher when missing fundamentals and variations in pitch salience were taken into account.

Parncutt (1988) radically simplified the pitch model of Terhardt et al. (1982) by removing all information about tuning and octave register, and neglecting masking on the assumption that many different voicings—inversions, spacings, doublings—are possible for a given chord type. The advantages of a simpler model are both scientific (it is more parsimonious and falsifiable; Nolan, 1997) and practical (it is more memorable, and hence useful in music theory and pedagogy). In general, a more parsimonious model may be more useful because it is more comprehensible, but it is not necessarily more accurate (Domingos, 1997). The model was also inspired by the even simpler model of Terhardt (1982), who predicted the root of a chord by a pattern-matching procedure involving the intervals between the fundamental and (typically audible) overtones of a harmonic complex tone. These intervals, when collapsed into the range P1 to M7 (0–11 semitones), are P1, P5, M3, m7, and M2 (or 0, 7, 4, 10 and 2 semitones).[3] Terhardt (1982) simply counted the number of harmonic intervals above each root candidate. In Parncutt (1988), I called these intervals "root supports" and weighted them relative to each other. For the present calculation (Parn88 in Table 1), these weights are set to P1/P8 = 10, P5 = 5, M3 = 3, m7 = 2, M2/M9 = 1, and m3 = 0. This set of weights differs from those in Parncutt (1988), in which I erroneously assumed the m3 to be a root-support interval, and has been used in all relevant publications since Parncutt (1994).

Summarizing, the correlation coefficients presented in Table 1 suggest that predictions based on Lerdahl's pitch space and Terhardt's virtual pitch algorithm model the K-K profiles most closely. Comparing the different predictors, those labeled "Lerdahl," "Butler," and "Parn88/89" are similar to each other, because all are similar to the stimulus profile of the chord progressions in the K-K experiments. "Lerdahl," "Parn88," and "Parn89" go beyond the stimulus profile in quantitatively similar, but theoretically different ways. Only "Parn88" and "Parn89" account for the reversal of the relationship between $\hat{3}$ and $\hat{5}$ in major and minor keys.

Comparison of Smith (1997) and Parncutt (1988)

Although correlations with the predictions of Smith (1997) in Table 1 are not particularly good, his model is conceptually interesting due to its original combination of psychoacoustical and historical ways of thinking. Smith modeled the K-K profiles by gradually building

[3]The following interval abbreviations are used throughout this paper: P1 = perfect unison (0 semitones); m2 = minor 2nd (1 sem); M2 = major second (2 sem): m3 = minor third (3 sem); M3 = major third (4 sem); P4 = perfect 4th (5 sem); A4 = aug 4th, d5 = dim 5th, TT = tritone (6 sem); etc.

up the major and minor scales according to psychoacoustic principles. He added new tones one by one, systematically investigating the dissonance of all (harmonic) intervals between each new tone and the other tones. Scale steps that minimized harmonic dissonance with existing scale steps were assumed to be preferred, and hence became more prevalent as tonal-harmonic syntax developed. Smith's approach is consistent with Krumhansl's assumption that the K-K profiles are primarily determined by prevalence. Since frequently sounded tones produce better goodness-of-fit judgments in probe-tone experiments, they presumably also affected the perception of musicians and audiences of the relevant historical period (Renaissance). As a result, they became stable points of reference in the tonal system.

In this paper, I combine historical and perceptual arguments in a different way. I argue that listeners in different historical periods learn by experience which tones best follow major and minor triads in musical contexts. The shape of the chroma salience profiles of major and minor triads is essentially given in advance: it is determined by the way pitch is perceived in non-musical sounds (especially speech). In this sense, the chroma salience profile of a chord may be regarded as its *perceptual microstructure*. The correlations in Table 1 between "K-K" and "Parn88" suggest that tones figuring prominently in the perceptual microstructure of a tonic triad are perceived as stable in the corresponding tonality. They are therefore sounded more often than unstable tones. The degree to which a tone is heard to complete a tonal passage (the probe tone rating) may depend primarily on how well that tone represents or stands for the tonic triad: that is, the salience of that pitch within the piece's main referential sonority. The harmonic or static aspect of the cognitive representation of MmT may thus be little more than a perceptual representation of the tonic triad. The fact that listeners from a wide range of musical backgrounds and levels of expertise produce consistent and stable tone profiles in probe-tone experiments is consistent with the idea that the sound of major and minor triads (and their typical continuations in tonal contexts) is highly familiar (overlearned) in Western culture.

Which model is preferable? Smith's (1997) model and my present approach (based on Parncutt, 1988) are similar in two respects. Both combine psychological and historical arguments, and both correlate significantly with the K-K profiles. The models differ in that Smith took the tonic *tone* as a point of departure and considered the consonance of different possible sonorities, whereas I start with the tonic *triad* and consider the salience of chromas within that triad.

A further similarity is that both models attempt to explain tonal structures on the basis of perceptual phenomena that are originally nonmusical (the perception of pitch and roughness), and to situate these explanations in a historical context. In that sense, they may be regarded as causal or axiomatic (Milne, 2009). Both begin by assuming a general preference for psychoacoustically based consonance among sonorities of different chromas. Both incorporate an explanation of the special status of major and minor triads in Western music. Both approaches propose a specific, perceptual-historical chain of events. In Smith's (1997) account, interval consonance determines scale-degree prevalence, which in turn determines goodness of fit (the K-K profiles) and tonal stability (in music theory). In my approach, pitch salience determines goodness of fit between individual tones and musical contexts, which in turn determines the prevalence of individual tones and the stability of scale steps.

To what extent is it possible to distinguish between models whose quantitative predictions match the data? How can we distinguish explanations of the major-minor system that come to similar conclusions on the basis of different premises? Against what objective criteria can Smith's explanation based on interval consonance be evaluated relative to the present explanation based on pitch salience? The models do not differ strikingly according to general qualitative criteria of parsimony or historical validity. Both models build on the idea that major and minor triads are consonant because they avoid rough seconds and tonally ambiguous tritones. Smith observes that the major and (natural or harmonic) minor scales promote perfect fourths/fifths and avoid tritones between tones of the tonic triad and other scale tones. In my approach, the tones of the major and minor scales are perceptually salient within their respective tonic triads.

It is possible that both models are correct. Both posit processes that may have influenced the historical development of tonal syntax. I prefer the pitch salience approach for the following reasons:

- The correlation coefficients between predictions and data are higher for the pitch salience model (see Table 1). Whether this difference can be regarded as significant is unclear, as discussed earlier.
- The pitch-salience model avoids arbitrary assumptions about the historical order in which new dissonances were added to existing consonances. Quantitative predictions are made directly on the basis of a single musical element, the tonic triad, rather than a set of

different elements. The stages of Smith's (1997) model do not correspond well to the historical development of tonal syntax. Smith assumed that major added-sixth chord (MM6) and minor seventh chord (mm7) are more consonant, and hence more prevalent, than major-minor (Mm7, dominant) seventh chords, but the reverse was the case in the music of the 18th and 19th centuries (Eberlein, 1994). The first known notated unprepared seventh chord—in Monteverdi's Madrigal *Cruda Amarilli*—was a Mm7 (Choron, as cited in Simms, 1975; see also Dahlhaus, 1986). According to Parncutt (1988, 2009), the Mm7 chord has the lowest *root ambiguity* of all possible tetrads in the chromatic scale. But preliminary analyses of 17th century music (Schütz, Buxtehude) have yielded no clear preference for Mm7 by comparison to MM7 and mm7 (Eberlein, personal communication, 1997); and mm7 (or MM6) and MM7 were more common that Mm7 in some late 20th century popular music styles, suggesting a change in the relative importance of fusion and roughness. In any case, the process by which tones are added cumulatively to existing sonorities in Smith's model does not reflect the history of tonal-harmonic syntax in a clearly interpretable way.

- The pitch-salience model accounts for a wider range of observable phenomena than Smith's (cf. Terhardt et al., 1982). It quantitatively predicts profiles of pitch salience in isolated sonorities (e.g., Thompson & Parncutt, 1997), scale-degree prevalence in tonal music (e.g., Aarden, 2003), and the perceptual fusion of musical intervals (DeWitt & Crowder, 1987). In music theory and analysis, it predicts chord roots and patterns of chord-scale compatibility (Parncutt, 1988, 1993). As a model of the K-K profiles, it predicts relationships between musical keys (Huron & Parncutt, 1993; Krumhansl, 1990), octave doubling in chord progressions (Huron, 1993), and expressive patterns of timing and dynamics in music performance (Sundberg, 1988; Thompson & Cuddy, 1997).

