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# ON MUSICAL DISSONANCE

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PSYCHOACOUSTIC THEORIES OF DISSONANCE OFTEN follow Helmholtz and attribute it to partials (fundamental frequencies or overtones) near enough in frequency to affect the same region of the basilar membrane and therefore to cause roughness, i.e., rapid beating. In contrast, tonal theories attribute dissonance to violations of harmonic principles embodied in Western music. We propose a dual-process theory that embeds roughness within tonal principles. The theory predicts the robust increasing trend in the dissonance of triads: major < minor < diminished < augmented. Previous experiments used too few chords for a comprehensive test of the theory, and so Experiment 1 examined the rated dissonance of all 55 possible three-note chords, and Experiment 2 examined a representative sample of 48 of the possible four-note chords. The participants' ratings concurred reliably and corroborated the dual-process theory. Experiment 3 showed that, as the theory predicts, consonant chords are rated as less dissonant when they occur in a tonal sequence (the cycle of fifths) than in a random sequence, whereas this manipulation has no reliable effect on dissonant chords outside common musical practice.

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**Key words:** consonance, dissonance, harmony, sensory roughness, tonality

IN THE PHYSICAL WORLD, THERE ARE VIBRATIONS IN AIR pressure and other elastic media, but no sounds. As Helmholtz (1877/1912, p. 7) remarked, "Sensations result from the action of an external stimulus on the sensitive apparatus of our nerves." Sounds depend on hearing and hearing depends on sensory organs that transduce physical vibrations into nerve impulses, and brains that transform these impulses into the subjective experience of hearing. In human beings, the sensory transducers are hair cells in the cochlea in the inner ear. Depending on their location on the basilar membrane, these hair cells differ in the frequencies to which they respond maximally, and so act as filters akin to a Fourier analysis, which recovers the underlying separate sinusoidal waves – the partials – that make up a complex pressure wave. The auditory cortex and other regions of the brain operate on the input of nerve impulses – in ways that no one fully understands – to create the subjective experience of hearing a world of sounds. And so we hear noises, speech, and music. A longstanding enterprise in psychophysics is to establish systematic relations between physical variables such as the amplitude of vibrations in air pressure (as measured in decibels), and subjective variables, such as loudness (as measured in sones). And, as in the case of loudness, psychophysics often shows that no simple relation exists between the two sorts of variable, and that in some cases higher-order cognitive processes play a part. Vision is comparable. Retinal cells transduce quanta of light into nerve impulses. Low-level processes recover such matters as abrupt changes in the intensity of light in the visual field; and high-level cognitive processes in the cortex enable viewers to perceive what things are where in the scenes in front of them (Marr, 1982).

Our present enterprise is psychophysical: it is to establish the relation between complex vibrations, i.e., chords created by musical instruments, and their dissonance, which is a subjective perceptual phenomenon. Chords, which are the simultaneous sounding of more than two distinct notes, do differ in the degree to which they sound consonant ("pleasant" and "stable") or dissonant ("unpleasant" and "unstable"). What exactly causes these differences is a deep puzzle that musicians, music theorists, acousticians, and psychologists have studied for centuries. Our goals are threefold. First, we aim to test whether individuals with experience in listening to Western music concur in their judgments of dissonance over many different sorts of chord, including all possible three-note chords and a representative sample of four-note chords.

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This body of results should be useful to theorists seeking to account for dissonance. Second, we aim to formulate a theory that integrates three common principles embodied in tonal music into a hierarchy of importance, and that combines this high-level cognitive component with an account of sensory roughness arising from interactions of partials on the basilar membrane. Third, we aim to test whether the resulting predictions of the theory account for our participants' judgments of dissonance. Readers should understand, however, what we are *not* attempting to do. Although we make considerable use of theories of tonality in formulating our theory, we are not trying to formulate a new analysis or definition of tonality. We merely make use of certain notions – manifestly implemented in tonal music, and accordingly analyzed in music theory – in order to frame principles that elucidate the cognitive processes underlying the perception of dissonance. To refer to the "perception of dissonance" is, of course, pleonastic: dissonance itself is a perceptual phenomenon, a complex and multifaceted one, which is an object of analysis in several disciplines concerning music and hearing.

In 1863, Helmholtz initiated the principal psychoacoustic approach to dissonance in terms of the roughness or beating of partials close together in frequency (see Helmholtz, 1877/1912). But, he also remarked that what counts as dissonant has changed over the history of music, and he commented, "…if the boundary between consonance and dissonance has really changed with a change of tonal system, it is manifest that the reason for assigning this boundary does not depend on the intervals and their individual musical effect, but on the whole tonal system" (p. 229).

There are thus two ways to think about dissonance. One way, which is psychoacoustic, is sensory and based on the transduction system that converts sounds to nerve impulses. The other way, which is the province of music theorists, is based on the principles embodied in tonal music. Helmholtz pioneered the psychoacoustic approach, but did not attempt to integrate it with tonal principles. Yet, to solve the puzzle of dissonance, we argue, calls for such an integration. The relevant principles of tonality must be tacitly represented in the minds of listeners, as a result of their experiences in listening to tonal music, or as some say, as a result of "enculturation" (Hannon & Trainor, 2007). We say that the principles are tacit, or unconscious, because introspection does not reveal them. They are therefore akin to the grammatical rules that underlie listeners' ability to understand sentences in their native language (see, e.g., Chomsky, 1995), or to the unconscious inferences that Helmholtz postulated in order to explain vision (Helmholtz, 1866/1962).

The organization of our article is straightforward. It begins with psychoacoustic approaches to dissonance, and describes an important difficulty that they encounter. Next, it considers musical accounts of dissonance, illustrates some of the abundant evidence that listeners acquire a tacit understanding of tonality, and outlines some central principles underlying tonal music. It then uses these principles to formulate a dual-process theory of dissonance that integrates both psychoacoustic and musical factors. It reports three experiments designed to test this theory. Finally, it draws some general conclusions about dissonance.

## Psychoacoustics and Sensory Dissonance

The physical realization of a single note played on a pitched musical instrument consists of a set of simultaneous sinusoidal waves of air pressure (i.e., a set of pure tones) that are superimposed to yield a single *complex tone*. Musical instruments create complex tones made up of these partials (pure tones), and for many musical instruments, including the human voice, strings, and wind instruments, the partials are harmonics i.e., integer multiples of the frequency of the fundamental – the complex tone's lowest partial. (The fundamental can usually be inferred from the harmonics if it is missing.) Helmholtz (1877/1912) and those who have followed him have tried to explain dissonance in terms of roughness, which is the rapid beating (oscillations in amplitude) created by interactions of adjacent partials. That is, when two partials are close enough in frequency — within a critical bandwidth — they stimulate the same region of the basilar membrane in the cochlea. Their joint stimulation produces beating at a frequency dependent on the difference between their two frequencies. Helmholtz realized that simple numerical ratios between the frequencies of a pair of notes do not create beating between their partials, and he provided a psychoacoustic explanation of the long-standing observation, dating back to Pythagoras, that harmony depends on simple ratios. From his experiments, Helmholtz (1877/1912) argued that roughness peaks when two pure tones beat at around 35 Hz (though others have reported higher frequencies for this peak, see, e.g., Zwicker & Fastl, 1990).

Plomp and Levelt (1965, Figure 10, p. 556) experimentally established a function for assessing the relative dissonance of two pure tones, based on roughness when their frequencies fall within a critical bandwidth. It peaks at a frequency difference equal to about 25% of the critical bandwidth, and it reaches a minimum when the two frequencies differ by about 125% of the critical bandwidth. The critical bandwidth in turn depends on the mean frequency of the two pure tones. Hence, Helmholtz was mistaken in assuming that his factor for maximal roughness was constant regardless of the mean frequency of the tones, but nevertheless he was right in supposing that sensory dissonance depends on beating.

Hutchinson and Knopoff (1978) used Plomp and Levelt's (1965) account to calculate the potential dissonance of dyads played in the lower register of a string instrument, taking into account both frequency and amplitude. The results agreed with the rank orderings of both music theory and psychological experiments. The authors extended their analysis, and showed how to compute the theoretical dissonance of triads (Hutchinson & Knopoff, 1979). For example, they obtained these roughness values for the principal triads: major: 0.139, minor: 0.1479, diminished: 0.2303, augmented: 0.149, where the larger the value, the greater the roughness. Hence, the major triad is the least rough, and the diminished triad is the most rough.

