

## Expectations for tonal cadences: Sensory and cognitive priming effects

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3 Expectations for Tonal Cadences: Sensory and Cognitive Priming Effects  
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## Abstract

Studies examining the formation of melodic and harmonic expectations during music listening have repeatedly demonstrated that a tonal context primes listeners to expect certain (tonally related) continuations over others. However, few such studies have (1) selected stimuli using ready examples of expectancy violation derived from real-world instances of tonal music; (2) provided a consistent account for the influence of sensory and cognitive mechanisms on tonal expectancies by comparing different computational simulations; or (3) combined melodic and harmonic representations in modelling cognitive processes of expectation. To resolve these issues, this study measures expectations for the most recurrent cadence patterns associated with tonal music and then simulates the reported findings using three sensory-cognitive models of auditory expectation. In Experiment 1, participants provided explicit retrospective expectancy ratings both before and after hearing the target melodic tone and chord of the cadential formula. In Experiment 2, participants indicated as quickly as possible whether those target events were in or out of tune relative to the preceding context. Across both experiments, cadences terminating with stable melodic tones and chords elicited the highest expectancy ratings and the fastest and most accurate responses. Moreover, the model simulations supported a cognitive interpretation of tonal processing, in which listeners with exposure to tonal music generate expectations as a consequence of the frequent (co-)occurrence of events on the musical surface.

*Keywords:* musical priming, tonal expectations, cognitive, sensory, tonal cadence

### Expectations for Tonal Cadences: Sensory and Cognitive Priming Effects

To account for the formation of expectations during music listening, an extensive body of research on the perception of Western tonal music has adopted a top-down, cognitive view of musical processing (Collins, Tillmann, Barrett, Delbé, & Janata, 2014), whereby listeners learn the temporal relations characterizing complex hierarchical organizational systems like tonality or meter over the course of exposure and then impose that knowledge on all subsequent musical experiences. From this point of view, composers seem to exploit the brain's predictive mechanisms by organizing musical events to reflect the kinds of statistical regularities that listeners will learn and remember (Krumhansl, 1990). The tonal cadence is exemplary in this regard. As a highly recurrent harmonic and melodic formula, the cadence provides perhaps the clearest instance of phrase-level schematic organization in the tonal system. As a consequence, cadences serve as closing gestures in a vast number of genres and style periods, since the cluster of constituent features that characterize cadences—such as a conventionalized harmonic (chord) progression and a falling melody—alerts listeners to the impending end of the phrase, theme, or larger section that subsumes them.

According to Huron (2006) and Meyer (1956), cadences are the most predictable, probabilistic, and specifically envisaged temporal patterns in all of tonal music. For this reason, cadences are routinely employed in experimental contexts to investigate cognitive processes related to the storage of harmonic and tonal structure in long-term memory (Krumhansl & Kessler, 1982), the perception of dynamic variations in tension (Bigand & Parncutt, 1999), and the priming of tones or chords from similar or identical tonal contexts (e.g., Koelsch, Gunter, Friederici, & Schröger, 2000). These findings have led researchers to suggest that listeners with exposure to tonal music possess schematic representations for cadences and other recurrent

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3 temporal patterns (Eberlein & Fricke, 1992; Eberlein, 1997; Gjerdingen, 1988; Meyer, 1967;  
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5 Rosner & Narmour, 1992; Sears, Caplin, & McAdams, 2014; Sears, 2015; 2016; Temperley,  
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7 2004).

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10         Nevertheless, recent simulations of tonal priming effects using sensory models of echoic  
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12 and auditory short-term memory have called into question the necessity of strictly cognitive  
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14 accounts (Bigand, Poulin, Tillmann, Madurell, & D'Adamo, 2014; Collins et al., 2014). From  
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16 the sensory point of view, facilitation effects arise when the preceding context shares sensory  
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18 features with the target event of the sequence. Whether cadences and other temporal patterns  
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20 reflect processing mechanisms related to learning and memory is thus inconsequential to sensory  
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22 accounts so long as the terminal events of the pattern share component tones or overtones with  
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24 the preceding context. What is more, studies examining the influence of sensory and cognitive  
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26 processes on the formation of tonal expectancies typically compose (or select) melodic or  
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28 harmonic (chord) sequences that control for the psychoacoustic similarities between the  
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30 preceding context and the terminal, target event (e.g., Tekman & Bharucha, 1998). As a result,  
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32 ecological validity tends to be low in the expectancy literature (Pearce, Ruiz, Kapasi, Wiggins, &  
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34 Bhattacharya, 2010), as participants are less likely to encounter such artificially constructed  
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36 stimuli in the natural environment.  
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42         To resolve these issues using ready examples of expectancy violation derived from  
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44 genuine musical materials, the present study compared the most common cadence patterns from  
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46 a representative corpus of tonal music against *cadential deviations* (Caplin, 1998; 2004; Sears, et  
47  
48 al., 2014), which initially promise the expected terminal events of a cadential formula but then  
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50 replace those events with unexpected melodic tones or chords. To account for the sensory and  
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52 cognitive mechanisms underlying tonal expectancies, we also simulated the reported findings  
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3 using three sensory-cognitive models of musical processing. The first is the echoic memory  
4 (EM) model (Leman, 2000), a sensory model of auditory expectations that simulated the priming  
5 effects for stimulus sets from 18 separate studies (Bigand et al., 2014). The second is the tonal  
6 space (TS) model (Janata et al., 2002), a sensory-cognitive priming model that has predicted the  
7 priming effects for the reaction-time (RT) data from seven separate studies (Collins et al., 2014).  
8 Finally, the third is the Information Dynamics of Music (IDyOM) model (Pearce, 2005), a finite-  
9 context (or *n*-gram) model simulating cognitive priming effects, which has been shown to predict  
10 behavioral (Omidie, Pearce, & Stewart, 2012; Pearce & Wiggins, 2006; Pearce, Ruiz, et al.,  
11 2010), electrophysiological (Egermann, Pearce, Wiggins, & McAdams, 2013), and neural  
12 evidence for melodic pitch expectations (Omidie, Pearce, Williamson, & Stewart, 2013; Pearce,  
13 Ruiz, et al., 2010).

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15 We first introduce the necessary music terminology and concepts and then review explicit  
16 and implicit behavioral methods for measuring tonal expectations, as well as the evidence  
17 obtained therefrom.