Differences Between Chroma Stability, Prevalence, and Salience

The match between the three posited kinds of chroma profile—stability, prevalence, and salience—is clearly not perfect, and the theory of their interrelationship is limited in its domain of application. Consider first the relationship between stability and salience.

Figure 1 compared the K-K profiles with chroma salience profiles of corresponding tonic triads (after Parncutt, 1988). The profiles differ in the following ways. In the key of C major, the chroma salience profile predicts that E^b and D are about equally stable, E and G likewise; B is less stable than B^b. All three predictions contradict both the K-K profile and music-theoretical intuition. In C minor, the chroma salience profile predicts that F is more stable than D, contradicting both the K-K profile and music-theoretic intuition; it also predicts that B is more salient than B^b.

These deviations can be explained in two ways. First, they may be due to familiarity with patterns that occur frequently in tonal music. Familiarity with the dominant-tonic progression, or short-term memory for the dominant triad (Parncutt & Bregman, 2000), can account for the relatively high values for the tones G and D in the K-K profiles in both modes. Both these tones belong to, and are perceptually salient within, the dominant triad, which was the penultimate chord in most of the progressions presented to listeners by Krumhansl and Kessler (1982). Familiarity with tonal music can also explain aspects of the tone profiles of Thompson and Parncutt (1997): the dyad CG produced a peak at E, and the dyad CE at G, which could not be accounted for by psychoacoustic pitch theory. Second, the deviations may be artifacts of voice leading between the final triad in Krumhansl's experiments and the probe tone. A combination of familiarity with common chords and effects of voice leading can account for the relatively high value at B in C major and at Bb in C minor, both in the K-K profiles and in the data of Parncutt (1993) for individual major and minor triads. When a probe tone on B follows a CEG-sonority, the C is heard to move to B (since the closest tone in the sonority to the probe is C) against an unchanging background of E and G. Larson (1997) explained the effect as follows: "In a melodic step, the second note tends to displace the trace of the first, leaving one trace in musical memory; in a melodic leap, the second note tends to support the trace of the first, leaving two traces in musical memory" (p. 105). The result may be a new triad in the mind of the listener: EGB. Since this triad is familiar and consonant, the probe-tone rating for B is relatively high. Similarly, when the probe tone Bb follows CEbG, the Bb may be heard as a continuation of the previous C, creating the triad EbGBb. A new triad may also be created by adding A to CEG to imply ACE, and by adding Ab to CEbG to imply AbCEb; but the corresponding pitches—A in C major, Ab in C minor—are already accounted for by Terhardt's (1972) model.

This approach can explain why Temperley (1999) reduced the value for Bb in Krumhansl's C-minor profile for theoretical purposes. But it cannot explain why he increased the value assigned to the leading tone in both modes, to account for its tonicizing role. For the following reasons, it may be appropriate to treat the leading tone separately. First, the K-K profiles may represent the tonic *triad*, whereas the leading tone effect involves the tonic *tone*. Second, the leading tone may have emerged in the 13th-14th centuries, whereas the relationship between the chroma salience profiles of triads and the chroma stability profiles of keys may have emerged in the 15th-16th centuries (cf. Parncutt & Prem, 2008).

There are also interesting differences between chroma prevalence and chroma stability profiles. Aarden (2003, cited in Huron, 2006b), calculated chroma prevalence profiles based on a large sample of melodies in major and minor keys. The rank order of prevalence for diatonic scale degrees was $\hat{5}$, $\hat{3}$, $\hat{1}$, $\hat{2}$, $\hat{4}$, $\hat{5}$ $\hat{6}$, $\hat{7}$ in major, and $\hat{5}$ & $\hat{1}$, $\hat{3}$, $\hat{4}$ & $\hat{2}$, $\hat{7}$, $\hat{6}$ in (natural) minor. These ranks differ from the K-K profiles in ways that are explicable in terms of virtual-pitch theory. In Aarden's sample (which is consistent with Krumhansl, 1990, Table 3.4), the tonic is presumably always perceived as $\hat{1}$ rather than $\hat{5}$—even when $\hat{5}$ is considerably more prevalent. The reason is evidently the strong root-supporting function of the P5 interval (Parncutt, 1988; Terhardt, 1982). This effect has presumably been perceived in both triadic sonorities and arpeggiated triads since about the 14th century. The difference between the prevalence and stability profiles is greater for the major key—presumably because the root of the major triad is clearer, which again has a psychoacoustical explanation. Such effects might be accounted for in a general quantitative approach by considering variations in pitch salience when calculating chroma prevalence; that is, by calculating a running measure of *cumulative chroma salience* in which more recent events are weighted more heavily (Huron & Parncutt, 1993; Parncutt, 1989).

The Tonic as Triad

Definitions and explanations for tonality in general and MmT in particular vary within and between humanities (Dahlhaus, 1967/1990; Eberlein, 1994) and sciences (Krumhansl, 2004; Vos, 2000). Part of the problem is the ambiguity of the term "tonic." In music theory, the tonic may be a single chroma, a chord comprising (as a rule) three chroma, or a scale (the tonic key as suggested by the key signature). Krumhansl and other music psychologists have used the word "tonic" in the sense of a single chroma—"a central reference pitch . . . is called the tonic, or tonal center" (Krumhansl, 1990, p. 16)—and denoted the tonic triad as Roman numeral I rather than "the tonic." The analyses of the previous section have supported a model of MmT based on pitch salience within the tonic triad, suggesting that the tonic in major-minor music is primarily a triad rather than a single tone or pitch. In this section, I present further evidence in favor of this idea from music theory and psychology.

Music-Theoretical Arguments

The idea of the tonic as a triad (rather than a tone) has a long history in music theory. Sonorities have functioned as points of departure, return and repose since the 14th century (Fuller, 1986). Later relevant developments in the history of theory were summarized by Lester (1978). Zarlino (1573) cited the final, fifth, and third of the modes as the principal cadence points—consistent with the idea that the most stable degrees of a major or minor scale are the tonic, fifth, and third (cf. Krumhansl & Kessler, 1982; Lerdahl, 1988). Lippius (1610, 1612) differentiated between major and minor modes on the basis of the tonic triad, and other 17th century theorists followed suit, even if they did not recognize the triad as a harmonic unit.

The beginnings of triadic prolongation can be seen as early as the 14th century in the music of Guillaume de Machaut (Fuller, 1986, pp. 38, 49). Theoretic accounts of triadic prolongation emerged in the 17th century (Rivera, 1984). According to Novack (1977):

> The history of polyphony through the Middle Ages and Renaissance reveals the emergence of a new concept of tonality followed by its gradual intensification. Two basic stages took place. First, the triad, major and minor, evolved as the basis for identifying the primacy of a tone. Second, the creative ear discovered and developed different ways of prolonging in time the tonal unity identified by this central triad. (p. 82)

For Riemann (1893), the *Tonika* was not only the tonic triad, but a family of sonorities that can function as a tonic relative to subdominant and dominant harmonies. Schenker (1906/1954) regarded a tonal work as a temporal unfolding, prolongation, or composing-out of its tonic triad (cf. Forte & Gilbert, 1982; Schachter, 1995). Schoenberg (1954) agreed that the tonic of a tonal work remains constant throughout, in spite of passing modulations to other keys (*tonicizations*). According to Larson (1997), "prolongation—and only prolongation—always determines which notes are heard as stable in a given context," consistent with the idea that the K-K profiles represent prolongations of the tonic triad.

Music-Psychological Evidence

The final tonic triad in a cadence has been found repeatedly to have the greatest effect on the tone profile following the cadence, and hence on the K-K profiles. Krumhansl and Kessler (1982) observed that the tone profile of an isolated major or minor triad correlates significantly with the profile produced by a cadential progression in which that triad is the tonic. Huron and Parncutt (1993) assumed that the last chord of a sequence contributes more to the composite profile than previous chords (recency effect) and that sensory memory decays exponentially with a half-life of roughly one second (Temperley, 2001, proposed a value of four seconds). Parncutt and Bregman (2000) found that, in tone profiles following subdominant-dominant-tonic and tonic-dominant-subdominant progressions, most of the variance is accounted for by the final chord. Aarden (2003) found that the K-K profiles are more similar to the chroma prevalence distribution of the tones at the end of phrases than to the overall chroma prevalence profile, and observed that “the probe-tone method for measuring key profiles encourages listeners to treat the probe tone as being in phrase-final position” (abstract).