Parncutt implemented an algorithm based on this research (see Bigand, Parncutt, & Lerdahl, 1996), and it is available at http://www.uni-graz.at/richard.parncutt/computerprograms.html. It predicts the roughness of complex tones made up from sinusoidal partials. Their amplitudes vary automatically as 1/*n*, where *n* is the number of the partial and ranges from 1 to 10. The standard curve, previously in a look-up table in Hutchinson & Knopoff (1978), is the output of the function, g(x), which is computed as:

$$\text{for } x < 1.2,\ g(x) = [e\,(x/a)\exp(-x/a)]^{i}$$
$$\text{for } x > 1.2,\ g(x) = 0,$$

where $e$ is the base of natural logarithms (2.718…), $x$ is the interval between two partials expressed in critical bandwidths also computed according to a function (see Hutchinson & Knopoff, 1978; Plomp & Levelt, 1965), $a$ is the interval for maximum roughness (about 0.25 cps), and $i$ is an index set to 2 to yield the standard curve. Although the algorithm predicts judgments of roughness, and ratings of the "tension" of various chords interpolated between constant chords (Bigand et al., 1996), these authors describe several factors that it fails to take into account, notably the mutual masking of partials (Terhardt, 1974), and the dependence of roughness on the waveform envelope. Another problematic assumption may be that roughness contributions for pairs of partials add in a linear way. In contrast, Kameoka and Kuriyagawa (1969) argued that each contribution should be raised to the power 4, added, and the sum raised to the power 0.25. This correction, however, should have no effect on the rank order of roughness from one chord to another.

Roughness contributes to the perception of chords and its sensory nature is corroborated in several findings: listeners report that it is unpleasant (Terhardt, 1974), they prefer chords without beats (McDermott, Lehr, & Oxenham, 2010), and it contributes to the judged "tension" of chords (Bigand et al., 1996). Other species such as macaques register roughnesss in auditory cortex, and the magnitude of this activity correlates with the dissonance of musical chords (Fishman et al., 2001). Of course, other factors may also contribute to sensory dissonance (see Bigand et al., 1996; Terhardt, 1984).

A critical problem with roughness is that it fails to predict the relative dissonance of the common triads. Experimenters have asked musicians and nonmusicians to listen to and then rate the "harmoniousness" of individual chords (e.g., Cook, 2001; Cook & Fujisawa, 2006; Roberts, 1986), and the results concur with the following rank order of increasing dissonance: major triads < minor triads < diminished triads < augmented triads. This trend is robust regardless of music training, and occurs in both Western and East Asian listeners. Yet, roughness predicts on the contrary that an augmented triad should be more consonant than a diminished triad (see the roughness values above).

Parncutt (1989, p. 141) suggested that this discrepancy might have cultural rather than sensory origins – a view that he later repudiated as unfalsifiable (Parncutt, 2006, p. 204). Cook (2006) doubts that culture alone can account for the discrepancy. He writes: "there are clearly structural features of 3-tone chords that contribute to their overall stability and that have less to do with culture than with acoustics" (p. 16). And he invokes a second acoustic factor based on Meyer's (1956) idea that if the intervals in a chord are undifferentiated, then there is no point around which their organization can occur. In root position, for instance, the two intervals in diminished triads are both minor thirds, in augmented triads they are both major thirds, and in suspended fourths they are both fourths. These identical intervals therefore render the chords unstable, and thereby create "tension." Cook's formalized version of Meyer's "tension" (T) depends on the relative size of neighboring intervals in triads, and is computed for each triplet combination of the partials of the three tones; this value of T is weighted and then added to roughness to yield a sonority index that predicts the correct rank order of the dissonance of triads. Cook argues that acoustical structure of triads can account for the major and minor scales of Western music and the consequences of these scales for harmony.

Different tuning systems for musical instruments can minimize roughness (and, thus, dissonance) for both harmonic and non-harmonic instruments

(Sethares, 1999). For instance, Western tuning currently divides the octave into twelve logarithmically equal intervals in frequency (i.e., 12-tet), which is a good compromise for instruments with harmonic partials. Likewise, if the octave is divided into some other number of parts, adjustments to the timbre of instruments with such a tuning also minimize dissonance. Conversely, given an instrument of some new and perhaps non-harmonic timbre, it is possible to devise an optimal tuning to minimize dissonance. Sethares (1999) has devised the appropriate algorithms to discover such timbres and tunings. In sum, any account of dissonance is likely to include a psychoacoustic or "sensory" component.

## Culture and Musical Dissonance

The composer and music theorist Norman Cazden dismissed psychoacoustic attempts to explain consonance and dissonance. They are not on a continuum, but "form instead the polar opposites of an either-or qualitative distinction" (Cazden, 1972, p. 218; cf. Lundin, 1947). Such judgments, he claimed, depend on a culturally determined system of music (i.e., on Western music of the past few centuries), and are not a property of chords but rather reflect the function of chords in a sequence. He wrote, "There is no such thing as a consonant or a dissonant interval or chord as such" (1972, p. 222). His underlying idea is straightforward: as listeners' familiarity with tonal music increases, they acquire a tacit knowledge of its principles, and these principles embody factors underlying consonance and dissonance. There is both historical and experimental evidence corroborating this hypothesis. The historical evidence is the change in acceptability of chords once thought unacceptably dissonant. For example, Rameau, the founder of modern harmonic theory (according to Bernstein, 2002, p. 778), declared in the early 18th century that sevenths are the origins of all dissonance (Rameau, 1722/1971, p. xlii). Yet, such chords became commonplace in classical music, and ninths became commonplace in the concert music of the late nineteenth century.

The experimental evidence begins with early twentieth century studies of the effects of repeated hearing on judgment. Meyer (1903) reported that harmonized music containing quartertones in its tuning at first sounds disagreeable, but with 12 or 15 repeated hearings most participants spontaneously remarked that it sounded better. One of them remarked, "I liked the last [playing] better than the first, because I became more used to the succession of chords" (p. 474). Valentine (1914) reported a similar tendency in which dissonant dyads became more pleasing over the course of 33 repetitions of all twelve possible dyads. The increase in liking as a result of familiarity is itself familiar to psychologists, because it occurs in many domains, not just music, and it is known as the "mere exposure" effect (Zajonc, 1968). The effects of familiarity are also born out by recent experimental studies. Musicians showed the influence of their expertise in comparison with nonmusicians in judgments of the consonance of intervals, and this difference was also reflected in event-related brain potentials (ERPs) in the perception of consonance when intervals were presented in isolation (Schön, Regnault, Ystad, & Besson, 2005). Likewise, Brattico et al. (2008) showed that musicians and nonmusicians differed in their change-related magnetic mismatch response — as measured using magnetoencephalography (MEG) — to a dissonant chord containing an unpleasant interval (AB♭E), a triad including a mistuned third (half way between a major and minor third), and a minor triad, all inserted in a context of major chords. The "mismatch" response reflects the accuracy of perceptual discriminations.

Individuals acquire an implicit knowledge of a musical culture — such as the characteristics of tonal music — simply from listening to music. Hence, as many studies have shown, they are sensitive to tonal aspects of music even if they have had no music training and acquired no explicit musical expertise (see e.g., Bigand, 2003; Blood, Zatorre, Bermudez, & Evans, 1999; Brattico, Tervaniemi, Näätänen, & Peretz, 2006; Pallesen, Brattico, & Carlson, 2003; Tillmann, Bharucha, & Bigand, 2000). At the age of five, children familiar with Western music respond faster to violations of key in the final chord of a sequence than to violations of harmony, but by the age of seven they respond rapidly to both (Schellenberg, Bigand, Poulin-Charronnat, Garnier, & Stevens, 2005; Trainor, 2005). Likewise, infants (and adults) rapidly pick up the transitional probabilities from note to note realized in a genre of music or in speech sounds (e.g., Saffran, Johnson, Aslin, & Newport, 1999).

What complicates matters is the nature of the particular aspects of tonality that listeners tacitly acquire. If music theory teaches us anything, it is that tonality is central, elusive, and controversial (cf., Christensen, 2002; Piston, 1987; Tymoczko, 2011). Fortunately, our task is not to provide a new definition or analysis of tonality, but merely to extract some general principles from the common practice of composers of tonal music. These principles will guide us in formulating a theory of the tacit knowledge likely to be acquired by listeners and used by them in assessing dissonance.