### 18 **Tonal Structure**

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20 Much of the world's music relies on musical scales that divide the octave—a doubling in  
21 frequency—into a moderate number of discrete and discriminable steps (Dowling & Harwood,  
22 1986). In equal-tempered music, the octave is typically divided equally into 12 steps (or  
23 *semitones*) along a logarithmic scale, subsets of which form the most common scales associated  
24 with Western tonal music (e.g., major, minor, pentatonic, etc.). The vast majority of these scales  
25 also depend on the perceptual phenomenon known as *octave equivalence* (Deutsch, 1999)—  
26 whereby pitches separated by a frequency interval representing a power of two are perceived as  
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3 similar—to reduce the vocabulary of pitches to 12 *pitch classes*, each of which receives a letter  
4 designation in music theory nomenclature (C, C#/Db, D, etc.).  
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8 For each of the 12 major and minor keys associated with the tonal system (one major and  
9 one minor for each pitch class), seven pitch classes (called *diatonic*) belong to the key, and five  
10 (called *chromatic*) fall outside the key. Together, the diatonic pitch classes form the degrees of  
11 the scale and are represented numerically with a caret above each numeral (see Figure 1a). Thus,  
12 C and G are the first and fifth scale degrees in the key of C major, and so receive the values 1  
13 and 5, respectively. Furthermore, two pitches presented simultaneously form a harmonic  
14 interval, combinations of which form chords. The diatonic chords associated with tonal harmony  
15 typically consist of two or more scale degrees ordered such that their intervals feature  
16 superimposed thirds—intervals that span three or four semitones—above the most perceptually  
17 stable scale degree of the chord, called the *root* (Rameau, 1722/1971; Parncutt, 1989). A chord  
18 featuring two superimposed thirds is called a *triad*, and the size of one or both of these intervals  
19 determines whether the triad is *major* (i.e., the lower interval spans four semitones, or a major  
20 third), *minor* (i.e., the lower interval spans three semitones, or a minor third), *augmented* (i.e.,  
21 both intervals feature major thirds), or *diminished* (i.e., both intervals feature minor thirds).  
22 Shown in Figure 1b, chords built in this way on each degree of the diatonic scale are represented  
23 using Roman numerals, with the letter case of the Roman numeral used to denote whether the  
24 chord features a major (uppercase) or minor (lowercase) triad.<sup>2</sup> In the key of C major, for  
25 example, an F major triad consists of the pitch classes F, A, and C, and given that F is the fourth  
26 degree of the scale, the chord receives the Roman numeral IV.  
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3 Broadly conceived, tonality refers to the systematic hierarchical organization of pitch  
4 phenomena such that certain tones and/or chords are perceived as more stable and serve as better  
5 completions than others (Bharucha & Krumhansl, 1983). This *tonal hierarchy* is perhaps best  
6 illustrated in Krumhansl and Kessler's (1982) seminal probe-tone studies, in which participants  
7 heard a short context consisting of a harmonic cadence (IV-V-I), and then indicated how well  
8 each of the twelve members of the chromatic scale fit with the preceding context. In the major  
9 key profile obtained by Krumhansl and Kessler (see Figure 1a), the tonic (1) received the highest  
10 fit ratings, leading them to suggest that it serves as the most stable reference point in the tonal  
11 system (see also Bharucha, 1984; Krumhansl, 1990). In descending order of fit, the tonic was  
12 then followed by the dominant (5), the remaining diatonic members (2, 3, 4, 6, and 7), and  
13 finally the other (chromatic) members (not labeled). In a subsequent study, Krumhansl,  
14 Bharucha, and Kessler (1982) also generalized these findings to the chords of the diatonic scale,  
15 noting that more stable chords like the tonic (I) and dominant (V) serve as better continuations in  
16 two-chord progressions, and so appear at the top of the harmonic hierarchy. What is more, these  
17 chords receive higher continuation judgments when they follow, rather than precede, the  
18 remaining diatonic chords (Bharucha & Krumhansl, 1983), suggesting that they appear at the  
19 ends of cadences and other recurrent closing patterns in tonal music because they serve as  
20 *cognitive reference points* (Rosch, 1975).  
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### 44 **Measuring Tonal Expectations**

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46 To measure the formation of expectations during music listening, behavioral studies  
47 employ explicit and implicit measures. Explicit measures typically consist of retrospective rating  
48 tasks, in which participants hear a musical context and then indicate the strength and specificity  
49 of their expectations for further continuation (Schmuckler, 1989), or they provide a measure of  
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3 uncertainty for the range of possible future outcomes (Hansen & Pearce, 2014; Huron, 2006, p.  
4 46). However, explicit measures have been criticized for conflating expectations derived from  
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6 explicit training with those resulting from implicit exposure (Bigand, 2003), so experimental  
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8 studies often employ implicit tasks using the priming paradigm, which assumes that the  
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10 processing of incoming events is affected by the context in which they appear; related or  
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12 repeated events are primed, thus facilitating processing (for a detailed discussion of experimental  
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14 methods in studies examining tonal expectations, see Huron & Margulis, 2010).  
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19 To account for tonal priming effects, researchers typically control for the sensory or  
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21 psychoacoustic similarities between the preceding context and the target by manipulating the  
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23 experimental stimuli so that (1) the context and the target share no component tone or chord  
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25 events (*repetition* priming); and/or (2) the selected timbre consists of a simple periodic  
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27 waveform like a sine tone to minimize the potential for shared overtones (*sensory* priming). In  
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29 the last three decades, priming studies have demonstrated that after short contexts, targets from  
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31 related tonal contexts were processed faster than unrelated targets even when the context and  
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33 target did not share sensory information or were separated by a silent interval or a white noise  
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35 burst (Bharucha & Stoeckig, 1987; Tekman & Bharucha, 1992). In longer contexts, participants  
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37 also demonstrated facilitated processing for related targets compared to less related targets  
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39 (Koelsch et al., 2007; Marmel et al., 2010), and this priming effect persisted even when the less-  
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41 related targets shared more tones with the context than related targets (Bigand et al., 2003).  
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43 These schematic priming effects also remained unaffected by veridical knowledge about how  
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45 each stimulus might proceed (Justus & Bharucha, 2001; Tillmann & Poulin-Charronnat, 2010).  
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51 Nevertheless, disentangling low-level sensory influences from cognitive accounts of tonal  
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53 expectancy remains a tremendous challenge, and appealing to the musical materials themselves  
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3 tends to complicate rather than clarify matters. Sensory or psychoacoustic accounts of tonal  
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5 harmony are deeply rooted in the history of Western music theory (e.g., Rameau, 1722/1971),  
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7 and they continue to find favor in contemporary scholarship (Large, Kim, Flaig, Bharucha, &  
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9 Krumhansl, 2016; Leman, 2000; Parncutt, 1989). Bigand et al. (2014) note, for example, that  
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11 tonal syntax reflects psychoacoustic constraints like octave equivalence and harmonic overtones,  
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13 as well as general auditory mechanisms related to the perception of acoustic dissonance (Plomp  
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15 & Levelt, 1965; Sethares, 1998), virtual pitch perception (Terhardt, 1974; Terhardt, Stoll, &  
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17 Seewann, 1982), and principles of auditory stream analysis (Bregman, 1990; Wright & Bregman,  
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19 1987). Note and chord events associated with the tonic and dominant also feature strong overlaps  
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21 in harmonic spectra, which suggests that properties of sounds could provide an “acoustic  
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23 foundation” for tonal syntax (Bigand et al., 2014, p. 3).  
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29 Unfortunately, because tonal priming studies often feature rhythmically isochronous,  
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31 chorale-like passages presented at relatively long inter-onset intervals (IOIs), with the target or  
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33 the preceding context recomposed in the unexpected condition, these stimulus sets do not  
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35 adequately reflect examples of expectancy violation derived from musical styles and genres to  
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37 which listeners might be exposed (Pearce, Ruiz, et al., 2010). To resolve this issue, recent studies  
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39 have demonstrated melodic and harmonic priming effects for genuine musical materials using  
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41 behavioral and psychophysiological measures (Aarden, 2003; Egermann et al., 2013; Koelsch,  
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43 Kilches, Steinbeis, & Schelinski, 2008; Steinbeis, Koelsch, & Sloboda, 2006; Pearce, Ruiz, et al.,  
44  
45 2010). Only two of these studies extended the reported findings to multi-voiced chord  
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47 progressions, however, and neither of these studies attempted to replicate their findings using  
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49 existing computational models of auditory expectation. Finally, no study to date has attempted to  
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3 staircase tonal expectations by comparing the most expected cadential sequences against their  
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5 less expected (and thus, less stable) cadential counterparts.  
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8 To address these issues, this study examined expectations for the terminal melodic tones  
9  
10 and chords from the most common cadence patterns associated with tonal music. To that end, we  
11  
12 adopted the stimulus-selection paradigm introduced in Sears et al. (2014), in which participants  
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14 provided completion ratings for passages from Mozart's keyboard sonatas that terminated with  
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16 cadences from one of the following five categories in contemporary tonal cadence typologies  
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18 (e.g., Caplin, 1998; 2004; Schmalfeldt, 1992): perfect authentic cadence (PAC), imperfect  
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20 authentic cadence (IAC), half cadence (HC), deceptive cadence (DC), and evaded cadence (EV).  
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22 Shown in the first example of Figure 2, the PAC category, which features a final chord  
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24 progression from a root-position dominant to a root-position tonic (i.e., a V–I progression with  
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26 the root scale degree in the lowest voice in each chord), as well as the arrival of the melody on 1,  
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28 serves as the quintessential closing pattern for musical repertoires spanning much of the history  
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30 of Western music (Margulis, 2005; Sears, 2016), and also routinely appears in the expected  
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32 condition in harmonic priming studies. The IAC category is a melodic variant of the PAC  
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34 category that replaces 1 with 3 in the melody but retains the V–I chord progression. Like the  
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36 PAC category, the IAC also typically appears at the ends of phrases or larger sections in tonal  
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38 music. These two categories therefore constitute *authentic cadences* and appear at the top of the  
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40 hierarchy of harmonic stability (Krumhansl et al., 1982). The HC category (third example in Fig.  
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42 2) concludes with dominant triad in root position and any chord member in the melody (i.e., a V  
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44 chord with 2, 5, or 7 in the melody). Unlike the PAC and IAC categories, the HC category  
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46 concludes with the less stable dominant chord, and thus appears below the authentic cadences in  
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48 the harmonic hierarchy and presumably elicits weaker expectations in anticipation of its  
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3 occurrence (Tillmann et al., 2008). Finally, the remaining two categories represent *cadential*  
4 *deviations* of the authentic cadence, which is to say that they initially promise an authentic  
5 cadence, yet fundamentally deviate from the pattern's terminal events. The DC category (fourth  
6 example in Fig. 2) leaves the pattern somewhat open by closing with a nontonic chord, usually  
7 vi, but the melodic line resolves to a stable scale degree like 1 or 3. Finally, the EV category  
8 (final example in Fig. 2) is characterized by a sudden interruption in the harmonic and melodic  
9 events of the pattern: the melody, instead of resolving to 1, often leaps up to another scale degree  
10 (such as 5), and the final harmony may be replaced by an unexpected, nontonic chord (for further  
11 details, see Sears et al., 2014). Together, these categories would be expected to appear at the  
12 bottom of the harmonic hierarchy.