An explanation of the K-K profiles based on a single chord is consistent with existing empirical approaches in both cognitive psychology (Krumhansl & Kessler, 1982; Tillman et al., 2000) and psychoacoustics (Parncutt, 1989, 1993; Terhardt et al., 1982; Thompson & Parncutt, 1997). Table 2 compares and contrasts the relevant stimulus materials and terminologies. In Terhardt’s psychoacoustic paradigm, listeners hear a complex sound and a pure tone in alternation, and adjust the frequency of the pure tone until the two sounds have the same perceived pitch. In Krumhansl’s probe-tone method, the frequency of the probe tone is fixed, and listeners judge how well the tone fits with the preceding context. The likelihood that a given pitch will be chosen in the Terhardt’s paradigm corresponds well with the mean goodness-of-fit judgment for a probe tone at that pitch in Krumhansl’s approach. (I am assuming that the correlation between results using these two methods would be very high; to my knowledge, this assertion has not been directly tested.) In both approaches, serial order effects (the effect of the preceding trial on the current trial) are minimized by randomly transposing each trial around the cycle of fifths and presenting trials in a random order that differs for each listener. The two approaches differ in that Krumhansl often established a tonal context before asking listeners to make judgments about a sound or sound sequence (typical of cognitive paradigms in other domains), whereas Terhardt (and I) aimed to study the perception of sounds presented in isolation (typical of psychoacoustic traditions).

The conflict between these two empirical approaches and accompanying theoretical edifices manifested itself in subtle ways. In his writings on musical pitch, Terhardt consistently avoided references to directly relevant work by Shepard (1982) and Krumhansl (1990). Krumhansl (1990) questioned the way in which Terhardt et al. (1982) interpreted the predictions of their pitch model: “the values of root salience do not relate linearly to the experimental effects, nor do they explain the differences between major- and minor-key contexts” (pp. 174–175); this problem can be solved by assuming that music history mediates the link between general principles of pitch perception and corresponding features of tonal musical structure (see Figure 4). Krumhansl’s (1990) criticism of Parncutt’s (1989) model of her key profiles was addressed by Parncutt (1994): the model can explain not only the K-K profiles but also the tone profiles of the specific chord progressions upon which the K-K profile are based (cf. Parncutt & Bregman, 2000).

In retrospect, the conflict between these two schools is surprising, considering the similarity of their research questions and methods. The conflict can in part be resolved, and the similarities highlighted, by using the terms *psychoacoustic* and *cognitive* in their original senses. Terhardt’s *psychoacoustic* approach to pitch perception is also an example of biological information processing, i.e., *cognition*, and Krumhansl’s probe-tone method—the empirical basis of her *cognitive* approach—is also *psychoacoustic* in that it addresses the relationship between acoustical signals and psychological responses.

TABLE 2. Investigating Musical Pitch Perception: Two contrasting Approaches

Approach	Stimuli	Task	Result	Model
Psycho-acoustic (Terhardt)	Test sound then reference tone	Equalize pitch of test and reference	Pitch salience profile	Virtual pitch perception
Cognitive-structural (Krumhansl)	Key context then probe tone	How well does tone follow context?	Profile of scale-step stability	Chroma prevalence distribution

Limitations and Caveats

Before continuing, allow me to clarify what I am *not* claiming. I am not claiming that listeners in a probe-tone experiment necessarily expect to hear the tonic triad at the end of a tonal passage, nor do they necessarily imagine (audiate) the sound of a tonic triad (including its pitch pattern and timbral qualities) when judging how well a probe tone fits the previous context. The observed high correlation between the chroma salience profile of the tonic triad and probe-tone rating profiles can instead be understood as the result of a long historical process during which tonal-harmonic syntax was intuitively adjusted by generations of composers. The process began as Western listeners gradually became familiar with the sound of the major and minor triads and their typical tonal contexts. The process was presumably complete by the middle of the 17th century, when final sonorities in polyphonic textures were almost always triads.

A second claim that I am *not* making is that the perception of tonal center is based on a kind of cognitive running calculation of chroma prevalence. Instead, the direct, real-time basis of MmT perception is familiarity with specific, prevalent pitch-time patterns (chord progressions and voice-leading patterns; Auhagen, 1994) or paradigms such as typical tonic-predominant-dominant-tonic progressions (Caplin, 1998). In an ecological approach (Clarke, 2005; Gibson, 1979), such patterns may be regarded as invariants that allow a tonic to be recognized.

A final caveat is that profiles of chroma salience, prevalence, and stability account only for static or harmonic aspects of the perception and cognition of MmT. They say nothing about the typical voice-leading patterns or harmonic progressions that allow tonalities to be recognized. An isolated, repeated, or sustained triad is not necessarily perceived as a tonic; a repeated triad at the end of a sonata-form development section may be heard as a dominant, and one could discuss whether the extended Eb major triad at the start of Wagner's *Rheingold* is perceived as a tonic. In major-minor tonal music, a chord must normally progress to its dominant and back again—better, first to a subdominant (or predominant) harmony and then to the dominant—before one can realistically speak of establishing or instantiating a tonality (Caplin, 1998).

The History of MmT

Eberlein (1994) asked why Western musical syntax is like it is, and not quite different. In this context we may now ask: Is the model relating chroma salience, prevalence and stability presented above consistent with details of music history? If so, how can historical developments be incorporated into a broader psychological explanation or model of the emergence of MmT?

I argue that MmT emerged in the Renaissance in parallel with the growing familiarity of Europeans with the sound of major and minor triads and the typical voice-leading contexts in which they were heard. Chroma prevalence profiles in tonal music are the end-product of a long evolutionary process that involved countless changes in tonal-harmonic syntax. These were in turn accompanied by corresponding changes in the way tonal music is perceived (Eberlein, 1993, 1994; Parncutt, 1996). Thus, to explain and understand tonal syntax, we need to explain and understand its early development. Consider the following three interrelated hypotheses:

1. The central role of learning. From a general psychological perspective, all perception depends on learning (Gibson, 1969). From a general musicological perspective, real-time musical experience always depends on past musical experience (Cazden, 1980). Thus, chroma stability profiles are primarily learned from exposure to music (Krumhansl & Kessler, 1982; Krumhansl, 1990). The French music theorist François-Joseph Fétis proposed that once Western listeners got used to the sound of the authentic cadence, they always expected the dominant seventh to resolve to the tonic, which fundamentally changed their experience and appreciation of medieval and Renaissance music. He surmised that, after experiencing and internalizing *tonalité moderne* (the tonal music of the 19th century), it was impossible to experience *tonalité ancienne* (the tonality of the Renaissance) as people of that time did—unless one became musically bilingual, a possibility suggested by the music critic and journalist Joseph d'Ortigue (Thomas Christensen, personal communication, 2007). Similarly, the results of psychoacoustical experiments that involve musical sounds are generally influenced by the musical backgrounds of the listeners (Parncutt, 1989), and the relationship between empirical results and the predictions of pitch models is generally mediated by music history.

2. The gradualness of perceptual-cognitive-cultural change. The chroma salience profiles of musical chords can only be perceived after repeated exposure to those chords over a long period. That could explain why non-musicians were generally unable to perform the experimental tasks of Parncutt (1993) and Reichweger and Parncutt (2009). This observation can also explain the gradualness of MmT's historical emergence. Different modern commentators, assuming different definitions of MmT, proposed that MmT came into being during the 15th, 16th, or 17th century (Besseler, 1952; Dahlhaus,

TABLE 3. T_n-types of Cardinality 3 (after Rahn, 1980)

prime form	012	013	014	015	016	024	025	026	027	036	037	048
inversion		023	034	045	056		035	046			047	

Note: 012 corresponds to C-C#-C, 013 to C-C#-D# etc.; 037 is minor and 047 is major

1967/1990; Eberlein, 1994; Randel, 1971). The adoption of major and minor triads as compositional and theoretical entities was a similarly long historical process. That process historically preceded, but also overlapped with, the historical emergence of MmT, suggesting a causal connection.

3. The relationship between chords and scales. A third hypothesis is that the chroma stability profiles of major and minor keys became psychologically real in the 16th-17th centuries—after the major and minor triads had become musically commonplace and therefore familiar to Western listeners, performers, composers, and improvisers in the 15th-16th centuries. Since then, the chroma stability profiles of major and minor keys have been essentially identical with the chroma salience profiles of the corresponding major and minor triads.

A systematic investigation of these hypotheses involves questions such as: When did major and minor triads first become familiar to European ears? When and how did this development affect harmonic-tonal syntax? But before embarking on a historical analysis, it is instructive first to ask why it was the major and minor triads, and not some other sonorities, that became so structurally important in Western tonal music.

What is Special About the Major and Minor Triads?

Within the chromatic scale, it is possible to construct exactly 19 different triad qualities, of which the major and minor triads are two (see Table 3). In the terminology of Rahn (1980; based on Forte, 1977), there are 19 *Tn-types*, or pitch-class (chroma) sets that are invariant under transposition but not under intervallic inversion.[4] The 19 Tn-types comprise 12 normal forms (Tn/TnI-types that are invariant under transposition and intervallic inversion), and intervallic inversions in those 7 cases where the inversion cannot be mapped onto itself by transposition. The minor triad 037 is one of the 12 asymmetrical normal forms; its intervallic inversion is the major triad 047.