Our starting point is that "tonality most often refers to the orientation of melodies and harmonies toward a referential (or tonic) pitch class" (Hyer, 2002, p. 726) – a view that has been amply corroborated experimentally (e.g., Krumhansl, 1990; Krumhansl & Kessler, 1982; Parncutt, 2011). And, as Hyer allows, we interpret "tonality" to refer to music that developed in Europe around 1600, that prevailed thereafter through the nineteenth century, and that was abandoned by composers such as Schoenberg and his followers around 1910. Yet, it continues to this day in one form or another in popular music and jazz, and it has re-emerged in concert music. Our concern is what these different genres of tonal music might have in common in harmony.

One commonality, as Hyer notes (2002), is that musicians agree that there are two basic genera, major and minor that govern both melodies and harmonies. The scale of C major, for example, contains seven pitch classes (C, D, E, F, G, A, B) that form the underlying material from which both melodies and chords can be constructed in music ranging from the opening theme in Mozart's piano sonata, No.1, in C major (K. 279) to the Beatles' song, *Getting Better*. Likewise, the scale of A minor in its harmonic form contains seven tones (A, B, C, D, E, F, G#) that provide the notes from which the chords of many compositions in a minor key are constructed, ranging from Beethoven's *Für Elise* to the verse of the Beatles' *While My Guitar Gently Weeps*. As Hyer reports, Gottfried Weber, the nineteenth century music theorist, derives diatonic chords from these two scales – a step that we also take presently.

A second principle in tonal music is that the major triad is privileged. As Rameau (1722/1971) remarked, it is the "perfect" chord (p. 64). As a result of experiments, Stumpf (1890) argued that the fusion of separate tones so that they sound like a single complex tone causes chords to sound consonant, and, conversely, tones that resist fusion sound dissonant. Stumpf later abandoned this hypothesis (see Plomp & Levelt, 1965, for the history of earlier psychoacoustic accounts). But, a version of this theory of "harmonicity" has been revived by McDermott et al. (2010). We can specify a chord in terms of its pitch classes, e.g., CEG, and their respective registers, e.g., $C_2G_3E_4$, where $_4$ denotes the octave beginning with middle C. McDermott et al. argue that the major triad (e.g., CEG) is the most consonant chord because it is the first three-note chord to be produced in the series of ascending harmonics (e.g., the initial partials of $C_2$ are $C_2C_3G_3C_4E_4$). In other words, the major triad is more likely to fuse than any other chord. Their studies have shown that roughness affects musicians and nonmusicians, but harmonicity depends to a greater degree on musical experience. Its effects were correlated with the number of years the participants had spent playing a musical instrument. This result implies that the acquisition of musical skill enhances an individual's preference for harmonic frequencies because of their importance in Western music. One difficulty with the harmonicity hypothesis is that a small set of lower harmonics tends to sound more consonant than a larger set including them, yet the smaller set does not fuse so well (see also Huron, 1991). Another difficulty is that it is not easy to infer the relative dissonance of two chords. Which should be more dissonant: a chord with notes corresponding to harmonics 4, 5, and 7, or one with notes corresponding to harmonics 4, 6, and 7? At present we lack an algorithm for answering such questions. Nevertheless, in the next section of the paper, we adopt a central implication of harmonicity for the consonance of major triads and of chords consistent with them.

A third principle in tonal music – one that also goes back to Rameau – is that chords are built from thirds. If we combine the major and minor scales with the construction of chords from thirds, we have the triads and seventh chords shown in Figure 1. This exercise is in the spirit of Weber (see Hyer, 2002), but all the triads and sevenths in Figure 1 are described by Rameau, including the chord that we have symbolized, m7b5, the half-diminished seventh (see Rameau, 1722/1971), and the chord that we have symbolized as augM7. The importance of thirds is also reflected in more recent theories. Longuet-Higgins (1979) showed that the set of musical intervals in relation to a given fundamental frequency was the set of ratios definable as the product of powers of the prime factors 2, 3, and 5. The consequence is that musical intervals are in effect vectors in a three-dimensional space of discrete cells, and the remoteness of an interval from one note to another is the magnitude of this vector. The three dimensions from the origin are then octaves, major thirds, and fifths. One nice consequence of the theory is that the diminished and augmented triads call for an interpretation in which the fifths are more remote from the root than in the case of the major and minor triads (see Steedman, 1994, for an exposition of this theory and its precursors).Tonality affects the perception of music (e.g., Huron, 2006; Krumhansl, 1990; Krumhansl & Toiviainen, 2003), and the apparent failure of psychoacoustics to account for the dissonance of triads has led many theorists to argue that dissonance depends on both psychoacoustic and tonal dissonance (e.g., Ball, 2008; Huron, 2008; McDermott, 2008; Parncutt, 1989; Trainor, 2008). The problem confronting theorists is therefore to formulate a

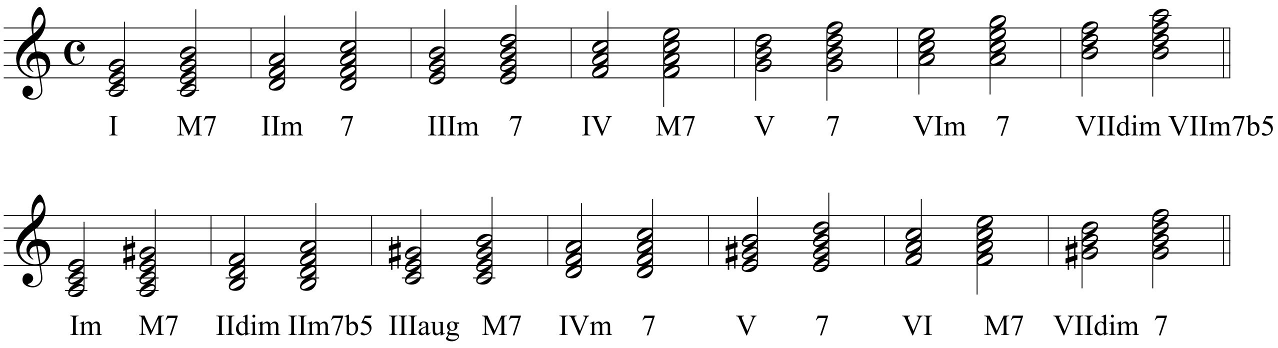


FIGURE 1. The chords formed in thirds from the scale of C major and from the scale of A minor. I, II, etc. = major triad, m = minor triad, dim = diminished triad, aug = augmented triad, 7 =minor seventh, M7 = major seventh, and b5 = flattened fifth.

"dual process" account that integrates these two factors in a way that is empirically testable (Parncutt, 2006). We now turn to a theory that is designed to solve this problem.

## A Dual-Process Theory of Dissonance

We propose that dissonance in music results from a combination of sensory and tonal dissonance, where "sensory" dissonance arises from the properties of the transducer and in particular from roughness (i.e., the rapid beating of partials), and "tonal" dissonance is a consequence of high-level cognitive processes that rely on a tacit knowledge of the principles of tonality. This hypothesis goes back to Helmholtz, and, as we remarked in the preceding section, it has more recent adherents, such as Terhardt (1984). Such a theory has to delineate the relevant factors of tonality, and to combine them with roughness in an account with testable consequences. The dual-process theory depends on the three principles of tonal music that we described in the preceding section. We now summarize these principles in the order of their importance.

The first principle is that tonal dissonance depends on the scales in which the pitch-classes of a chord can occur. It stipulates that chords occurring in a major scale should be less dissonant than chords occurring only in a minor scale, which in turn should be less dissonant than chords occurring in neither sort of scale. Figure 1 shows chords composed of thirds in the scales of C major and A minor. Because the major, minor, and diminished triads all occur in major scales (and in minor scales), they should be less dissonant than the augmented triad, because it occurs only in minor scales. Similarly, the chords of major sevenths (e.g., CEGB), minor sevenths (e.g., DFAC), sevenths (e.g., GBDF), and half-diminished sevenths (e.g., BDFA) occur in major scales and so they should be less dissonant than minor triads with major sevenths, e.g., ACEG♯, augmented triads with a major sevenths (e.g., CEG♯B) and diminished sevenths (e.g. A♭FBD), which occur only in minor scales. Likewise, the latter should be less dissonant than sevenths that occur in neither major nor minor scales, such as sevenths with flattened fifths, e.g., FABE♭. Of course, these latter sorts of chord, which cannot be formed in either sort of scale, may occur in music of an extended tonality: the preceding sevenths with flattened fifths, for example, are common in modern jazz (see Johnson-Laird, 2002), but they should be more dissonant than chords that occur in a major or minor scale.