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26 [Insert Figure 2 about here.]  
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28 To measure tonal expectancies, this study employs a converging-methods approach. In  
29 Experiment 1, participants were presented with a *truncated* stimulus that omits the final, target  
30 melodic tone and chord of the cadence; they then heard a *nontruncated* version of the stimulus  
31 that includes the final events. Following the truncated stimulus, participants indicated the  
32 strength and specificity of their expectations for a musical continuation. Following the  
33 nontruncated stimulus, participants then indicated how well the final target melodic tone and  
34 chord fit with the expectations they had formed during the preceding context. To measure  
35 expectancies implicitly, Experiment 2 adopted the priming paradigm, in which participants  
36 indicated as quickly as possible whether the target melodic tone and chord from each stimulus  
37 were in or out of tune relative to the preceding context. Accuracies and response times (RTs)  
38 were then collected to determine whether the preceding context primed participants to expect  
39 tonally related or repeated (i.e., identical) target events. Finally, to account for the findings from  
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3 these experiments, we simulated the results using three sensory and/or cognitive computational  
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5 models of tonal expectation.  
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## 7 8 **Experiment 1**

### 9 10 **Method**

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12 **Participants.** Participants were 40 members (20 female) of the Montreal community  
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14 recruited through the Schulich School of Music and the McGill University classified ads. Ages  
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16 ranged from 18 to 46 ( $M = 24$ ,  $SD = 6$ ). Twenty participants with musical training equivalent or  
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18 superior to second-year-university level formed the musician group, and twenty participants with  
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20 less than one year of musical training comprised the nonmusician group. To limit any effects  
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22 caused by familiarity with the stimuli, no participant with more than two years of formal study  
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24 on the piano was permitted to take part. All participants provided informed consent, and the  
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26 study was certified for ethical compliance by the McGill University Research Ethics Board.  
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31 A questionnaire was administered to assess musical preferences and training. Musicians  
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33 and nonmusicians reported listening to an average of 21 and 16 hours of music each week,  
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35 respectively, and all but two participants self-identified as music lovers. The musicians practiced  
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37 their primary instruments for an average of 20 hours each week and had been playing their  
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39 primary instruments for an average of 6 years. All of the participants reported normal hearing,  
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41 which was confirmed with a standard audiogram administered before the experiment (ISO 389-8,  
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43 2004; Martin & Champlin, 2000).  
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47 **Materials.** The stimuli consisted of 40 excerpts selected from Mozart's keyboard sonatas  
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49 containing an equal number for each cadence category (8 each; see Appendix A). To examine  
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51 expectations both before and after the terminal harmonic and melodic events of the excerpt, two  
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53 versions of each excerpt were created: a *truncated* version that omits the terminal target melodic  
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3 tone and chord, and a *nontruncated* version that includes the target melodic tone and chord.  
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5 Because these excerpts only present expected phrase endings, it was assumed that the selected  
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7 stimuli would not represent the full range of the expectancy strength and specificity scales, since  
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9 passages selected from the beginning or middle of a musical phrase could potentially generate  
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11 weaker expectations (Escoffier & Tillmann, 2008; Pearce, Müllensiefen, & Wiggins, 2010;  
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13 Tillmann & Marmel, 2013). So as not to bias ratings of expectation toward one end of the  
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15 expectancy scales, eight foil stimuli that terminate in the middle of a musical phrase were also  
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17 selected from Mozart's keyboard sonatas, thus encouraging listeners to use the lower end of the  
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19 scale.  
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24 Following the experimental design employed in Sears et al. (2014), performance features  
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26 (such as dynamics and rubato) were neutralized and the tempo of each stimulus was determined  
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28 by convention. The duration of the truncated excerpts ranged from 5 to 15 s ( $M = 8.49$ ,  $SD =$   
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30  $2.61$ ). To ensure that unwanted differences concerning the terminal harmonic and melodic events  
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32 would not affect expectancy ratings while preserving the stylistic integrity of each excerpt, the  
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34 durations of the target melodic tone and chord were recomposed to 900 ms and any melodic  
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36 dissonances (such as a melodic suspension or appoggiatura) were removed. These steps ensured  
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38 an optimal balance between ecological validity on the one hand and stimulus control on the other  
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40 (Sears, 2015). Each stimulus was first created with the notation software Sibelius (Avid  
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42 Technologies, Burlington, MA) and then realized as a .wav sound file at a sampling rate of 44.1  
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44 kHz and 16-bit amplitude resolution using a piano physical model created by PianoTeq (Modartt  
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46 S.A.S., Ramonville Saint Agne).  
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51 **Design and Procedure.** Participants were presented with a randomized set of 40 stimuli  
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53 and 8 interspersed foils. After listening to the truncated version of each stimulus, participants  
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3 rated the strength of their expectation that the music would continue (*Expectancy Strength*), and  
4 the specificity of their expectation for a musical continuation (*Expectancy Specificity*) on  
5  
6 continuous analog scales that were subdivided into seven discrete categories labeled from 1 to 7  
7  
8 (called analogical-categorical scales; Weber, 1991). For the expectancy strength scale,  
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10 participants were instructed that a value of 1 indicates that they had no expectations that the  
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12 music would continue, whereas a value of 7 indicates that they had very strong expectations that  
13  
14 the music would continue. On the expectancy specificity scale, a value of 1 indicates that they  
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16 had no specific idea how the music would continue, whereas 7 indicates that they had a very  
17  
18 specific idea how the music would continue. In addition to their expectancy ratings, participants  
19  
20 also responded to the statement: “Following this excerpt, the end of the passage is imminent,” on  
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22 a 4-point Likert scale labeled from *strongly agree* to *strongly disagree*. Next, participants  
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24 listened to the *nontruncated* version of the same stimulus and rated on a 7-point analogical-  
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26 categorical scale how well the target melodic tone and chord fit with the expectations they had  
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28 formed when they heard the truncated version, with a rating of 1 indicating that the musical  
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30 continuation fit very poorly, and a rating of 7 indicating that it fit very well. For every trial, the  
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32 scales appeared on the screen from top to bottom in the following order: strength, specificity,  
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34 imminence, and fit. To familiarize the participants with the range of stimuli and the experimental  
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36 task, the session began with an exposure phase and a practice phase consisting of 12 additional  
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38 stimuli. After completing the experiment, participants filled out a short questionnaire addressing  
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40 their music background.  
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49 **Analysis.** Data were analyzed with a linear mixed effects model (LMM) approach (West,  
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51 Welch, & Galecki, 2007), an alternative to conventional regression models (MLR, ANOVA,  
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53 etc.) that allows the researcher to control for random sources of variance without the loss of  
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3 statistical power resulting from data aggregation across subjects or stimuli, which is a frequent  
4 preliminary step in repeated-measures designs (e.g., F1 and F2 ANOVAs, RM-ANOVA). As  
5 suggested by Baayen et al. (2008), we included crossed random effects for participants and items  
6 (musical excerpts). All mixed-effects analyses were conducted with the software R (2.15) using  
7 the packages lme4 (Bates, Maechler, & Bolker, 2011) and languageR (Baayen, 2012). Following  
8 Barr, Levy, Scheepers, & Tily (2013), all models included a full random effects structure as  
9 specified by the design of the experiment, with intercepts for each participant and by-participant  
10 slopes for the within-subject fixed factor of cadence category (PAC, IAC, HC, DC, EV), and  
11 with intercepts for each musical stimulus and by-stimulus slopes for the between-subjects factor  
12 of musical training (musicians, nonmusicians).<sup>3</sup> To examine more specific hypotheses about the  
13 potential differences between cadence categories, we also included two planned comparisons  
14 using the lsmeans package (Lenth, 2014), corrected with Bonferroni adjustment: the first to  
15 examine the predicted linear or quadratic trends for each rating scale using a polynomial contrast  
16 (*Polynomial*), and the second to determine whether authentic cadences elicit significantly higher  
17 expectancy fit ratings relative to cadential deviations (*Authentic vs. Deviations*), as was  
18 demonstrated in Sears et al. (2014). Finally, to visualize the effects of the included fixed factors  
19 on participant ratings after controlling for the random variance in the dataset, the figures present  
20 the estimated means and standard errors determined by the model.