Of the 19 triad qualities, the major and minor triads are the most consonant, because only they satisfy both of the following criteria, derived from Terhardt's (1976) two-component model of consonance (Parncutt, 1988). First, they include the P5/P4 interval, which ensures fusion, clarity of the root, and hence clarity of harmonic function in a tonal progression. Second, they exclude the roughest harmonic intervals—the minor and major seconds and their inversions (the major and minor sevenths)—which ensures smoothness (or lack of roughness). Incidentally, no tetrad (chord of four chromas) can satisfy both these criteria, since a tetrad containing a P5/P4 must also include at least one second/seventh. Thus, the major and minor triads are the only sonorities of three *or more* chromas with a P5/P4 and no seconds. This simple, general explanation makes other more speculative or complex explanations for the central role of major and minor triads, such as the theory of harmonic dualism (Harrison, 1994; Hauptmann, 1853; Jorgenson, 1963; Oettingen, 1913; Riemann, 1905), redundant.

The Historical Emergence of Major and Minor Triads

Seen retrospectively, the major and minor triads were gems waiting to be discovered. But the criteria underlying the above arguments were largely irrelevant during the Middle Ages. The assumption that medieval and Renaissance music was based on the 12-tone chromatic scale is problematic. The sonorities that we now refer to as major and minor triads—and whose identity Lippius (1610, 1612) and Rameau (1721/1971) assumed to be preserved under chordal inversion—only appeared after a long period of compositional experimentation during which voice leading and melody were the guiding principles and modern concepts of chord construction and sonority did not yet exist. While it is important to avoid *presentism*—the distortion of interpretations of the past by the introduction of anachronistic modern concepts (Christensen, 1993)—no historical treatment can be entirely free of this problem, just as no ethnomusicological study of non-Western music by Westerners can entirely avoid ethnocentricity.

[4]The term "inversion" is used in this paper in two different senses, *intervallic* and *chordal*. The intervallic inversion of an interval of x semitones is an interval of 12-x semitones. The chordal inversion of a sonority or three or more notes (root position, first inversion, etc.) involves changing the register of the individual tones so that a different chroma is in the bass. The two terms have essentially the same meaning for dyads but not for sets of three or more tones.

TABLE 4. Historical Overview of Developments in Western Tonal Syntax

Century	Schools, composers, sources	Music-structural developments
11th–12th	Saint Martial school; Codex Calixtinus	• 2-part counterpoint (*organum*) • discant improvisation
12th–13th	Notre Dame school: Léonin, Pérotin (*ars antiqua*)	• 3- and 4-part counterpoint • 3rds, 6ths →imperfect consonances
14th	Vitry, Machaut (*ars nova*)	• double-leading-tone cadence • parallels forbidden but tolerated
15th	Dunstable, Dufay, Ockeghem	• falling-fifth cadence in 3 and 4 parts • *fauxbourdon:* parallel $^6_3$ triads • *falsobordone:* chains of $^5_3$ sonorities
16th	Palestrina, Lassus	• most sonorities are $^5_3$ (major&minor) • final triad replaces final fifth • *tierce de Picardie*
17th	Monteverdi, Lully, Schütz	• seventh chords, SDT progressions • theory of triads and inversions

If the perception and cognition of MmT depends on the historical developments that led to its emergence, a model of tonal cognition should be consistent with that historical process. Table 4 and Figure 3 give a schematic overview of that historical development. The first consistent use of harmonic thirds—first as passing dissonances, later as theoretically recognized consonances—may be regarded as a perceptual-historic precondition for the first consistent use of triads—again, first as passing dissonances, and eventually as theoretically recognized consonances—which in turn was a prerequisite for the first consistent use of triads as final chords, and hence for the emergence of MmT.

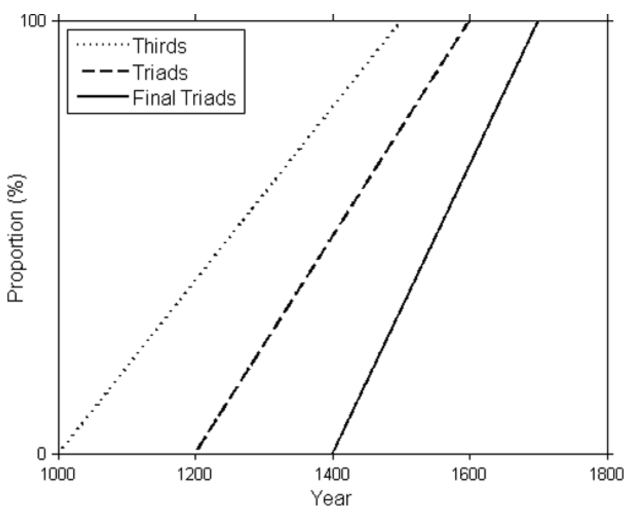

FIGURE 3. Semiquantitative sketch of historical variations in the prevalence of selected pitch structures in European music. Dotted line: assumed prevalence of harmonic major and minor third intervals, by comparison to other harmonic intervals. Broken line: assumed prevalence of major and minor triads ($^5_3$ sonorities) by comparison to other sonorities (excluding phrase endings). Full line: assumed prevalence of major and minor triads at phrase endings, by comparison to other simultaneities. The full line also corresponds roughly to the theoretical recognition of major and minor triads as well as the development of MmT.

The figure is intended to be no more than a sketch; the exact location and shape of the lines in the figure could only be reliably determined by a detailed analysis of representative databases of musical scores from different historical periods. Such an analysis may only be feasible from about 1200, due to a general lack of notated music before that time. Even after 1200, most music heard and played was not written down and is therefore unavailable for analysis today (Judd, 1998). In the Middle Ages, folk, sacred, and secular music was in part passed down by oral tradition and in part improvised—at least, to the extent that a concept of improvisation can exist in the absence of a written tradition against which to contrast it (Treitler, 1991). Might the tonal-harmonic syntax of this non-written music have differed consistently from that of contemporary written sources? I assume here that any such differences were small enough that the schematic representation of Figure 3 remains valid.

The historical development of tonal-harmonic syntax is well documented (e.g., Dahlhaus, 1967/1990; Eberlein, 1994; Finscher, 1994–1998; Michels, 1994; Randel, 1986). Beginning at the left of Figure 3, there were no harmonic thirds in 9th century organum, in which the added voice (*vox organalis*) generally moved in parallel with the *vox principalis* at an interval of a P4 or P5 below it. In 11th and 12th century discant, the lower part could move not only in parallel but also in oblique motion (one tone held while the other moved) and in stepwise contrary motion (Aquitanian polyphony, St. Martial repertory; the treatise *Musica enchiriadis*); a harmonic third could result from contrary stepwise motion, for example from a P1 to a P5 or vice-versa.

Composers from the 13th century onward gradually developed a sense of vertical sonority (Crocker, 1962; Fuller, 1986). In the late 13th century, harmonic thirds and the major sixths had become so familiar that theorists began to regard them as imperfect consonances. Around 1300 there was a transition from *discantus* (two-voice note-against-note harmonization) to *contrapunctus*, based on a skeletal progression of consonant dyads called the *fundamentum* (Fuller, 1986).

Early instances of what we now call major and minor triads can be found in 13th century three- and four-part organum. Perotin's *Sederunt principes* is one of the earliest known examples of music in four parts. Notated around 1200, it includes two structurally significant, and therefore apparently deliberate, major triads in root position (Flotzinger, 1984; Motte, 1981). The earliest frequent and consistent use of triads occurred in *double leading-tone cadences*, in which a $^{6}_{3}$ sonority (in modern terminology, a first-inversion minor triad) resolved to a $^{5}_{8}$ sonority (open fifth, e.g., G3B3E4—F3C4F4). These and other cadences emerged when voice-leading conventions for two-part textures (e.g., stepwise contrary motion from m3 to P1, M3 to P5, and M6 to P8) were applied to three-part writing (Eberlein, 1993). Almost one half of the 108 compositions preserved in the late 13th century *Bamberg Manuscript* close with a double leading-tone cadence (Eberlein & Fricke, 1992). Double leading-tone cadences were commonplace during the 14th century, and were gradually replaced by other cadential formulas during the 15th.