The second principle embodies an aspect of harmonicity (see McDermott et al., 2010) that we described earlier: chords that are consistent with a major triad are more consonant than chords that are not consistent with a major triad. The principle applies to chords that contain the major triad and its inversions, and so major triads should be more consonant than minor triads and diminished triads. But, the principle generalizes to chords with four or more pitch classes. Hence, a chord of a seventh, such as GBDF, is consistent with a major triad (GBD) because the seventh, F, occurs in a major scale in which the triad also occurs (the scale of C major), whereas a chord, such as GBDE♭, is not consistent with a major triad because the added note does not occur in a major scale containing the major triad.

The third principle is that chords built from intervals of a third should be more consonant than chords that are not built from thirds. Chords can be built from thirds both directly (e.g., ACE) and indirectly (e.g., CEB, where a third is missing from the chord), and the principle allows for just one missing third intervening between two pitch classes a fifth apart. The principle predicts that all such chords should be more consonant than chords not built from thirds, e.g., CGD.

The three principles – the use of diatonic scales, the central role of the major triad, and the construction of chords out of thirds – are all embodied in tonal music. We do not claim that they exhaust the principles of tonal music (cf., e.g., Tymoczko, 2011), and some music that abides by them may not be tonal. Certainly, the principles considered individually apply to music that is not tonal. For example, the use of diatonic scales occurs in music prior to tonality, such as Ambrosian chant. But, the conjunction of the three principles is common to almost all tonal music. One other principle is important in our theory, but we defer it until later: sequences of chords in tonal music are governed by constraints, such as the cadence from dominant to tonic.

In the theory, the three tonal principles are nested one within another according to their order above, and we have implemented the theory in a computer program (its Lisp code is under the heading 'A study of dissonance' at http://psych.princeton.edu/psychology/research/johnson_laird/music.php). This program computes the tonal dissonance of any chord, and yields a series of levels of tonal dissonance. Each level contains multiple chords, and so the theory postulates that their relative dissonance depends on roughness. As a practical matter, we used Parncutt's (1989) algorithm to compute roughness (x 100 for greater legibility in our figures below), but we used its output solely to predict the rank order of dissonance within each level. To rely on rank order rather than absolute values of roughness is to discard a considerable amount of information, but our reasons for this modification are that a rank order is more conservative, and more likely to be preserved in other procedures for assessing roughness. To illustrate the role of roughness, consider the chords CGBD and CDEG. They both occur in a major key, are consistent with a major triad, and can be built indirectly from thirds. But, CGBD has a roughness of 28.06, whereas CDEG has a roughness of 24.08. Hence, CGBD should be more dissonant than CDEG.

Granted that tonal dissonance affects the perception of chords, the sequence in which a series of chords are judged should affect their dissonance. The fourth and final principle of our theory is that tonal chords — those built from a major scale, consistent with a major triad, and built from thirds — should sound more consonant in a tonal sequence, such as a cycle of fifths for their roots, than in a sequence that is random. Analogous context effects have been reported before. Gardner and Pickford (1943) played dissonant chords in various settings, consisting of one preceding chord and one following chord, and they reported that the setting affected the rating of the dissonance of the intervening chord. They do not describe the chords that they used, but in a subsequent study they played the chord, CAFE, reading from the root upwards, in various passages, some by well-known composers, and its context had a reliable effect on its dissonance ratings (Gardner & Pickford, 1944). The authors, however, do not present the context, or report which contexts had what effects on the ratings of the test chord. And their procedure is vulnerable to a potential confound: the participants may have judged the euphony of the transitions from one chord to another rather than the dissonance of the test chord.

In summary, the three principles of tonal harmony predict a trend in increasing dissonance, and, within each level of dissonance, roughness predicts a detailed rank order. The role of roughness is not trivial, and we will show that it accounts for some of the variance in the experimental results – thereby providing a corroboration of the role of sensory factors in dissonance, and a demonstration of the practical value of Parncutt's algorithm, even though the spectral structure of the chords in our experiments may differ from the idealization that his algorithm assumes.

## Experimental Studies

A problem in evaluating any dual-process theory is the dearth of systematic data on the rated dissonance of more than a few different sorts of chord (e.g., Cook, 2001; Cook & Fujisawa, 2006; Kameoka & Kuriyagawa, 1969; Kuusi, 2009). Unfortunately, the number of possible chords in Western music is too large for a feasible psychological investigation of all of them. If we ignore register, there are 165 possible four-note chords in Western music, and still greater numbers of five- and six-note chords. Yet, a test demands more comprehensive data than are in the literature. Our first experiment therefore examined all possible three-note chords (i.e., chords composed from three different pitch classes). Our second experiment similarly examined a large and representative sample of all possible four-note chords, excluding only some chords containing three adjacent pitch classes, such as C, C♯, and D. And our third experiment examined a set of tonal chords and a set of non-tonal chords, and the participants rated them in tonal sequences and random sequences. The procedure was the same in all three experiments, but the materials differed. Following an oft-used paradigm (e.g., Cook & Fujisawa, 2006; Roberts, 1986), the participants heard a chord and then rated its dissonance. To generalize over the population, and to reduce the possibility of residual effects from one experiment to another, each experiment tested a different sample of participants.

## Experiment 1

### METHOD

*Participants*. The participants were recruited online from the Princeton University community, including undergraduates, graduate students, and others, and paid the standard university rate for their participation. All the participants reported that they had normal hearing, and no data were discarded in the analysis of this or any of the experiments. Experiment 1 tested 27 participants (their mean age was around 23, and there was a slight majority of female participants over males, but a computer glitch in this experiment failed to record ages and gender). The participants were familiar with Western music, and included both musicians and nonmusicians.

*Materials*. The stimuli were all 55 of the possible three-note chords shown in Figure 2. These chords consist of 19 distinct triplets of pitch classes, and each of them occurred in root position and in two inversions, except for the augmented triad, which has the same intervals in its inversions as those in its root position. (By the "inversion" of a chord, we mean merely the transposition of an upper note to a lower register so that it becomes the bass note, and thus, as Figure 2 shows, one inversion of CEG is EGC and another is GCE.) The register of the pitch classes in the chords was designed so that the chords spread over about an octave and a half, in order to make the chords comparable to those that occur in music (except in cases that contrasted inversions containing minor ninths with either those containing semitones, e.g., chords 10b and 10c, or major sevenths, e.g., 14a and 14c). Each chord was transcribed into the Sibelius music program, which synthesized them as piano chords. They were exported as MP3 files, and presented under computer control using a program written in the programming language C+, which played the MP3 files diotically through headphones. Playback was at a volume loud enough for the participants to hear the chords easily (35-40 dB). Chords for all three experiments can be heard (in the same order as in the Figures below) under the heading 'A study of dissonance' at: http://psych.princeton.edu/psychology/research/johnson_laird/music.php.The chords were played in a different random order to each participant.