## 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 **Results**

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47 Figure 3 displays line plots of the estimated mean expectation strength, specificity, and fit  
48 ratings of musicians and nonmusicians for each cadence category. Excerpts from the foil  
49 condition have also been plotted for comparison, but only responses to the cadence categories are  
50 presented in the analyses that follow, resulting in a preliminary dataset of 1600 trials (40 stimuli  
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3 × 40 participants). Results are reported for expectation strength, expectation specificity and  
4  
5 phrase completion for the truncated stimuli and then expectation fit for the nontruncated stimuli.  
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8 [Insert Figure 3 about here.]  
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10 Shown in Table 1, Type III Wald  $F$  tests of a mixed  $5 \times 2$  LMM of the expectation  
11 strength ratings with Kenward-Roger approximation for the denominator degrees of freedom  
12 revealed a significant effect of cadence category (Halekoh & Højsgaard, 2014). Because the  
13 authentic cadences (PAC, IAC) and the cadential deviations (DC, EV) only differ in their  
14 terminal harmonic and melodic events, it was predicted that the truncated stimuli from the HC  
15 category would receive the lowest expectancy strength ratings. As expected, a polynomial  
16 contrast of the cadence categories revealed a significant quadratic trend from the PAC to EV  
17 categories,  $B = 1.99$ ,  $t = 3.37$ ,  $p < .001$ , with the estimated means exhibiting a U shape from the  
18 outer cadence categories (PAC and EV) to the inner category (HC), and with the HC category  
19 receiving the lowest strength ratings overall ( $M = 5.04$ ,  $SE = .21$ ). The model estimates also  
20 suggested a main effect of training on expectation strength, with nonmusicians providing lower  
21 ratings than musicians overall, but this effect was not significant, and there was no interaction  
22 between the two factors.  
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40 The expectation strength and specificity ratings averaged across participants for each  
41 stimulus were highly correlated,  $r(38) = .85$ ,  $p < .001$ , as was found in Schmuckler (1989). Type  
42 III Wald  $F$  tests revealed main effects of cadence category and training, as well as a significant  
43 interaction (see Table 1). The PAC and HC categories received the highest and lowest specificity  
44 ratings, respectively, and polynomial contrasts revealed the same U-shaped quadratic trend in the  
45 ratings for both groups (musicians,  $B = 2.45$ ,  $t = 2.65$ ,  $p = .021$ ; nonmusicians,  $B = 2.02$ ,  $t = 2.43$ ,  
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60  $p = .036$ ). Musicians also provided significantly higher specificity ratings than nonmusicians.

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3 The 4-point Likert-scale ratings for the statement, “following this excerpt the end of the  
4 passage is imminent,” provided similar results to those observed for the analogical-categorical  
5 scales of expectation strength and specificity (see Figure 3). Given the ordinal nature of the  
6 dependent variable, the ratings were entered into a proportional-odds mixed effects model  
7 (Christensen, 2015). To examine main effects and interactions, a likelihood ratio test was  
8 calculated for each fixed effect that compares the full fixed (and random) effects model to a  
9 reduced model that only excludes the effect of interest (West et al., 2007). Model comparisons  
10 revealed a significant effect of cadence category,  $\chi^2(8) = 38.77, p < .001$ , and training,  $\chi^2(5) =$   
11  $11.29, p = .046$ , and there was a significant interaction,  $\chi^2(4) = 11.29, p = .023$ . The PAC and HC  
12 categories again received the highest and lowest ratings, respectively, and a quadratic trend was  
13 observed in the ratings of both musicians,  $B = 10.52, z = 5.66, p < .001$ , and nonmusicians,  $B =$   
14  $4.96, z = 3.36, p < .001$ . However, nonmusicians also demonstrated a bias to *agree* or *strongly*  
15 *agree* throughout the experimental session, as indicated by the higher average ratings even for  
16 the foil stimuli, which ended in the middle of a musical phrase.

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35 Shown in Table 1, a mixed  $5 \times 2$  LMM of the expectation fit ratings for the nontruncated  
36 stimuli revealed a significant effect of cadence category, but musical training and the interaction  
37 were not significant. As expected, the authentic cadence categories (PAC, IAC) received  
38 significantly higher fit ratings than the cadential deviations (DC, EV) for both groups (musicians,  
39  $M_{\text{diff}} = -2.00, t = 6.08, p < .001$ ; nonmusicians,  $M_{\text{diff}} = -1.18, t = 4.51, p = .008$ ). What is more,  
40 polynomial contrasts revealed a significant decreasing linear trend from the PAC to the EV  
41 categories for the fit ratings of both musicians,  $B = -7.03, t = -6.84, p < .001$ , and nonmusicians,  
42  $B = -4.16, t = -5.03, p < .008$ , a finding that replicates the ordering of cadence categories  
43 observed in previous studies (Sears et al., 2014; Sears et al., 2018).