In the polyphonic writing of 14th century *ars nova* (Table 4), three- and four-part sonorities regularly incorporated harmonic thirds and sixths. The sonorities that we now call root-position triads were generated when perfect intervals (e.g., a P5) were combined with imperfect intervals (e.g., a third); "first inversions" occurred when two imperfect intervals were combined (e.g., a third and a sixth; Kühn, 1973). 14th century sonorities may thus be divided into *perfect* (e.g., $^{8}_{5}$), *imperfect* (containing one perfect and one imperfect interval and often corresponding to later major and minor triads, usually in root position), and *doubly imperfect* (containing two imperfect intervals and often corresponding to minor triads in first inversion; Fuller, 1986, p.43).

In the music of Machaut, sonorities that we now call "minor triads" often occurred in first inversion. First-inversion minor triads also feature prominently in the chord voicings recommended by Sancta Maria (as cited in Schubert, 2002). This feature of 14th-16th century music and music theory is consistent with the data of Krumhansl and Kessler (1982) and predictions of Parncutt (1988). The first inversion of the minor triad fuses almost as well as the root position, because the minor third above the conventional root is almost as salient as the root—and more salient than the fifth (see Figure 1). In the minor K-K profile, $\hat{3}$ is more stable than $\hat{5}$. Steinke et al. (1993; 1997/1998) obtained roughly equal ratings for $\hat{3}$ and $\hat{5}$ following a iv-V-I progression a minor key, although their listeners had heard $\hat{5}$ twice (in V and i) but $\hat{3}$ only once (in i).

The prevalence of non-cadential triads (in root position or first inversion) gradually increased in the works of Machaut (early 14th century), Dunstable (early 15th century), Dufay (mid 15th century) and Ockeghem (late 15th century), and in the various late 14th and early 15th century three-voice English discant compositions compiled in the *Old Hall Manuscript*. In the 14th century, triads were becoming familiar to European ears both as sonorities (harmonically, as simultaneities) and in arpeggiated form (melodically). Machaut occasionally used chains of thirds as quasiharmonic elaborations of primary and secondary tonal areas in his monophonic songs (Leech-Wilkinson, 1996). The melody of the virelai *Douce dame jolie* (mid-14th century) is based on what we would now call an arpeggiated G-minor triad, and ends on the root. During the same period, Machaut also used triadic sonorities in his polyphonic works—and the two seem to be related (Leech-Wilkinson, personal communication, 1997). The relationship between successive and simultaneous presentations of major and minor triads, which seems obvious to modern listeners, may thus have originated in the 14th century. The stability relationships between tones in triadic formations (in modern terms: the root is typically most stable) in both melodic and harmonic presentations may also date from this period.

The prevalence of major and minor triads further increased with the 15th century improvisational practice of *Fauxbourdon* (from roughly 1430 to 1510, but with origins in the 14th century), which involved stepwise chains of 6–3 chords (i.e., first inversion major and minor triads) that typically started, ended, or were interrupted by 8–5 chords (open fifths). From about 1460, Dufay was writing sequences of $^{5}_{3}$ sonorities (4-voice Fauxbourdon). Harmonic progressions in the 15th century became increasingly conventional (Rivera, 1979), and sonorities started to take on what later theorists described as structural and even harmonic-functional roles (Blackburn, 1987; Crocker, 1962; Kühn, 1973; Randel, 1971).

According to the anonymous 14th century author of *Cum notum sit* (as cited in Fuller, 1986, p. 44), the listener's mind "finds repose" at the perfect consonance at the end of a song. In a similar vein, Pelinski (as cited in Fuller, 1986, p. 55) considered that Machaut motets are punctuated by points of rest on held sonorities that outline harmonic progressions at a higher structural level. While imperfect sonorities often preceded perfect sonorities at cadences, sometimes a phrase closed with an imperfect sonority, and Tinctoris (1477/1950) observed that although counterpoint should generally begin and end with a perfect concord, it is possible for a song to begin and even to end with an imperfect concord (Rivera, 1979). It is arguable, however, whether such cases represented genuine points of cadential arrival (Bain, 2003).

Tonal closure in Renaissance music was still usually achieved by octave-unison or open-fifth ($^{8}_{5}$) sonorities, but major $^{5}_{3}$ sonorities also started to function as final chords (e.g., Dunstable, Ockeghem) around 1450. Theoretical examples of this procedure appear in the writings of Cochlaeus (1507, as cited in Rivera, 1979). Around 1500, composers started to close minor passages with major thirds or triads (Picardy third), which became a standard device in late Renaissance and Baroque music (Randel, 1986). But it was not until the mid 17th century that the final-triad ending became the norm, reflecting the establishment of MmT.

In the 16th century vocal counterpoint of Palestrina and Lassus, most sonorities of three or four voices were $^{5}_{3}$ chords. Powers (1981) noted that "The primary tonal elements of Renaissance music are pitch-classes and triads, to all intents and purposes acoustically the same as those of 18th and 19th century music, and there is much in the detail of tonal relationships in Renaissance polyphony that is comfortably familiar. The sonic surface is sometimes faintly exotic, often charmingly vague and undirected to our ears, but hardly alien" (p. 428). The sound of major and minor triads as fused sonorities was familiar to European ears by the start of the Renaissance (around 1430) and became increasingly familiar during the following century. Since triads were always embedded in a contrapuntal context and immediately preceded and followed by other tones, composers and listeners must also have been sensitive to the goodness of fit between individual tones and major and minor triads—by analogy to the method by which chroma salience profiles are determined in modern psychoacoustic experiments (this assertion could be tested in future research by counting how often particular tones immediately precede or follow particular chords in computer databases of Renaissance music). In this sense, we may assume that the chroma salience profiles of typical major and minor triads were familiar to 16th century listeners.

If Krumhansl and Kessler (1982) had carried out their experiments in the 16th century using the typical cadential formulae of the time, their results would presumably have been similar to today. But not the same, because when modern listeners versed in functional music theory listen to 16th century vocal music, they cannot always assign the tonic, dominant and subdominant functions of Riemann (1893) to individual sonorities. In the motet *Prophetiae Sibyllarum*, for example, Lassus used "the chromatic vocabulary fashionable in the 1550s" (Haar, 2002) and built "triads on ten different degrees, six of which result in harmonies foreign to the mode" (Lowinsky, 1961, p. 39), initiating an era of "triad atonality" that extended into the 17th century (Lowinsky, 1961). The difference between then and now lies to a considerable extent in the dynamic, contrapuntal aspect of tonality—not the static, harmonic aspect, as represented by stability profiles.

The Emergence of Major and Minor Scales

During the Renaissance, two significant developments in tonal-harmonic syntax occurred in parallel: triads gradually replaced fifths as final sonorities, and the major and minor scales gradually supplanted the modes. Conventional historical wisdom has it that the second development was a result of applying the rules of *musica ficta*: leading tones were added to Dorian and Mixolydian cadences, the tone B was flattened in Lydian and Dorian to avoid prominent tritones, and the third was raised in final cadences (Lowinsky, 1961; cf. Novack, 1977; Powers, 1998). The tonal syntax of the 16th century may be interpreted as either late modal polyphony or early MmT; if the two structural concepts coexisted, this was a period not only of transition but also of overlap (Powers, 1992). The correlation between chroma prevalence profiles in major-minor music and the chroma salience profiles of tonic triads is consistent with the assumption that the emergence of major and minor scales was a consequence of the increasing use of major/minor triads as referential and final sonorities. More generally, it is consistent with Eberlein's (1994) assumption that composers and performers were guided not only by convention and tradition, but also by perception and intuition.

Triads and Tonality in the History of Music Theory

The perception of music today (including MmT) depends not only on the history of musical structure but also on the history of music theory—historical treatises about musical structure. Early music scholars agree that early music cannot reasonably be performed and interpreted without consulting the theoretical treatises of the period; theoretical treatises about music provide information about musical style and structure that scores from the same period do not (Eva Leach, personal communication, 2008). Historical developments in Western musical structure were evidently influenced by a broad range of factors, from universals of individual psychology to specific details of European cultural history. These factors include universals of pitch and time perception; psychological processes of intuitive compositional creativity and aurally guided trial and error; local traditions of music pedagogy, performance, composition and improvisation; the psychological and political roles of music in religion and society; and the history of ideas including music theory (see Figure 4).