*Procedure*. Participants were tested individually in a quiet room. Prior to the experiment, they completed a brief online questionnaire recording their age, gender, and musical experience. The computer then presented a description of the task, and the main instructions verbatim were as follows:

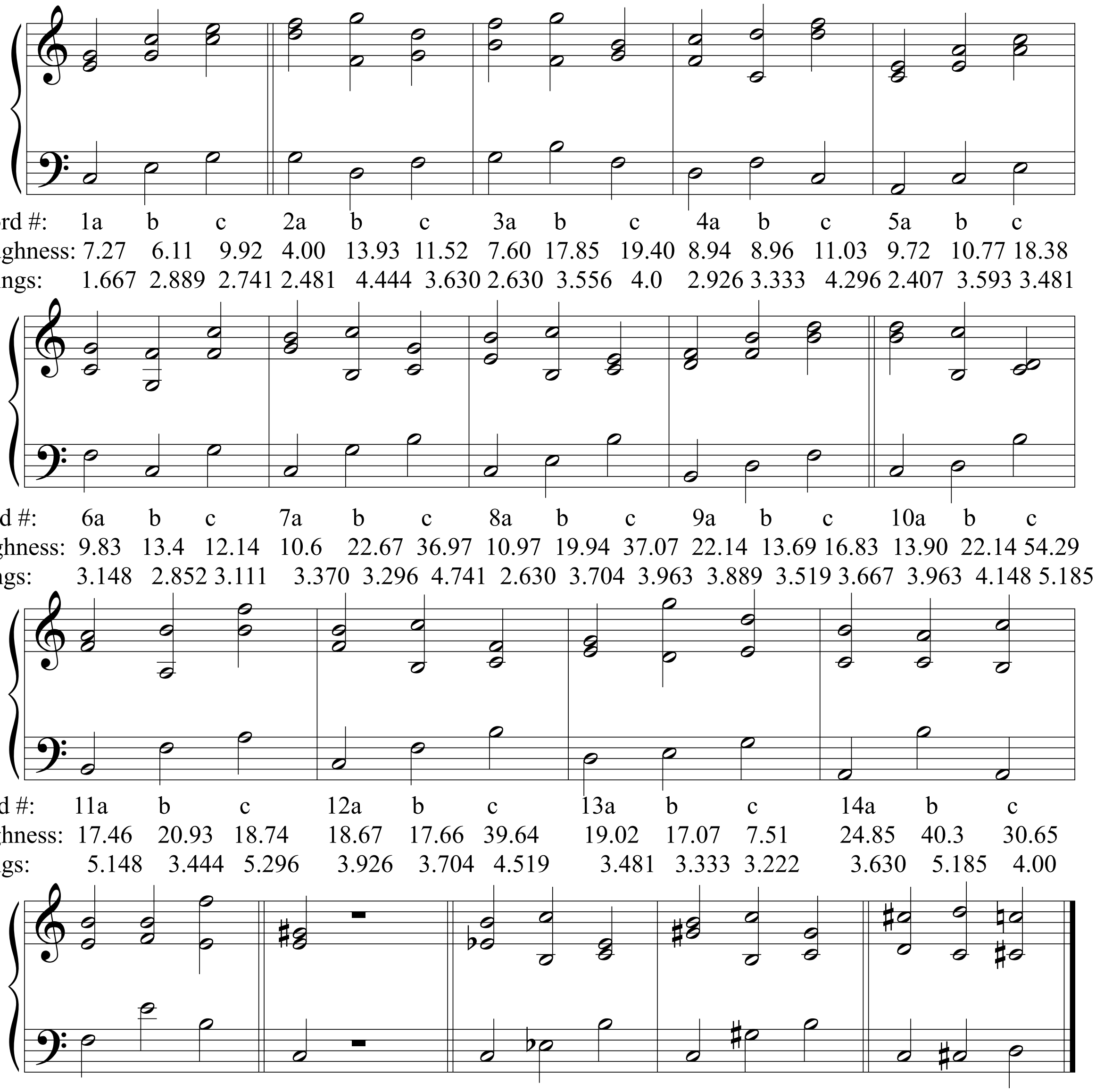
> You will be asked to listen to and rate 61 chords on a scale of 1-7. '1' corresponds to a chord that is highly pleasant (consonant); '4' corresponds to a chord that is neutral (neither consonant nor dissonant); '7' corresponds to a chord that is highly unpleasant (dissonant). You will hear each chord only once, so please attend carefully to each chord before making your judgment.

We used "pleasantness" in the instructions for the benefit of the nonmusicians, because "consonance" and "dissonance" alone might have confused them (cf. Butler & Daston, 1968), and because experiments have shown that for musically untrained individuals, consonance and pleasantness are similar concepts (Guthrie & Morrill, 1928; van de Geer, Levelt, & Plomp, 1962) and represent the same dimension in semantic space, i.e., evaluation (Plomp & Levelt, 1965, p. 553). A corollary is that this practice is common in experimental studies of consonance and dissonance (e.g., Brattico et al., 2008; Cook & Fujisawa, 2006; McDermott et al., 2010).

There were six practice chords followed without a break by the experimental chords. The practice chords were used to give participants experience of the range of possibilities from the outset, and were not distinguished in any way from the chords in the experiment proper. Practice chords included two that were highly consonant, two of intermediate dissonance, and two that were highly dissonant. Participants heard each chord for 2 s, and then rated its dissonance by moving a slider on the computer screen to the appropriate scale point, and they responded in their own time. The computer program recorded the participant's dissonance rating, and then presented the next chord. The participants were debriefed at the end of the experiment.

### RESULTS AND DISCUSSION

The participants had a reliable consensus in their ratings of the dissonance of the 55 three-note chords (Kendall's coefficient of concordance, $W = .47$, $p < .0001$, two-tail). Figure 2 presents each of the chords, its roughness (x 100) as computed by Parncutt's program, and the mean of the participants' ratings of dissonance on the seven-point scale. (The standard errors in the ratings for each chord for this experiment and the other experiments are on the webpage with the URL cited in the Materials section above). A crucial task for any theory of dissonance is to account for the results of the four triads, and so we deal with them first, and then with the basic chords and their inversions, where the standard errors are shown in parentheses:



| Chord #: | 1a | b | c | 2a | b | c | 3a | b | c | 4a | b | c | 5a | b | c |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Roughness: | 7.27 | 6.11 | 9.92 | 4.00 | 13.93 | 11.52 | 7.60 | 17.85 | 19.40 | 8.94 | 8.96 | 11.03 | 9.72 | 10.77 | 18.38 |
| Ratings: | 1.667 | 2.889 | 2.741 | 2.481 | 4.444 | 3.630 | 2.630 | 3.556 | 4.0 | 2.926 | 3.333 | 4.296 | 2.407 | 3.593 | 3.481 |

| Chord #: | 6a | b | c | 7a | b | c | 8a | b | c | 9a | b | c | 10a | b | c |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Roughness: | 9.83 | 13.4 | 12.14 | 10.6 | 22.67 | 36.97 | 10.97 | 19.94 | 37.07 | 22.14 | 13.69 | 16.83 | 13.90 | 22.14 | 54.29 |
| Ratings: | 3.148 | 2.852 | 3.111 | 3.370 | 3.296 | 4.741 | 2.630 | 3.704 | 3.963 | 3.889 | 3.519 | 3.667 | 3.963 | 4.148 | 5.185 |

| Chord #: | 11a | b | c | 12a | b | c | 13a | b | c | 14a | b | c |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Roughness: | 17.46 | 20.93 | 18.74 | 18.67 | 17.66 | 39.64 | 19.02 | 17.07 | 7.51 | 24.85 | 40.3 | 30.65 |
| Ratings: | 5.148 | 3.444 | 5.296 | 3.926 | 3.704 | 4.519 | 3.481 | 3.333 | 3.222 | 3.630 | 5.185 | 4.00 |

| Chord #: | 15a | b | c | 16 | 17a | b | c | 18a | b | c | 19a | b | c |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Roughness: | 26.39 | 35.40 | 38.53 | 16.07 | 17.27 | 25.87 | 41.16 | 21.64 | 23.31 | 39.95 | 30.42 | 29.1 | 33.88 |
| Ratings: | 4.815 | 5.296 | 5.333 | 5.259 | 5.593 | 5.815 | 4.148 | 5.630 | 4.259 | 5.296 | 5.593 | 5.852 | 6.667 |

FIGURE 2. The 19 basic chords and their inversions in Experiment 1 in their predicted order of dissonance, their roughness values (x 100), and the participants' mean ratings of their dissonance (from "1" = "highly pleasant" to "7" = "highly unpleasant"). The double bar-lines divide the chords into six levels of increasing tonal dissonance according to the dual-process theory.

Major triad (CEG): roughness 7.27; rated dissonance 1.67 (*SE* = 0.01)
Minor triad (ACE): roughness 9.72; rated dissonance 2.41 (*SE* = 0.25)
Diminished triad (BDF): roughness 22.14; rated dissonance 3.89 (*SE* = 0.30)
Augmented triad (CEG#): roughness 16.07; rated dissonance 5.26 (*SE* = 0.23)

This pattern is consistent with past empirical investigations of triads (e.g., Cook, 2001; Cook & Fujisawa, 2006; Roberts, 1986), and the same trend occurs in data including inversions. In the experiment, 26 out of the 27 participants rated the augmented triad as more dissonant than the other triads (binomial test, $p << .001$, one-tail, where "<<" signifies a probability very much less than .001, in this case $p = .50 \times 10^{-15}$).