## Discussion

As expected, ratings of expectation strength, specificity, and phrase completion exhibited a U-shaped pattern across the selected cadence categories, with the PAC and HC categories receiving the highest and lowest ratings, respectively. These findings from real musical examples support the view that tonic harmony elicits stronger and more specific expectations for its occurrence than does dominant harmony within the tonal system (Bharucha & Krumhansl, 1983), and so appears at the top of the harmonic hierarchy (Krumhansl et al., 1982). When the stimuli included the terminal, target melodic and harmonic events in the nontruncated condition, however, ratings of expectation fit demonstrated the same descending linear trend observed in other experiments, with the HC category positioned not at the bottom of expectancy fit scale, but somewhere in the middle (Sears et al., 2014; Sears, 2016; Sears et al., 2018). Taken together, these two findings suggest that the half cadence serves as the weakest category *in prospect* as a result of the relatively weak and unspecific expectations it affords, yet finds itself near the middle of the expectancy fit scale *in retrospect* by virtue of the fulfilment of those expectations, however weakly formed (Burstein, 2014). Finally, the cadential deviations received the lowest average fit ratings for both groups, suggesting that they violated listener expectations, and so appear at the bottom of the harmonic hierarchy.

## Experiment 2

### Method

**Participants.** Just as in Experiment 1, participants were 40 nonpianists (20 female) recruited using the same services, 20 of whom were musicians. Ages ranged from 18 to 35 ( $M = 23$ ,  $SD = 4$ ). Musicians and nonmusicians reported listening to an average of 17 and 14 hours of music each week, respectively, and all but four of them self-identified as music lovers. The

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3 musicians practiced their primary instruments for an average of 19 hours each week, and had  
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5 been playing their primary instruments for an average of 12 years. All of the participants  
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7 reported normal hearing. Four of the participants from Experiment 1 also participated in  
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9 Experiment 2. The mean accuracies and response times across all stimuli for these participants  
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11 did not significantly differ from those of the remaining participants, however, and Experiment 2  
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13 was conducted six months after Experiment 1, so we elected to include their data.  
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17 **Materials.** The stimuli were the same as those employed in Experiment 1, but all foil and  
18  
19 truncated stimuli were omitted, resulting in a set of 40 stimuli. To create the intonation task for  
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21 Experiment 2, the terminal, target melodic and harmonic events in each stimulus were presented  
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23 both in tune and out of tune (i.e., the final melodic tone and chord were tuned 40 cents sharp  
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25 relative to the preceding musical context), resulting in 40 in-tune and 40 out-of-tune (foil) trials  
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27 for the session.  
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31 **Design and Procedure.** The experimental session was divided into two phases. In the  
32  
33 first training phase, participants were presented with a randomized set of 20 additional stimuli  
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35 selected from Mozart's keyboard sonatas, and containing an equal number from each cadence  
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37 category. Given that the temporal duration from the beginning of the trial to the target melodic  
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39 tone and chord varied for each stimulus (see Appendix A), it was necessary to provide a visual  
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41 cue to alert the participants to the onset of the target (Pearce et al., 2010; Tillmann & Marmel,  
42  
43 2013). Shown in Figure 4, in each trial a yellow diamond playback cursor was provided at the  
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45 top of the screen that moved from left to right along a playback bar, and a black vertical line was  
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47 placed near the end of the playback bar with a black circle directly above it to mark the onset of  
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49 the terminal target melodic tone and chord. When the playback cursor reached the black line, the  
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51 circle turned green, at which point participants were instructed to judge as quickly and accurately  
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3 as possible whether the chord marked by the black line was in or out of tune by pressing one of  
4 two buttons on the keyboard, labeled “in” and “out,” respectively. Following the completion of  
5 each trial in the training phase, visual feedback was provided on the screen to indicate whether  
6 the response was correct or incorrect. In the second experimental phase, participants performed  
7 the in-tune/out-of-tune judgment without feedback, and the 80 trials were randomized such that  
8 the target and foil conditions of each stimulus were not presented within five experimental trials  
9 of each other. After completing the experiment, participants filled out a short questionnaire  
10 addressing their music background.  
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21 [Insert Figure 4 about here.]  
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24 **Analysis.** As suggested by Jaeger (2008) and Quené and van den Bergh (2008), response  
25 accuracies were analyzed with mixed-effects logistic regression models (GLMMs), with the  
26 accuracy of the response as a binomial dependent variable. To estimate a linear regression model  
27 on proportion data, GLMMs transform proportions onto an unbounded log-odds scale, so all  
28 estimates in the following analyses are reported on the log-odds scale. For transparency,  
29 however, the plotted GLMM estimates were back-transformed onto a probability scale [0-1].  
30 Correct RTs were analyzed with linear mixed effects models (LMMs).  
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## 40 **Results**

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42 Bigand et al. (2003) and Tillmann & Marmel (2013) excluded out-of-tune foils from the  
43 analysis under the assumption that they do not constitute lawful musical events. However, we  
44 first examine the impact of the intonation task on accuracies and response times before  
45 considering the effect of the cadence categories for the in-tune trials. Responses preceding the  
46 onset of the target melodic tone and chord were deemed too early ( $RT < 0$  ms) and were  
47 excluded from the analysis (13 trials, or .8%). Moreover, because RT data typically feature long-  
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tailed distributions that violate assumptions of normality and homogeneity of variance in repeated-measures designs, Ratcliff (1993) recommends eliminating the top 5% of the RTs in the long tail (i.e., the slowest, outlier responses across participants and experimental conditions).

This procedure excluded an additional 67 trials from the analysis (RT range: 4–1000 ms).

Figure 5 displays line plots of the estimated mean accuracies and correct RTs of musicians and nonmusicians for the in-tune and out-of-tune trials. For response accuracies, a mixed  $2 \times 2$  LMM for the factors of intonation (In Tune, Out of Tune) and musical training (musicians, nonmusicians) revealed a significant effect of training,  $\chi^2(1) = 31.90, p < .001$ , with the responses of musicians generally at ceiling across the experiment. The effect of intonation and the interaction between training and intonation were not significant, however. As expected, Type III Wald  $F$  tests for the correct RTs also did not reveal significant effects of intonation or training, or an interaction between the two.

[Insert Figure 5 about here.]

To examine the effect of the cadence categories, the following analysis omits the out-of-tune foil trials following Bigand et al. (2003). For response accuracies, Type III Wald chi-square tests revealed significant main effects of cadence category,  $\chi^2(4) = 14.78, p = .005$ , and training,  $\chi^2(1) = 21.15, p < .001$ , and a significant interaction,  $\chi^2(4) = 12.93, p = .012$ . Shown in Figure 6, the planned comparison between the authentic cadence categories (PAC, IAC) and the cadential deviations (DC, EV) revealed that for the nonmusician group, the estimated odds of correctly identifying the intonation of the target melodic tone and chord were higher for authentic cadences than for cadential deviations,  $B = 2.76, z = 5.03, p < .001$ . The same trend emerged for the musician group, but the effect was not significant,  $B = .42, z = .64, p > .05$ . Polynomial contrasts also revealed a significant decreasing linear trend from the PAC to EV categories for

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3 the nonmusician group,  $B = -9.40$ ,  $z = -5.32$ ,  $p < .001$ , but not for the musician group,  $B = -1.39$ ,  
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5  $z = -.67$ ,  $p > .05$ .

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8 [Insert Figure 6 about here.]