As a rule, music-theoretical innovations followed rather than preceded corresponding practical innovations in Western history (Meyer, 1989; Rivera, 1979). Concepts corresponding to the modern terms *sonority*, *root,* and *inversion* emerged gradually in the theoretical treatises of the 15th-17th centuries; for an overview, see Gallo, Groth, Palisca, and Rempp (1989). (The theorists in question did not use these specific terms, and in any case the *lingua franca* of the theoretical treatises of the period was Latin.) This was evidently only possible after the sound of major and minor triads, the contexts in which they appeared, and their functions in those contexts had become familiar and part of what we might today call *auditory culture* (Bull & Back, 2003). Other compositional innovations arose from theoretic considerations or were

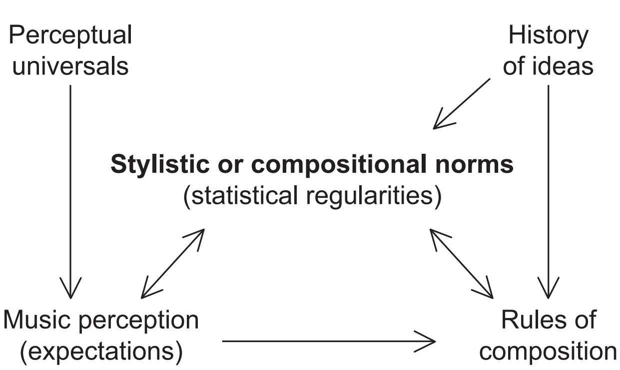

FIGURE 4. Perceptual-historical model of the development of tonal syntax (after Eberlein, 1994).

guided by contemporary theory and teaching. Medieval composition was largely based on learned systems of rules, and innovations emerged when old rules were applied in new contexts (Eberlein, 1994). In the 17th and 18th centuries, theorists such as Werckmeister (1687), Heinichen (1711) and Mattheson (1713) enumerated the 24 major and minor keys before composers such as J. S. Bach used them.

The idea that the lowest pitch somehow governs a sonority or represents its foundation is already evident in the *contrapunctus* tracts and in the *solus tenors* of the 14th century (Davis, as cited in Fuller, 1986). The idea is implicit in the *Quattuor principalia musicae* by John of Tewkesbury (mid 14th century), in which concords are "reckoned in some sense from the lowest sounding part. Indeed, 14th century discant describes primarily the construction of intervals *over* the tenor" (Crocker, 1962, p. 14).

The existence of major and minor triads as unified entities (rather than as mere coincidences of intervals), and recognition of the superior consonance of the major triad, emerged during the Renaissance. According to Tinctoris (1477/1950), improvisations can begin or end with an imperfect concord—that is, with the interval of a third or sixth, or with a triadic sonority (Rivera, 1979). Theorists such as de Podio (1495), Gafori (1496), and possibly Tinctoris (1475/1951) already seem to have had a "grasp of triads as unified totalities rather than as mere coincidences off separate intervals" (Rivera, 1979, p. 93).

Sixteenth century theorists "displayed a distinct preference for triadic sonorities in four voices" (Schubert, 2002, p. 525), but continued to discuss them in terms of their component intervals. Zarlino (1573) regarded $^{5}_{3}$ and $^{6}_{3}$ sonorities as essential components of composition, and distinguished between major and minor triads, but did not present a clear concept of triadic inversion (Lester, 1978; Rivera, 1978). The chord voicings recommended by Sancta Maria (as cited in Schubert, 2002) were, in modern terminology, mostly major and mostly in root position. Avianius (1581) distinguished major from minor triads and suggested that the *basis* (root) can occur in any voice; he referred to $^{5}_{3}$ chords as *perfect consonances*, $^{6}_{3}$ as *imperfect consonances*, and $^{6}_{4}$ as *absurd consonances*, suggesting a rudimentary concept of the root and of inversion, and systematically enumerated all diatonic triads in tabular form (Rivera, 1978).

It was not until about 1600 that theoretical concepts of triad, root, and inversion emerged. Burmeister (1606) called the root, third, and fifth of a triad basis*, media,* and *suprema* (Rivera, 1978). In the writings of Harnisch (1608), the term basis became synonymous with the modern root, and $^{6}_{3}$ chords were considered inversions of $^{5}_{3}$ chords (Lester, 1978; Rivera, 1978). Campion (1618) noted that four-part chord progressions generally begin with a $^5_3$ triad whose bass is doubled (Schubert, 2002).

Perhaps the earliest unambiguous reference to chordal roots may be found in Lippius (1612). He referred to major and minor triads as *trias harmonica* and as *totalis consonantia*, and regarded triads as more fundamental than harmonic intervals. Moreover, he demonstrated the concept of chordal inversion (Rivera, 1984). His emphasis on the functional importance of the bass line, which, during the early 16th century, had gradually emancipated itself from the discant-tenor structure (Rivera, 1979) and included more leaps, may be interpreted as a reference to chordal roots. Moreover, his religiously based concept of the triad's completeness and perfection may be interpreted as a reference to its perceptual fusion and smoothness. Lippius also recommended that the root be doubled most often, the fifth only once, and the third never; and that the triad sounds best in root position, which beginner composers should use exclusively (Rivera, 1984).

Lippius (1612) linked modes to triads, defining each mode in terms of its first, third, and fifth degrees. He claimed that the Ionian, Lydian, and Mixolydian modes are "natural" (and therefore vigorous and cheerful) because their (tonic) triad is major, while the Dorian, Phrygian, and Aeolian are soft (*mollior*) and therefore weak, sad, and serious because their triad is minor—an early statement of the relationship between the old modal system and emerging major-minor tonal system, and an important starting point for modern research in music psychology on the emotional connotations of major and minor. Similar ideas were expressed by Crüger (1630).

The theoretical treatises of the Renaissance suggest that composers strove for maximum perceptual fusion of sonorities through appropriate choice of doublings and inversions. In psychoacoustic terms, composers strove to maximize the pitch salience of the root (Parncutt, 1996). According to Rivera (1984), "If one had to find one word that would express the essence of early harmonic theory, that word would be sonority. Full triadic sonority has become a major consideration in the writing of music." (p. 74). These ideas were in circulation over a century before Rameau (1721/1971) who, inspired by Sauveur (1701), realized that chordal roots need not necessarily correspond to sounding tones, but may be implied (*basse fondamentale*), and that the theoretical basis for this phenomenon is the *corps sonore*, corresponding to the modern concept of the harmonic series. Rameau's concept lacked a mathematical formulation to predict the root of common chords, in particular the minor triad; two and a half centuries later, Terhardt's model of pitch perception allowed Rameau's concept to be formulated as an empirically testable algorithm (Parncutt, 1988; Terhardt, 1982). In the theory of Riemann (1914/1915; see Wason & Marvin, 1992), triads were so structurally and functionally important that every tone in a piece of music could be regarded as the root, third or fifth of a major or minor triad.

This brief analysis of relevant history of music theory is consistent with my claim that the stability profiles of major-minor music emerged gradually in the consciousness of performers, listeners, and composers in the 15th-17th centuries. Table 5 attempts to give a more comprehensive overview of this development, based on the *Three Worlds* concept of Karl Popper (Popper & Eccles, 1977). Popper divided reality into three distinct kinds, which I interpret as the physical world (World 1), conscious experience (World 2), and information and knowledge (World 3). Popper's labels for the three worlds (1, 2, and 3) correspond to the order in which aspects of MmT corresponding to the three worlds emerged. In the 14th to 16th centuries, major and minor triads and the beginnings of MmT emerged in music performance (World 1). Our source of information about this development is written—music notation—and belongs to Popper's World 3; but in an ecological approach the original process occurred in World 1. In the 15th to 17th centuries, these new sound patterns stabilized within World 2, the experience and cognition of listeners, performers and composers. In the 16th-18th centuries, music theorists

TABLE 5. Cultural Emergence of Major-Minor Triads and Tonalities in Popperian Cosmology

Popper's world	**World 1 (Physics)**	**World 2 (Experience)**	**World 3 (Knowledge)**
Representation of major-minor triads and tonality	Performance (notation)	Familiarity (tonal cognition)	Conceptualization (verbal cognition)
Approximate historical period	14th-16th century	15th-17th century	16th-18th century

explored and created discourses and terminologies for talking and writing about these patterns—a development within World 3, the world of information and knowledge. The first of these three developments was evidently a pre- or corequisite for the second, and the second for the third: the increasing prevalence of major and minor triads in the 14th-16th centuries made listeners increasingly familiar with these sounds in the 15th-17th centuries, which in turn triggered theoretical considerations of the nature, function, and perception of these sounds in the 16th-18th centuries. This simple model is no more than a first attempt to unify a complex body of historical, psychological, and music-theoretical evidence.

MmT as Implication-Realization

Having summarized *historical* relationships between the perception of individual chords and the perception of MmT, we move now to the question of what *psychological* processes are operating in real time as a piece of music moves toward and away from a tonal center. Meyer (1956) invoked the idea of implication (or expectation) and realization (or inhibition) to explain aspects of musical syntax and semantics: "Emotion or affect is aroused when a tendency to respond is arrested or inhibited" (p. 14). Inspired by Meyer, Narmour (1977) considered the concept of implication in relation to Schenkerian analysis. Narmour (1990) went on to develop an implication-realization model of melodic expectancy, in which, for example, a melodic leap may imply a step in the opposite direction. Huron (2006b) supplemented Meyer's theory of expectation with evolutionary arguments to account for more complex emotional responses to music such as awe, humor, and chills.