This result is contrary to predictions based on roughness, but corroborates the dual-process theory: an augmented triad occurs only in harmonic minor keys, whereas the other triads all occur in major keys.

Table 1 summarizes the mean roughness values and dissonance rankings for the six increasing levels of tonal complexity of three-note chords. The predicted trend over the six categories was highly reliable (Page's $L = 2381.00$, $z = 9.70$ $p << .001$, one-tail, henceforth all $p$ values are one-tail unless otherwise stated). We assessed the correlation between the predictions and the observations using the Pearson's product-moment correlation coefficient $r$, which varies from +1 for a perfect linear correlation to −1 for a perfect inverse linear correlation. Overall, roughness values correlated with dissonance ratings of the 19 basic chords, $r(18) = .76$, $p <.0025$, but the dual-process predictions correlated significantly higher with the ratings of dissonance, $r(18) = .91$, $p << .001$. A hierarchical regression analysis showed that the addition of tonal principles to roughness yielded a significant increase in the proportion of variance accounted for by the model ($R^2$ change = .33, $F(1, 16) = 43.317$, $p << .001$). The standardized regression coefficients and coefficient of determinations at each step of the regression are on the same webpage as the URL in the Materials section.

For the 13 basic chords with a clear tonal root (all but chords 6, 12, 13, 16, 18, and 19 in Figure 1), the rated dissonance of the root position was highly correlated with the mean ratings over the chords' inversions, but roughness predicted that the root position should be less dissonant than inversions. The mean ratings of dissonance for these chords in root position was reliably smaller than the mean rating for their inversions for 12 out of the 13 chords (binomial test, $p < .0025$).

The results showed that the participants tended to agree about the relative dissonance of the chords. They also replicated the results of previous studies of the dissonance of triads (e.g., Cook & Fujisawa, 2006; Roberts, 1986). These two observations suggest that the instructions and procedure provided a valid method to assess dissonance. We examined the relation between our participants' musical experience and their ratings of dissonance, but we spare readers the details because it had no reliable effect on their dissonance ratings. The results corroborated the predictions of the dual-process theory: both roughness and the tonal principles contributed to the participants' judgments. The contribution of roughness suggests that Parncutt's (1989) algorithm can be usefully applied to our stimuli despite the fact that the algorithm embodies an idealization about their spectra. Perhaps the use of ranks rather than absolute values contributed to its efficacy.

TABLE 1. Mean Roughness and Mean Ratings of Dissonance (and their Standard Errors) for the Three-Note Chords in Experiment 1, Based on the Scale in which the Chord Occurs, Whether or Not it is Consistent with a Major Triad, and Whether it is Built from Thirds or Not.

| Scale | Major Triad | Thirds | Roughness | Rating | *SE* |
|---|---|---|---|---|---|
| Major | Consistent | Thirds | 7.27 | 1.67 | 0.01 |
| | Inconsistent | Thirds | 10.42 | 2.94 | 0.15 |
| | | Not thirds | 20.05 | 4.16 | 0.14 |
| Minor | Inconsistent | Thirds | 16.07 | 5.26 | 0.23 |
| | | Not thirds | 19.46 | 5.61 | 0.15 |
| Neither | Inconsistent | Not thirds | 30.42 | 5.59 | 0.20 |

## Experiment 2

Three-note chords are common in tonal music, but so too are chords composed of four distinct pitch classes. As a further test of the dual-process theory, Experiment 2 examined 48 four-note chords, which are a representative sample from the set of possible four-note chords (Tymoczko, 2006).

### METHOD

*Participants.* Experiment 2 tested 39 participants (23 females, 13 males; mean age 23.1 years) from the same population as before. All the participants were familiar with Western music, and included both musicians and nonmusicians.

*Materials and procedure.* All four-note chords are inversions of 43 basic chords, but it is not feasible to test all 165 possible chords. We therefore chose a representative sample of four-note chords in the following way. Of the 43 basic chords, 8 have at least three adjacent semitones, which are highly dissonant, and so the experiment examined just two of them (2 chords). Of the remaining basic chords, it examined some in one inversion (21 chords), eleven in two inversions (22 chords) in order to have a representative sample of inversions, one instance of each of the two chords with 2 possible inversions (2 chords), and the diminished seventh that has equivalent intervals in all its inversions (1 chord). Participants rated the dissonance of the resulting 48 chords (corresponding to either one or two inversions of 37 basic four-note chords) using an identical procedure to Experiment 1.

### RESULTS AND DISCUSSION

The participants showed a reliable consensus in their ratings of the dissonance of four-note chords (Kendall's coefficient of concordance, $W = .57$, $p << .001$, two-tail). Figure 3 presents each of the chords, its roughness (x 100), and the participants' mean ratings of dissonance on the seven-point scale. (Standard errors are on the webpage with the URL cited in the Materials section of Experiment 1.) Table 2 summarizes the mean roughness values and dissonance ratings according to tonal complexity for four-note chords. The predicted trend over the six increasing levels of tonal complexity was highly reliable (Page's $L = 3302.00$, $z = 12.20$ $p << .001$). Overall, roughness values alone had a very low correlation with the ratings of the dissonance of the 37 basic chords ($R^2 = .23$), whereas the dual-process predictions correlated significantly higher with the ratings of dissonance, $R^2 = .84$, $F(1, 36) = 181.30$, $p << .001$). Finally, the effect of inversions on the 11 chords was better accounted for by the dual-process theory than by roughness alone. Two of the eleven pairs yielded the same ratings, and roughness alone predicted only four of the nine differences correctly, whereas the dual-process theory predicted eight of the nine (binomial test, $p < .25$). Once again, the