9  
10 Type III Wald  $F$  tests of the fixed effects from the  $5 \times 2$  LMM of the correct RTs  
11 revealed a significant effect of cadence category,  $F(4, 40.79) = 3.19$ ,  $p = .023$ , but the main  
12 effect of training and the interaction were not significant. The planned comparisons revealed that  
13 nonmusicians responded more quickly to the terminal melodic tone and chord from the authentic  
14 cadence categories relative to the cadential deviations,  $M_{\text{diff}} = -70.02$  ms,  $t = -2.92$ ,  $p = .018$ . The  
15 same trend emerged for musicians, but the effect was marginal,  $M_{\text{diff}} = -53.38$  ms,  $t = -2.45$ ,  $p =$   
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## Discussion

Participants were faster and more accurate for the terminal melodic and harmonic events from the authentic cadence categories (PAC, IAC) compared to the cadential deviations (DC, EV). These effects were weaker (or nonsignificant) for the musician group, however. This finding suggests either that musicians remained unaffected by the relatedness of the target melodic tone and chord to the preceding context—a hypothesis that contradicts the findings from Experiment 1—or that the simplicity of the secondary task for the selected foil condition may have influenced the magnitude of the observed priming effect. Nevertheless, the correct RTs from both groups demonstrated a significant increasing linear trend from the PAC to the EV categories, thereby replicating the expectancy fit ratings from Experiment 1. For the HC

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3 category, participant responses again appeared somewhere in the middle compared to the other  
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5 categories, indicating a processing benefit relative to the cadential deviations but a processing  
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7 cost relative to the authentic cadence categories.  
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### 10 **Simulations**

11  
12 The purpose of the simulations is to determine whether the priming effects observed in  
13  
14 Experiments 1 and 2 result from sensory processes accumulated over the duration of echoic  
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16 memory (the EM model), from top-down, cognitive processes reflecting implicit exposure over  
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18 the course of many years (the IDyOM model), or from some combination of these two processes  
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20 (the TS model).  
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24 **Echoic Memory.** Leman's (2000) model of echoic memory (EM) attempted to account  
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26 for Krumhansl and Kessler's (1982) tonal probe-tone judgments by comparing the immediate  
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28 pitch percept with the integrated pitch image computed over the window of echoic memory  
29  
30 (Krumhansl, 1990). The EM model determines the similarity (or *tonal contextuality*) between an  
31  
32 immediate auditory image of the target tone and/or chord (the *local pitch image*, or LPI) with a  
33  
34 more global auditory image of the preceding context integrated over the duration of echoic  
35  
36 memory (the *global pitch image*, or GPI) using the Pearson correlation coefficient  $r$ . According  
37  
38 to Bigand et al. (2014), the tonal contextuality index therefore represents the tension of the LPI  
39  
40 with respect to the GPI, with high values indicating high correlations, and thus, low levels of  
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42 tension (see Appendix B for further details).  
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47 **Tonal Space.** Unlike the EM model, the Tonal Space (TS) model assumes that tonal  
48  
49 contexts are maintained in regions of the brain mediating interactions between sensory,  
50  
51 cognitive, and affective information (Janata et al., 2002, p. 2169). Thus, the TS model was  
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53 designed to account for both sensory *and* cognitive priming effects by projecting the output pitch  
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3 images from the EM model to the surface of a torus using a self-organizing map (SOM)  
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5 algorithm (Kohonen, 1995). The authors trained the SOM using the pitch images from the EM  
6  
7 model integrated with a 2-s time constant that were extracted from a melody that was explicitly  
8  
9 composed to modulate through all 24 major and minor keys over the course of approximately 8  
10  
11 minutes (Collins et al., 2014, p. 42). Like the EM model, Janata et al. (2002) also integrate the  
12  
13 activation patterns over time to incorporate effects of echoic memory. Thus, at any point during  
14  
15 the stimulus input, the relative activations across the map that have been accumulated over  
16  
17 echoic memory represent the effects of long-term schematic knowledge on the tonal expectancies  
18  
19 of listeners.  
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24 **Information Dynamics of Music.** Although the TS model simulates the influence of  
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26 schematic knowledge on tonal expectancies, it fails to consider whether a SOM can account for  
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28 tonal priming effects in isolation. Furthermore, SOMs have been criticized in recent years  
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30 because they generally do not represent the contextual relations between contiguous events on  
31  
32 the musical surface (Collins et al., 2014). In this regard, the Information Dynamics of Music  
33  
34 model (IDyOM) offers a suitable alternative, since it explicitly simulates long-term statistical  
35  
36 learning of sequential dependencies between events in tonal music (Pearce, 2005). In short,  
37  
38 IDyOM is a finite-context (or *n*-gram) modeling framework that predicts the next melodic tone  
39  
40 or chord in a musical stimulus by acquiring knowledge through unsupervised statistical learning.  
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#### 44 **Method**

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47 Each model simulation predicted the target melodic tone and chord given the preceding  
48  
49 context (i.e., the truncated condition) for each stimulus. For the EM and TS models, the LPI was  
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51 set to .1 s to represent the immediate pitch percept (Leman, 2000), and the GPI was set to 4 s to  
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53 correspond with previous published evidence for the duration of echoic memory (Darwin &  
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3 Turvey, 1972). Following Collins et al. (2014), for each stimulus from Experiment 2 we  
4  
5 computed the correlation between the LPI and GPI as a continuous time series at a sampling rate  
6  
7 of 26 Hz for both models. To obtain a single estimate for each stimulus comparing the target  
8  
9 melodic tone and chord with the preceding context, the correlation time series for the EM and TS  
10  
11 models were averaged over the time window corresponding to the duration of the target events.  
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14  
15 For IDyOM, providing a suitable training corpus of Mozart's keyboard sonatas was  
16  
17 beyond the scope of the present study, so the model was trained to predict the target melodic tone  
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19 and chord in each stimulus using a corpus of 50 movements from Haydn's string quartets (Sears  
20  
21 et al., 2018). In doing so, our assumption is that the sequential dependencies between melodic or  
22  
23 harmonic events in a corpus of string quartets will roughly correspond to those found in Mozart's  
24  
25 keyboard sonatas. Following Sears et al. (2018), we included a melodic model that estimates the  
26  
27 target note event from the upper-voice melody in each stimulus (`melody`), a harmonic model  
28  
29 that estimates the target chord event (`harmony`), and a composite model that combines the  
30  
31 predictions from the melodic and harmonic models into a single probability estimate  
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33 (`composite`), thereby representing pitch-based expectations more generally (see Appendix B).  
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## 38 **Results**

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40 To examine the effect of the cadence categories individually, one-way ANOVAs were  
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42 specified for each model simulation. However, Levene's test revealed heteroscedastic groups for  
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44 two of the three models, so we report Welch's  $F$  test and estimate effect size using estimated  $\omega^2$   
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46 (Cohen, 2008). Finally, to address whether the estimates from the model simulations correspond  
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48 with the linear increase demonstrated in the fit ratings (Experiment 1) and correct RTs  
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50 (Experiment 2), a polynomial contrast was also included that estimates the goodness-of-fit of the  
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52 predicted trend without assuming equal variances.  
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Figure 7 presents line plots of the simulation estimates for the EM and TS models for each cadence category. The y-axis is inverted so that decreasing correlation estimates correspond to increasing RTs. A one-way ANOVA for the correlation estimates did not reveal a significant effect of cadence category for the EM model,  $F(4, 17.24) = 1.98, p = .142$ , est.  $\omega^2 = .09$ , and the polynomial contrast did not exhibit the linear trend that was observed in the fit ratings and RTs,  $B = -.10, df = 15.33, t = -.90, p = .381$ . For the TS model, however, the mean correlation estimates demonstrated a marginal effect of cadence category,  $F(4, 15.61) = 3.02, p = .050$ , est.  $\omega^2 = .17$ , but with excerpts from the HC category receiving the lowest estimates on average,  $M = .61, SE = .12$ . As a consequence, the polynomial contrast was not significant,  $B = -.35, df = 8.43, t = -1.90, p = .093$ .

[Insert Figure 7 about here.]

Figure 8 presents line plots of the information content (IC) estimates from IDyOM for each cadence category. Probability estimates can become vanishingly small in  $n$ -gram models, so we report the IC estimates (Cleary & Witten, 1984). Given the probability of event  $e_i$ , IC is  $\log_2 \frac{1}{p(e_i)}$ , and so represents the degree of contextual unexpectedness or surprise associated with  $e_i$ .

[Insert Figure 8 about here.]