The relationship between chroma prevalence and stability in a tonal context, and chroma salience within the tonic triad, suggests that the tonic triad at the end of a passage of major-minor music is a *realized implication*. Its nonappearance, for example, at an interrupted cadence, violates expectancy and seems at some level to surprise, arouse, disappoint, or frustrate the listener. Depending on context, the nonappearance of an expected tonic may strengthen the expectation of that tonic at the next cadence. The emotional connotations of implication-realization effects may account for the strong feeling of tonal closure that follows the "long, firm, and unequivocally resolved section in the tonic at the end, dramatic if need be, but clearly reducing all the harmonic tensions of the [classical] work" (Rosen, 1972, p. 75).

Larson (1997) observed that key determination and melodic continuation are interdependent, consistent with the idea that the tonic triad is not only a referential sonority, but also the realization of an implication. The implication-realization process involves familiarity with major-minor tonal syntax: each key is characterized by typical harmonic and contrapuntal progressions, to which enculturated listeners are sensitive.

This raises the difficult question, explored by Vos and Leman (2000), of the algorithmic relationship between harmonic-contrapuntal progressions and key centers. The present theory suggests a new approach to modeling that relationship: the expectation involves the relationship between the chroma prevalence distribution of the music and the chroma salience profile of the tonic triad. The key-finding models of Krumhansl (1990), Huron and Parncutt (1993), and Temperley (1999) may be regarded as implementations of this idea, given that the K-K profiles correspond closely to the chroma salience profile of the tonic triad.

The proposed mathematical and conceptual relationship between chroma prevalence, stability, and salience invites the following speculations regarding the perceptual-historical evolution of chroma stability profiles. As major and minor triads became commonplace (15th century), listeners, performers, and composers became familiar with and internalized their chroma salience profiles. These were reflected by distributions of melodic continuation: how often given tones immediately followed given chords. As major and minor triads increasingly took on the function of tonics (points of reference and of closure) in musical forms and structures (16th century), composers gradually and intuitively changed the prevalence distributions of their music to match the chroma salience profiles of the corresponding tonic triads, which increased the music's perceptual coherence. The prevalence of specific harmonic and contrapuntal progressions was adjusted by trial and error, constrained by existing compositional rules and intuitive or perceptual preferences. As composers became more sensitive to the perceptual microstructure of major and minor triads (17th century), the correspondence between prevalence distributions and tonic chroma salience profiles strengthened, as did the feeling of key, the perceived strength and clarity of the tonal organization, and the feeling of resolution or closure at cadences. An empirical test of this claim would involve extensive statistical analyses of computer databases of musical scores and is beyond the present scope.

If an implication-realization relationship exists between tonic triads and the passages of music in which they are embedded, it should operate both forwards and backwards in time. The tonic triad is referential not only as the realization of a preceding passage of music in the corresponding key, but also as an implication that generates the following passage. The opening tonic triad implies the following music, which in turn implies the final triad. This idea is consistent with Schenker's (1906) claim that the tonic triad generates the tonal structure of a whole musical work.

Several other implication-realization effects occur simultaneously at an authentic cadence. First, in chains of falling fifths and thirds such as the familiar chord progression IV-II-V-I, each chord implies the next. The most salient chromas implied by a major or minor triad are the three notes; next in order of salience are the missing fundamentals at fourth and sixth intervals above the root (see Figures 1 and 2). If, in a triadic progression, the root of a chord falls by a fifth or a third to the root of the following chord, the missing fundamentals in the first chord correspond to notes in the second chord, creating an implication-realization relationship (Parncutt, 1999, 2005). Like Meyer's gap-fill process, this implication-realization effect may be associated with a dynamic quality of moving forward (here, toward a cadence), by contrast to the static quality of chord sequences that move in the opposite direction. Second, the leading tone, which is tonally unstable both harmonically (due to its low perceptual salience relative to the tonic triad) and melodically (due to its motion tendency), resolves to its nearest salient neighbor, the tonic. Third, the dissonant seventh of the dominant resolves by step to a consonant tone in the tonic triad (generally the third, since the fifth can be held over from the previous chord). To explain this tension-relaxation or dissonance-resolution relationship, it is not necessary to assume an explicit preference for falling resolutions (as suggested by Larson & VanHandel, 2005).

An implication-realization approach invites speculations concerning the emotional character of MmT. First, the emotional connotations of tonal cadences (a listener's response to the appearance or nonappearance of an expected tonic) would appear to be well described by Meyer's (1956) theory of emotion and meaning, at the several simultaneous levels of implication-realization just described. Listeners experience different emotional responses when implications are realized or violated. Second, the classical style may be characterized by the generation, through a combination of tone distributions, voice leading, motivic development and so on, of clear implications and their systematic realization or violation. These multiple implication-realization effects may represent the essence of the "classical" sense of balance—an aspect of classical music's emotional quality.

Conclusions

Several different models may be constructed for the K-K profiles, all of which are significant predictors ($p < .01$). The stimulus model of Butler (1989), and my (1989) elaboration of that model that additionally accounted for variations in masking and pitch salience, may quantitatively explain the results of the experiments of Krumhansl and Kessler (1982), but cannot explain how the K-K profiles can be invoked by an impoverished stimulus such as a melodic fragment or scale passage (see Krumhansl and Shepard, 1979)—nor can they shed light on the origins of the cadential chord progressions upon which the K-K experiments were based, without the argument becoming circular. Lerdahl's (1988) pitch-class space is appropriately hierarchical, but if the space is considered as a model of the K-K profiles the argument again becomes circular, since the hierarchical levels on which the space is based are derived from the phenomenon that we are trying to explain: MmT itself. Similarly, Bharucha's (1998) connectionist model allows us to conceptualize how MmT is processed in the brain, but cannot explain its origins.

The correlation between the chroma stability profiles of major and minor keys and the chroma salience profiles of their tonic triads suggests that MmT differs from historically older forms of tonality in one important respect: the tonic is a triadic sonority rather than a single tone or chroma. The perceptual coherence of major-minor tonal music may ultimately be based on a correlation between the perceptual microstructure of the tonic triad (the chroma salience profile) and the structure of the music that precedes and/or follows the tonic triad (the chroma prevalence profile).

Central to this theory is the music-theoretic concept of *stability*. I am assuming that a scale step that induces a feeling of closure when sounded at the end of a passage is considered stable; a scale step that tends to move is considered unstable. The most stable pitches of major and minor tonalities belong to the tonic triad. Following Krumhansl and Kessler (1982), I have regarded the stability of each scale step in the chromatic scale not as a yes/no criterion, as music theory tends to do, but as a continuously variable real parameter; and I have assumed that it depends primarily on its prevalence in a passage of music. Reinterpreting Schenker's (1906/1954) concept of a tonal work as a prolongation of its tonic triad, I have also assumed that the prevalence of a scale-step depends on its salience within the tonic triad. Putting these two claims together, I have assumed that chroma salience in the tonic triad determines chroma prevalence, which in turn determines chroma stability. But chroma salience can also influence chroma stability directly, consistent with claims of Butler (1989), Leman (2000), and Parncutt (1989) that chroma stability profiles depend on short-term memory for immediately preceding sounds. Thus, the three profiles—salience, prevalence, stability—are interdependent and possibly mutually reinforcing.

These arguments support the following tentative historical-perceptual account of the origin of MmT. In the Renaissance, major and minor triads emerged as the most promising triadic candidates for tonic sonorities, and were increasingly perceived and composed as points of reference. The chroma prevalence profiles of musical passages gradually approached the chroma salience profiles of their final triads, enabling MmT to emerge from the older modal system. In this historical sense, the chroma salience profile may be regarded as the original profile from which chroma prevalence and stability profiles are derived.

Perceptual coherence in tonal music is promoted by a range of factors, one of which is the correlation between the chroma prevalence profile and the chroma salience profile of the tonic triad. Other factors are historically older and based on the voice-leading practices and traditions of the Middle Ages and Renaissance; they include continuity of texture (number of voices) and the size of melodic intervals within voices by comparison to intervals between voices (Huron, 2001). A further ingredient is the intrinsic balance of formal structures such as sonata form. Together, such factors can account for the balance and orderly character of the Western classical style (Rosen, 1972). The preference for balance and order may in turn be a consequence of the promotion and commissioning of music by political, social, and cultural elites (Keller, 2007): MmT articulates "a social world organized by means of values such as rational control and goal-oriented striving for progress—the values upon which leaders of the upwardly mobile bourgeoisie traditionally have grounded their claim to legitimacy, authority, and 'universality'" (McClary, as cited in Treitler, 1999, p. 366).