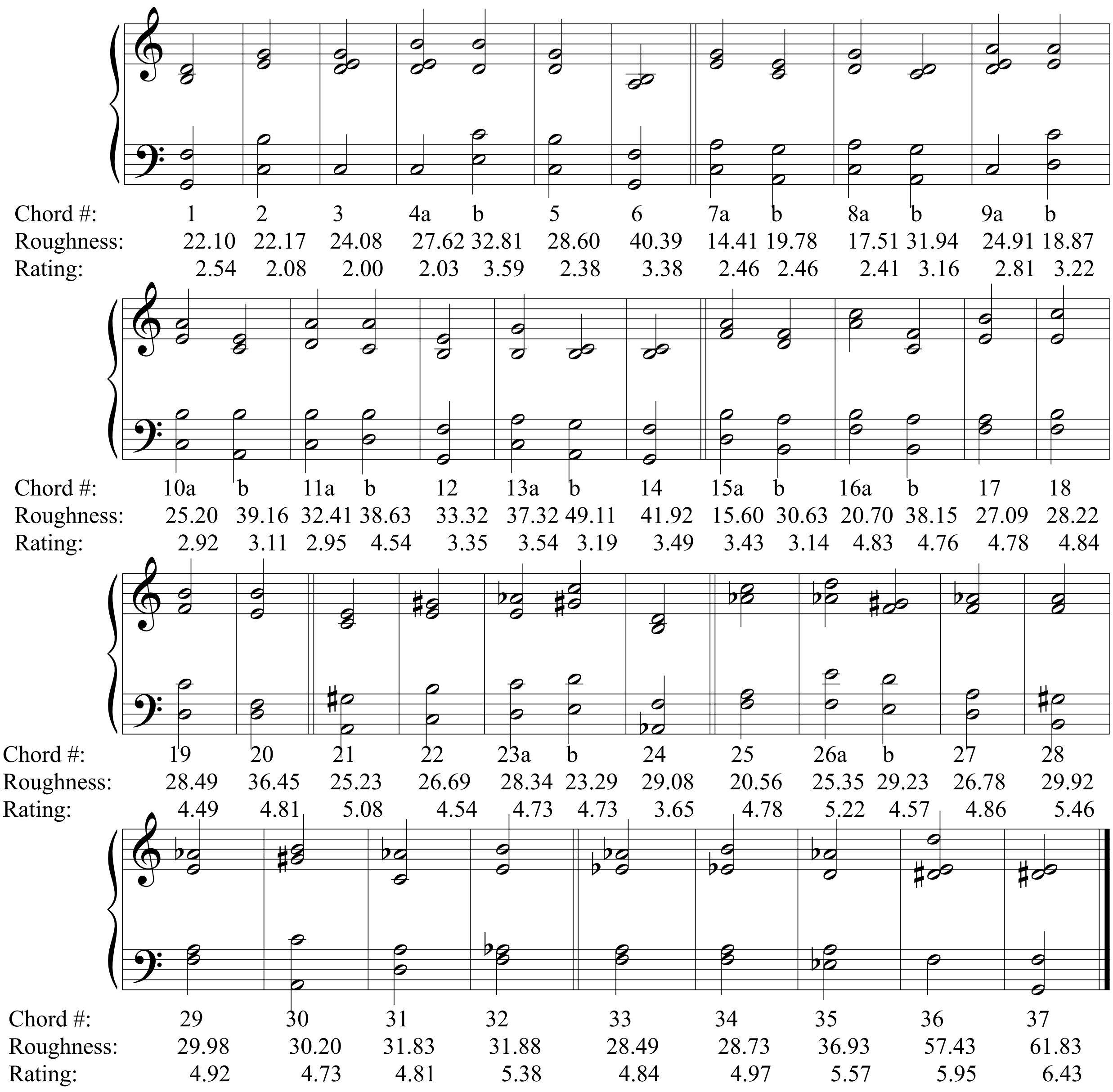


FIGURE 3. The 37 basic chords and their inversions in Experiment 2 in their predicted order of dissonance, their roughness values (x 100), and the participants' mean ratings of their dissonance (from "1" = "highly pleasant" to "7" = "highly unpleasant"). The double bar-lines divide the chords into six levels of tonal dissonance according to the dual-process theory.

TABLE 2. Mean Roughness and Mean Ratings of Dissonance (and their Standard Errors) for the Four-Note Chords in Experiment 2, Based on the Scale in which the Chord Occurs, Whether or Not it is Consistent with a Major Triad, and Whether it is Built from Thirds or Not.

| Scale | Major Triad | Thirds | Roughness | Rating | *SE* |
|---|---|---|---|---|---|
| Major | Consistent | Thirds | 27.34 | 2.40 | 0.10 |
| | | Not thirds | 28.38 | 2.99 | 0.11 |
| | Inconsistent | Not thirds | 26.09 | 4.53 | 0.14 |
| Minor | Inconsistent | Thirds | 27.34 | 4.50 | 0.12 |
| | | Not thirds | 28.31 | 5.02 | 0.10 |
| Neither | Inconsistent | Not thirds | 42.68 | 5.55 | 0.11 |

participants concurred in their ratings, and the results corroborated the dual-process theory.

## Experiment 3

As we argued earlier, the dual-process theory predicts that tonal chords should be more consonant in a tonal sequence than in a random sequence, even though the sequence cannot have any effect on their sensory dissonance. In contrast, the dissonance of non-tonal chords should be less affected by the sequence in which they are rated. The experiment tested these predictions by examining two sets of chords in tonal and random sequences. The chords in one set were tonal according to the theory: they were constructed from a major scale, consistent with a major triad, and built out of thirds. The chords in the other set were non-tonal: they were not consistent with a major triad, and not constructed from thirds. Experiment 1 corroborated their predicted difference in dissonance (see below).

### METHOD

*Participants*. Experiment 3 tested 37 participants (25 females and 12 males, with a mean age of 23.0 years) from the same population as before.

*Materials and procedure*. The tonal chords were the major triad, the seventh, the minor seventh, and the minor triad, i.e., transpositions of chords 1a, 3a, 4a, and 5a, in Figure 1, and overall they were rated in Experiment 1 with a mean dissonance of 2.4 on the seven-point scale. The non-tonal chords were A♭G♭D, CBG♭, AE♭D, and GBBb, in various transpositions of chords 11a, 15a, 15c, and 18b in Figure 1, and overall they were rated with a mean dissonance of 4.89 on the seven-point scale. The difference in the mean dissonance ratings of the two sets of chords was reliable (Mann Whitney $U = 0.0$, $N = 8$, $p < .025$). The two sorts of chords were presented either in tonal sequences based on the cycle of fifths (e.g., VI II V I), or in random sequences with a random choice of root for each chord. In the tonal sequences, the final I chord was either the major triad D♭FA♭ (in a transposition of 1a) or the dissonant chord D♭CA♭♭ (in a transposition of 15a). Participants were told nothing about these manipulations; as far as they were concerned, they were simply asked to rate the dissonance of one chord after another on a seven-point scale. This method was designed to minimize the participants' focus on the transitions from one chord to another. The procedure was the same as in Experiments 1 and 2.

### RESULTS AND DISCUSSION

The ratings of each chord in each sequence are presented in Figure 3. (Standard errors are on the webpage with the URL cited in the Materials section of Experiment 1.) The overall mean ratings of the dissonance of the chords on the seven-point scale were as follows, where *SE* denotes the standard errors:

Tonal chords in a tonal sequence: 2.75 ($SE = 0.19$)
Tonal chords in a random sequence: 3.26 ($SE = 0.15$)
Non-tonal chords in a tonal context: 5.07 ($SE = 0.16$)
Non-tonal chords in a random context: 5.15 ($SE = 0.15$)

Overall, context had a reliable effect on dissonance: chords in a tonal sequence had a mean rated dissonance of 3.9, whereas chords in a random sequences had a mean rated dissonance of 4.2 (Wilcoxon test, $z = 3.90$, $p < .0025$). As the means above suggest, however, there was an interaction: the effect of context was reliably greater for tonal chords than for non-tonal chords (Wilcoxon, $z = 3.15$, $p < .0025$). Its effect on the two chords that occurred in all the different sequences bore out the interaction. The major triad yielded a significant increasing trend in rated dissonance: 2.03 at the end of a tonal sequence of tonal chords, 2.31 at the end of a tonal sequence of non-tonal chords, and 2.95 in a random sequence of both sorts of chord (Page's $L = 505.50$, $z = 4.25$, $p << .001$). In contrast, the non-tonal chord 15a yielded no such trend: 5.05 at the end of a tonal sequence of otherwise tonal chords, 5.03 at the end of a tonal sequence of non-tonal chords, and 5.14 in a random chord sequence (Page's $L = 465.00$, $z = 0.34$, $p > .50$). In sum, the experiment showed that chords that are readily construed as tonal sound less dissonant in tonal sequences based on the cycle of fifths, whereas chords that are not construed as tonal do not differ reliably in their