The simulation estimates from IDyOM revealed a significant main effect of cadence category for all three viewpoint models (*melody*,  $F(4, 14.05) = 14.87, p < .001$ , est.  $\omega^2 = .57$ ; *harmony*,  $F(4, 17.31) = 9.41, p < .001$ , est.  $\omega^2 = .46$ ; *composite*,  $F(4, 16.87) = 12.28, p < .001$ , est.  $\omega^2 = .53$ ). The polynomial contrast also exhibited a significant increasing linear trend from the PAC to the EV categories for each model (*melody*,  $B = 12.39, df = 7.53, t = 6.85, p < .001$ ; *harmony*,  $B = 8.71, df = 16.31, t = 4.84, p < .001$ ; *composite*,  $B = 21.11, df = 10.28, t =$

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3 6.96,  $p < .001$ ). Thus, the cadence categories whose terminal melodic and harmonic events  
4 elicited lower fit ratings and slower responses times were also less predictable on average.  
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8 To examine the strength of this covariation, Table 2 presents the intercorrelations  
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10 between the model simulations and the mean fit ratings and RTs collected in Experiments 1 and  
11 2, respectively. For the model simulations, the EM and TS models did not produce significant  
12 correlations with any of the participant responses. Conversely, IDyOM featured moderate-to-  
13 strong correlations with nearly every response variable,  $r$  range: .34–.79. In each case,  
14 participants were faster and provided higher fit ratings for target events that received lower IC  
15 estimates by IDyOM, with the composite model receiving the highest correlations compared to  
16 the other model simulations.  
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## 25 26 **Discussion**

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28 Of the model simulations examined here, IDyOM provided the best fit with the  
29 experimental data from Experiments 1 and 2, with the EM and TS models generally producing  
30 null results. What is more, the IC estimates shown in Figure 7 correspond very closely with the  
31 IC estimates calculated for the cadences from a much larger dataset of Haydn's string quartets  
32 (Sears et al., 2018), suggesting that these findings may generalize to other classical composers  
33 and genres that feature similar melodic and harmonic organizational principles. In the melodic  
34 viewpoint model, the PAC, IAC, HC, and DC categories received much lower IC estimates on  
35 average than the EV category, presumably because the former categories conclude with stepwise  
36 motion into a stable scale degree in the melody (e.g., 1 or 3), whereas the latter category  
37 typically features an unexpected leap. In the harmonic viewpoint model, the DC and EV  
38 categories—which conclude with unexpected terminal chords—received higher IC estimates  
39 than the remaining categories, resulting in the same linear trend that was previously observed in  
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3 the average fit ratings and RTs. Finally, estimates from the composite viewpoint produced the  
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5 strongest correlations with the behavioral responses from both experiments and from both  
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7 training groups.  
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### 10 **General Discussion**

11  
12 The goal of this study was to explore the underlying mechanisms responsible for the  
13  
14 formation of tonal expectations during music listening using examples of expectancy fulfilment  
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16 (PAC, IAC, HC) and violation (DC, EV) derived from real music. Previous studies have  
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18 typically employed specially composed (or selected) isochronous chord sequences terminating  
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20 with an authentic (V–I) cadence in the expected condition, and then simply recomposed the  
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22 target (or context) events in the unexpected condition(s). We adopted an alternative approach by  
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24 selecting genuine musical stimuli that terminate with one of the five most common cadence  
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26 categories in tonal music. In Experiment 1, participants provided the lowest strength and  
27  
28 specificity ratings for truncated stimuli from the HC category. When the terminal events  
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30 followed the preceding context in the nontruncated condition, however, the authentic cadence  
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32 categories received the highest fit ratings (PAC, IAC), followed by the HC category in the center  
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34 of the expectancy fit scale, and finally the cadential deviations (DC, EV), which received the  
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36 lowest fit ratings overall. The correct RTs in Experiment 2 generally replicated these findings,  
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38 with stimuli terminating with an authentic cadence eliciting facilitation effects for both musicians  
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40 and nonmusicians, thereby suggesting that authentic cadential contexts prime listeners to expect  
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42 a tonic chord with a stable scale degree like 1 or 3 in the upper-voice melody. Moreover, the  
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44 mean RTs across all five cadence categories demonstrated the same linear trend that was  
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46 observed in Experiment 1, with the PAC, IAC, and HC categories eliciting the fastest and most  
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48 accurate responses, followed by the DC and EV categories.  
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3 The cadence categories also elicited larger differences in the specificity and phrase  
4 completion ratings of musicians compared to nonmusicians in Experiment 1. In Experiment 2,  
5 however, this trend was not present, with the speed of responses showing no difference between  
6 musicians and nonmusicians, and accuracy demonstrating larger differences between cadence  
7 categories for nonmusicians than musicians. The relatively weaker effects found in Experiment 1  
8 for the nonmusician group may have been due to the musician group's increased familiarity  
9 either with the experimental tasks (strength, specificity, phrase completion, and fit), with  
10 technical terms relating to the experiments, or with the stimuli, which were derived from a well-  
11 known repertoire associated with the common-practice period. Bigand (2003) has championed  
12 implicit behavioral tasks like the priming paradigm for precisely these reasons.  
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26 To compare sensory or psychoacoustic explanations of tonal priming effects with  
27 cognitive accounts, we simulated the findings from both experiments using the EM (sensory)  
28 model, the TS (sensory-cognitive) model, and IDyOM (cognitive). The EM and TS models  
29 provided few notable results and generally failed to explain the pattern of results. Instead,  
30 IDyOM provided the best fit to the data, replicating the linear trend observed in the expectancy  
31 fit ratings in Experiment 1 and the RTs in Experiment 2, and demonstrating significant  
32 correlations between the experimental findings and the model predictions for the melody, the  
33 chord progression, and a composite probability estimate representing both musical parameters.  
34 These findings suggest that listeners generate expectations for potential continuations as a  
35 consequence of the frequent (co-)occurrence of events on the musical surface. However, this is  
36 not to say that sensory or psychoacoustic explanations for the priming effects observed here—or  
37 reported elsewhere—play no role in expectancy formation; only that the models representing  
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3 these explanations generally fail to account for the priming effects observed in the present  
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5 experiments.  
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8       Taken together, the simulations reported in this study provide evidence in support of a  
9  
10 functional interpretation of tonal processing, in which listeners with exposure to tonal music  
11  
12 retain long-term, schematic knowledge about the statistical dependencies between contiguous  
13  
14 events. This knowledge allows listeners to generate expectations during music listening, with the  
15  
16 syntactic relationships between tonal events activating schematic representations that either  
17  
18 facilitate or inhibit the processing of continuations heard later. This is not to say that schematic  
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20 knowledge is fixed across a group of listeners; the depth (or specificity) of that knowledge will  
21  
22 vary from one person to another (Margulis, 2005). When confronted with a perfect authentic  
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24 cadence, for example, listeners with relatively little exposure to music of the high classical  
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26 period may hear a V–I chord progression, while those with a great deal of experience in the  
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28 instrumental repertoires of Haydn, Mozart, and Beethoven may possess a schematic  
29  
30 representation that is nearly isomorphic with the encountered exemplar. But in our view, many of  
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32 the features that characterize these cadences also characterize the tonal system in general. To be  
33  
34 sure, even in today’s vast musical landscape, listeners with exposure to tonal music might form  
35  
36 schematic representations for temporal patterns spanning a wide number of genres and style  
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38 periods sharing similar characteristics (e.g., jazz, pop-rock, classical). But no matter the manner  
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40 or specificity of the representation, the important point here is that much of this knowledge lies  
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42 beneath the conscious surface, reflects implicit rather than explicit learning strategies, and goes  
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44 far beyond verbal description.  
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## Footnotes

<sup>1</sup>In recent publications, this model has also been called the periodicity pitch model (Leman, 2000; Collins et al., 2014), and the auditory short-term memory model (Bigand et al., 2014; Marmel, Tillmann, & Delbé, 2010). To avoid confusion, and given that we only apply this model to simulate the duration of echoic memory, we will prefer the *Echoic Memory* (EM) model.