Thus, the longevity and popularity of the major-minor tonal system in diverse styles and cultures may be a combined consequence of several factors:

- a social factor—the persistent association of tonal music from the classical period with the upper (or upper middle) classes (Shepherd, 2003);
- a cultural factor—the persistent myth of classical music's perfection (Johnson, 2002);
- a political factor—the global dominance of Western music (Agawu, 2003); and
- a cognitive factor—MmT's clearly perceptible structure, which facilitates storage in and retrieval from memory (Deutsch, 1980; Krumhansl, 1990; Tillmann et al., 2000).

Regarding the last factor, some may regard the posited relationship between salience, prevalence, and stability profiles as evidence for the "naturalness" of the major-minor system, which of course depends on how the word "natural" is defined. But since so many aspects of the major-minor system and its history are culture bound, it is not possible to conclude that the system is superior to other Western tonal systems or to the tonal systems of non-Western cultures (Becker, 1986). Tonal systems in different cultures must first be considered in their own terms and in their own contexts. Comparative studies are only possible when all aspects of an empirical study are crossculturally balanced—a goal that crosscultural studies in music psychology are only beginning to approach (cf. Balkwill, Thompson, & Matsunaga, 2004).

In music theory, the idea that the tonic is primarily a triad and not a tone is an intuition based on the score. In music psychology, it is an observation based on empirical studies. Although the conclusions are similar, the approaches are fundamentally different, since they are based on different representations of music. Music theory is based on musical scores; music psychologists such as Krumhansl (1990) and Tillmann et al. (2000) are interested in psychological representations of music that incorporate the listener's implicit knowledge. My arguments are based on a perceptual or experiential representation of music that accounts for masking, missing fundamentals, and variations in pitch salience (Parncutt, 1989).

Implications

If the theory presented in this paper is valid, it has diverse implications for future research in music psychology, music theory/analysis, and music history.

Psychology. The idea that the tonic in major-minor music is a triad rather than a tone could inspire new experimental procedures to identify the tonic of a passage. Why not play a "probe triad" and ask how well it fits the preceding passage—or for musically trained listeners, ask if the triad is the tonic (as suggested by Parncutt & Bregman, 2000)? Auhagen and Vos's (2000) overview of procedures to determine the tonic covered several different methods based on the "tonic as tone" idea, but did not consider the "tonic as triad."

In an ecological approach (Clarke, 2005; Gibson, 1979), objects are normally perceived directly and holistically. Our attention tends to focus primarily on whole objects and not on their individual perceptual attributes. Moreover, objects in the environment are generally perceived *relative* to each other and to the perceiving organism (cf. Gibson & Adolph, 1992). If tonics are in some way analogous to everyday perceptual references, ecological theory predicts that the tonic is *always* a sonority (i.e., a complex tone, harmonic dyad, or chord)—in *all* music that has perceptible tonal references.

Theory and analysis. A theory of tonal music that is based on pitch salience within the tonic triad can explain fundamental concepts such as chord and key relations (cf. Krumhansl, 1990; Parncutt, 1989). It could lay the foundation for a new music-theoretical paradigm for purposes of research, teaching, analysis, and composition. In music analysis, it may be interesting to convert musical scores into an experiential representation using a pitch perception algorithm. For ease of reading, the salience of pitch events might be notated by the size of musical noteheads.

History. If the tonic is primarily a sonority (rather than a single pitch) both in MmT and other kinds of tonality, interesting historical hypotheses can be generated by considering the internal perceptual structure of that sonority. Consider first musical styles in which the tonic is clearly a single tone. A harmonic complex tone such as a sung phoneme has several audible partials whose frequencies correspond to lower elements of the harmonic series; a non-harmonic tone such as a Gamelan gong creates a non-harmonic pattern. According to Terhardt et al. (1982), the *spectral pitch pattern* is supplemented by a *virtual pitch pattern* which, in the case of a harmonic complex tone, includes pitches at intervals such as P8 and P5 above and below the tonic.

Is the final (*finalis*) of medieval plainchant a tonic in this sense? The final has a perceptible internal structure, namely the audible harmonic partials, which are more often perceived by *overtone listeners* than by *fundamental listeners* (Schneider et al., 2005; Seither-Preisler et al., 2007). Chant may sound most coherent if the pitch commonality between the tones of the chant and the internal structure of the final is maximized. This idea suggests that the most prevalent modes should correspond to a harmonic series above the final (with octave transpositions). Moreover, dissonant intervals such as tritones, semitones, and minor sixths against the final should be avoided. Combining these two principles we might predict the rank order of final prevalence to be G, D, A, C, F, E, B.

An analysis of Antiphons, Allelujas and Hymns by Apel (as cited in Gauldin, 1983) was consistent with this prediction. Apel also cited the following statistics by Jesson for Ambrosian chant: finalis on B, 1%; F, 9%; D, 22%; G, 41%. Similarly, Huron and Veltman (2006) observed that the most common modes in the *Liber usualis* were 1 (Dorian) and 8 (Hypomixolydian); and Hansen (as cited in Gauldin, 1983) found that the preferred final tones in the oldest Tracts and Graduals were G, D and A.

In a preliminary analysis of chants documented by Bryden and Hughes (1969), we (Parncutt & Prem, 2008) selected chants for analysis as follows. From Volume 1 of Bryden and Hughes, in which chants are listed in order of title, we selected all chants on the first 20 pages (475 chants in all). From Volume 2, in which chants are ordered according to successive pitch intervals in semitones, we selected all chants on pages 20, 40, 60 . . . 340. We considered only initial and final tones, and ignored other features such as the tenor and the plagal/authentic distinction. The rank order of finals, from most to least prevalent, was G D E F C A B; of starting tones, G D C F E A B; and of tones in any position, G D F A C E B. When considering these results, recall that chant was not confined to the 7-tone diatonic scale (the tone B was often inflected to Bb, especially in Lydian and Dorian modes). The relatively low prevalence of the Ionian mode (on C) in medieval plainchant and its omission from the conventional tetrachord of finals (D, E, F, G) may be a consequence of the dissonance of the semitone interval B-C: the semitone is the only interval class that is usually not audible between the spectral pitches of a complex tone such as a phoneme. This effect may also have reduced the prevalence of the Lydian mode (on F). An alternative explanation is that the semitone was not present in the pentatonic set upon which Gregorian chant was originally based. The semitone was also associated with femininity, sexuality, and the exotic and may have been avoided for those reasons, particularly in sacred music (Leach, 2006).

If this theory is correct, chant modality and MmT have some basic perceptual features in common. The stability of a scale degree in a mode or key is primarily determined by its perceived prevalence, which depends on the number of tone onsets on that scale degree, its total duration, position (tones at the start and end of phrases or passages are more salient—primacy and recency effects), and—in performance—the loudness, articulation, and timbre of individual tones. But there are exceptions: in a major key, $\hat{5}$ is generally more prevalent than $\hat{1}$, but $\hat{1}$ is more stable because it is more salient in the $\hat{1}$–$\hat{5}$ dyad (Terhardt et al., 1982). In chant, the most prevalent tone is usually not the first or last (final), but other tones such as the tenor (for statistical data see Huron & Veltman, 2006).

The main referential sonority in polyphonic music from the 12th to the 15th centuries was the open-fifth sonority $\binom{8}{5}$. Novack (1977) wrote that "by the beginning of the 13th century the fifth appears as an acceptable and frequent consonance in the intermediary and final cadences. Of equal importance is the manner in which the fifth is prolonged in time" (p. 85). He then analyzed an example of such prolongation from two-voice Notre-Dame organum. It would be interesting to compare the chroma salience profile of the $^{8}_{5}$ sonority with chroma prevalence profiles in computer databases of medieval and Renaissance music.

Skipping to a quite different period and tonal world, the main referential sonority of tonal jazz (from blues to bebop) may be the tonic major-minor seventh chord (Mm7) (McGowan, 2008). The present theory can explain why the blues scale includes "blue notes" at the m3 (clashing with the background M3) and d5 (clashing with the background P5). Terhardt et al. (1982) predicted virtual pitches and their salience on the basis of subharmonic coincidences. Applying Terhardt's model to the Mm7 chord, the m3 of the blues scale lies both a P5 below the m7 and a M3 below the P5. Similarly, the d5 lies both a M3 below the m7 and a m7 below the M3. (The subharmonics of the Mm7 chord also include the M6 and m6 above the root; these are inconspicuous as passing tones because they are familiar from MmT.)

A more detailed comparison of extant tonal styles with the predictions of this theory is beyond the present scope. Such a project should systematically search for styles that contradict and hence falsify the theory.

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