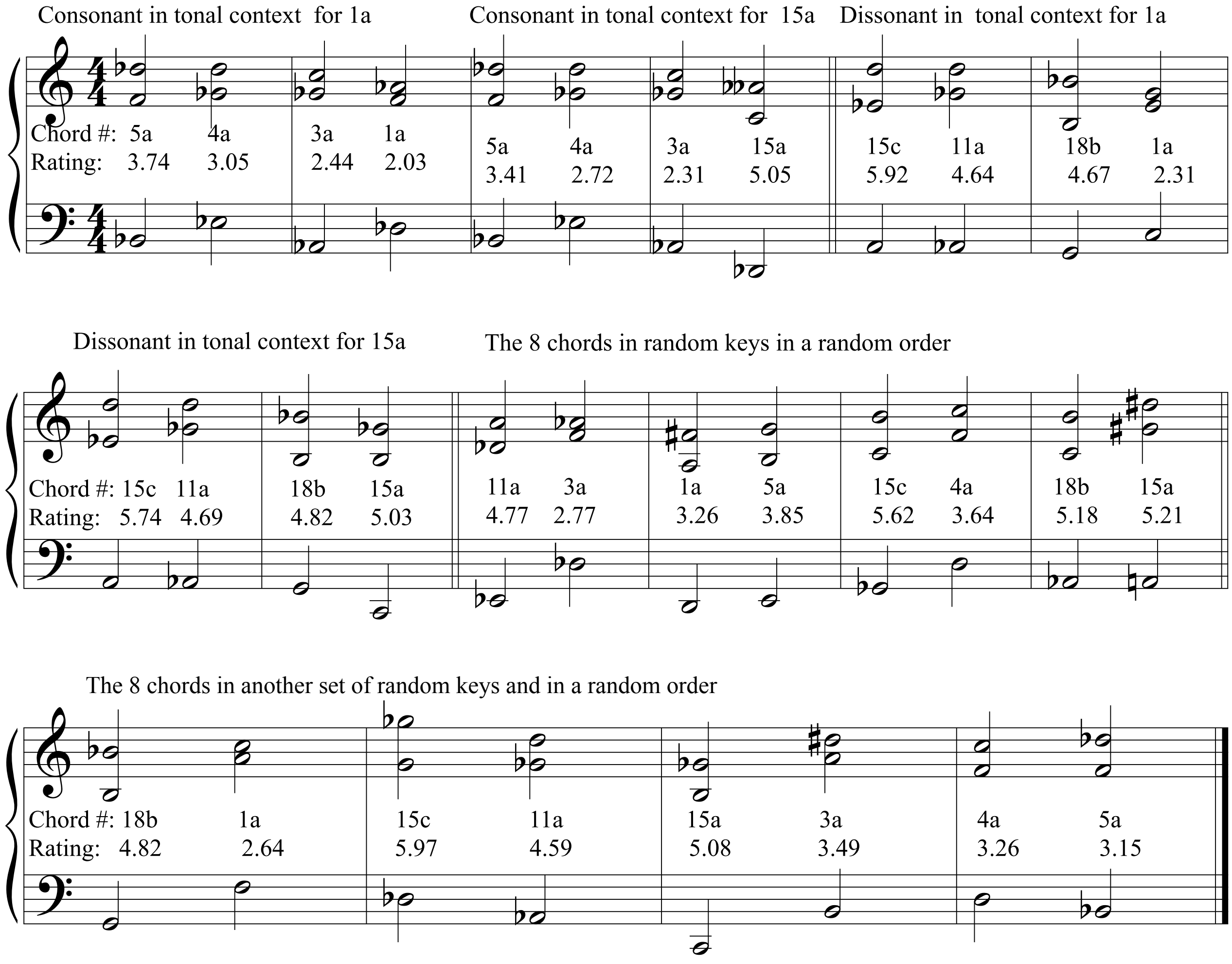


FIGURE 4. The sequences of chords in Experiment 3 with the tonal sequences of two measures each, and the two separate random orders for all eight chords, and the participants' mean ratings of their dissonance (from "1" = "highly pleasant" to "7" = "highly unpleasant").

dissonance depending on their context. This result corroborates the tonal component of the dual-process theory, and bears out the need for theories of dissonance to take tonality into account: factors that affect sensory dissonance of chords in isolation, such as roughness, are most unlikely to be affected by context.

## General Discussion

The scientific puzzle of dissonance has attracted many putative solutions. Some theories invoke psychoacoustic factors, such as the roughness of adjacent partials (Helmholtz, 1877/1912; Plomp & Levelt, 1965), the tension of equal intervals in a chord (Cook, 2009), and the regularity of the waveform (Tramo, Cariani, Delguette, & Braida, 2003). Other theories discount such factors and depend instead on purely musical considerations (Cazden, 1972). The evidence, which we reviewed earlier, shows overwhelmingly that listeners — even without music training — acquire a tacit knowledge of tonality, and so violations of these principles lead to dissonant chords (Huron, 2006; Peretz, Gaudreau, & Bonnel, 1998; Szpunar, Schellenberg, & Pliner, 2004). Many theories, however, allow for both sensory and tonal factors to affect dissonance (McDermott et al., 2010). Such theories need to make predictions about the relative dissonance of any chords (cf. Parncutt, 2006), and so they need to integrate sensory dissonance with principles of tonality that listeners can tacitly acquire.

The dual-process theory described in this article relies on three principles that appear to be embodied in tonal music:

1. The distinction between major and minor genera (Hyer, 2002), and in particular the increasing trend in dissonance of chords in major scales, in minor scales only, and in neither sort of scale.
2. The privileged status of the major triad as the most consonant chord of all (McDermott et al., 2010; Rameau, 1722/1971).
3. The construction of tonal chords out of thirds (Rameau, 1722/1971).

These principles one within another yield increasing levels of dissonance, bounded at one end by the major triad and at the other end by chords that are in neither sort of scale and not constructed out of thirds. Within each of these levels, the theory postulates that dissonance depends on the psychoacoustic factor of roughness.

The theory applies directly to chords that occur in Western music, which may include adjacent partials that create roughness. Hence, skeptics might argue that the whole enterprise is circular – a theory based on tonality and roughness is applied to music that embodies tonality and roughness. Several arguments, however, rebut the claim of circularity. An initial point is that the theory also applies to atonal chords and chords in serial compositions. More importantly, if the theory were truly circular then there would be no need to test it empirically, and no point in doing so, because it would be true a priori. In fact, there was no guarantee prior to Experiment 1 that participants would concur in their judgments of the dissonance of 55 chords. If they concurred reliably in a way that was inconsistent with the predictions, then the theory would have been refuted. The agreement in their ratings, which was statistically significant, shows that they had a tacit understanding of dissonance. They perceived and agreed about a property of the chords they heard, and their ratings suggest that this property reflected a combination of roughness and the musical concept of dissonance. They accordingly concurred that the triads showed an increasing trend in dissonance: major < minor < diminished < augmented. And they consistently rated the major triad as the least dissonant chord, whereas they rated a chord made up of C, C♯, and D, as the most dissonant three-note chord. Of course, they could also have concurred in a way that refuted the predictions of the theory. And this possibility also shows that the enterprise was not circular.

One other argument against circularity may be helpful. The three tonal principles in our theory and their integration are not obvious. Indeed, many other putative principles can be extracted from the vast literature on tonality, but these other principles are unlikely to predict our results, e.g., minor chords are more dissonant than major chords (Bigand et al., 1996), chords in complete cadences are more consonant than chords in other sorts of cadences (e.g., Dahlhaus, 1990), chords whose notes correspond to frequencies lower in the harmonic series of a single note are more consonant than other chords (e.g., Stumpf, 1890), and chords are consonant if they contain no dissonant intervals, such as seconds, sevenths, and tritones (Apel, 1972).

To what extent is the dual-process theory restricted to the modern system of tuning, which divides the octave into twelve tones of equal logarithmic steps (12-tet)? We conjecture that the theory ought also to apply to just or well-tempered tuning, which should primarily affect roughness as opposed to tonality. Sethares (1999) has shown that there are many, many other possible sorts of tuning, and that with appropriate timbres – to minimize roughness in dyads – they sound acceptable. We conjecture that chords in such tunings will sound dissonant as a consequence of the two factors in our theory: roughness and experience with the music. The difficulty in testing such a theory is that few people have a lifetime's experience of listening to music with chords in any tuning other than 12-tet.

The dual-process theory may not be the last word on the topic of dissonance. It may well be possible to improve the theory. An improved account of psychoacoustic factors, incorporating, say, Cook's (2009) concept of the tension created by equal intervals, may lead to greater predictive power (see also Terhardt, 1984). Even computations of roughness tailor-made to the spectra of the stimuli might improve the theory's predictions, though it does already account for a large proportion of the variance in the ratings. However, we doubt whether any purely psychoacoustic theory could alone account for the results of our experiments. No such theory is likely to explain the greater consonance of tonal chords in a tonal sequence than in a random sequence, and the lack of any reliable effect of sequence on dissonant chords (Experiment 3).

An improved account of tonality might also improve the theory's predictions. For instance, theorists have argued that voice leading may contribute to consonance. As Wright and Bregman (1987) and Huron (2001) have suggested, a pair of tones that are dissonant are likely to be less dissonant if voice leading yields the perception that they are in different musical streams. This process of segregation, in turn, depends on several Gestalt-like factors that organize auditory perception, e.g., asynchronous onsets as opposed to "common attack." Similarly, the voice leading from one chord to another may also affect the perception of consonance or dissonance (Tymoczko, 2011). But, we doubt whether any purely tonal theory could alone account for the results of our experiments. Indeed, the results suggest both that no theory of dissonance can dispense with roughness, which appears to affect all listeners, and that no theory of dissonance can dispense with tonal factors, which appear to affect all listeners with experience of tonal music. We found that the extent of participants' music training had no reliable effect on their dissonance ratings, which suggests that mere exposure to Western music suffices for the acquisition of tacit principles of tonality. A dual-process theory therefore appears to be essential. The tonal principles embodied in the present theory reflect the common experience of listening to tonal music: the scales in which a chord occurs matter, the major triad is the anchor for tonality, and tonal chords are constructed from thirds. These principles should apply to any chords in the Western system of tuning. Helmholtz (1877/1912) should have the last word: his account of dissonance as dependent on a psychoacoustic factor (roughness) and on a cultural factor (tonality) seems to be correct.

## Author Note

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