<sup>2</sup>Major triads are composed of a minor third on top of a major third, and minor triads have the reverse arrangement. None of the diatonic chords built on the Western major scale feature augmented triads (stacked major thirds). A diminished triad (stacked minor thirds) appears as the vii<sup>o</sup> chord in Figure 1B, which consists of the pitch classes B, D, and F.

<sup>3</sup>Unfortunately, there is currently no standard method for the inclusion and decomposition of the variance from the random effects of a linear mixed effects model. Thus, measures of effect size for omnibus statistics (i.e., main effects and interactions) are not reported here, but we do report effect size measures for the planned comparisons using the estimated means of the fixed effects (*B* for polynomial contrasts, and the unstandardized mean difference for all other comparisons).



Supplementary Material

The Supplementary Material is available at: [qjep.sagepub.com](http://qjep.sagepub.com)

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## Figure Captions

Figure 1. Top (a): Krumhansl and Kessler's (1982) major-key profile, which represents the goodness-of-fit ratings averaged across participants for the 12 pitch classes following an authentic cadence that consisted of the chord sequence, IV–V–I. The profile shown here applies to the key of C major, with the 12 pitch classes and seven diatonic scale degrees provided below. Pitch classes represented by two note names (e.g., C#/Db) denote enharmonic equivalents (i.e., pitch classes that are in principle acoustically identical but notationally distinct). Bottom (b): The seven diatonic triads for the key of C major, with pitch classes above and Roman numerals below. Open (whole) notes indicate the degrees of the scale. Letter case represents whether the Roman numeral refers to a major (uppercase) or minor (lowercase) triad, and an open circle superscript refers to a diminished triad (see footnote 2).

*Figure 2.* Five stimuli representing the five cadence categories. The context passage appears on the left, and the target melodic tone and chord appear on the right with scale degree and Roman numeral annotations. Köchel index for Mozart's works are indicated with the movement in lowercase Roman numerals and measure numbers. PAC Category: K. 281, i, mm. 5–8. IAC Category: K. 311, i, mm. 1–4. HC Category: K. 333, iii, mm. 60–64. DC Category: K. 457, i, mm. 42–48. EV Category: K. 281, ii, mm. 96–99.

*Figure 3.* Line plots of the estimated mean expectation strength, specificity, Likert-scale, and fit ratings of musicians (in blue) and nonmusicians (in red) for each cadence category and the foil category. The bottom-left plot presents the estimated mean cumulative probabilities calculated

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3 from the Likert-scale ratings for the statement, “the ending is imminent.” Right y-axis presents  
4 thresholds of the response scale: Strongly Agree (SA), Agree (A), Disagree (D), and Strongly  
5 Disagree (SD). Whiskers represent  $\pm 1$  standard error.  
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12 *Figure 4.* The display used to present the stimuli and collect behavioral responses in Experiment  
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19 *Figure 5.* Line plots of the estimated mean proportion correct and correct response times of  
20 musicians and nonmusicians for in-tune and out-of-tune trials. Whiskers represent  $\pm 1$  standard  
21 error.  
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28 *Figure 6.* Line plots of the estimated mean proportion correct and correct response times of  
29 musicians and nonmusicians for each cadence category. Whiskers represent  $\pm 1$  standard error.  
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35 *Figure 7.* Line plots of the correlation estimates from the EM and TS models for each cadence  
36 category. The y-axis is inverted so that decreasing estimates correspond to increasing RTs in  
37 Figure 4. Whiskers represent  $\pm 1$  standard error.  
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44 *Figure 8.* Line plots of the information content estimates from IDyOM for each cadence  
45 category. Left: Melodies were predicted using an optimized combination of the viewpoint  
46 models `melint` and `csd`  $\otimes$  `cpitch`, and harmonic (chord) progressions were predicted with the  
47 viewpoint model `vintcc` (see Appendix B). Right: Composite represents the joint probability of  
48 the melodic and harmonic viewpoint models. Whiskers represent  $\pm 1$  standard error.  
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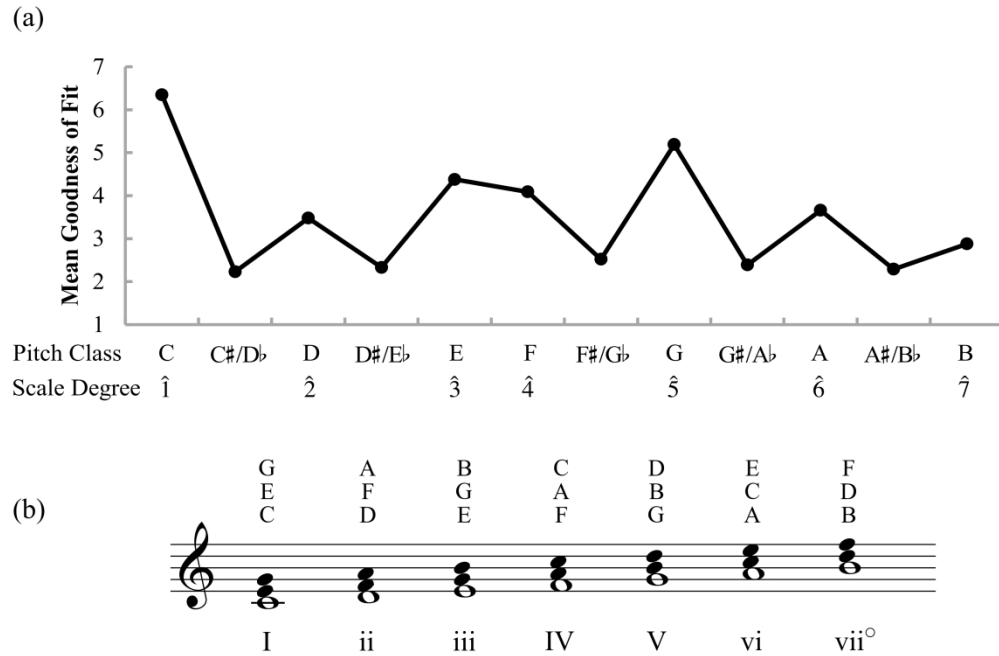


Figure 1. Top (a): Krumhansl and Kessler's (1982) major-key profile, which represents the goodness-of-fit ratings averaged across participants for the 12 pitch classes following an authentic cadence that consisted of the chord sequence, IV–V–I. The profile shown here applies to the key of C major, with the 12 pitch classes and seven diatonic scale degrees provided below. Pitch classes represented by two note names (e.g., C#/D $\flat$ ) denote enharmonic equivalents (i.e., pitch classes that are in principle acoustically identical but notationally distinct). Bottom (b): The seven diatonic triads for the key of C major, with pitch classes above and Roman numerals below. Open (whole) notes indicate the degrees of the scale. Letter case represents whether the Roman numeral refers to a major (uppercase) or minor (lowercase) triad, and an open circle superscript refers to a diminished triad (see footnote 2).

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Figure 2 displays five musical stimuli, each consisting of a piano accompaniment on the left and a target melodic tone and chord on the right. The stimuli are categorized as follows:

- Stimulus 1 (PAC):** The piano accompaniment features a treble clef, a key signature of two flats, and a 2/4 time signature. The target chord is a major triad (C4, E4, G4) with scale degree 1 and Roman numeral I.
- Stimulus 2 (IAC):** The piano accompaniment features a treble clef, a key signature of two sharps, and a 3/4 time signature. The target chord is a major triad (F#4, A4, C5) with scale degree 3 and Roman numeral I.
- Stimulus 3 (HC):** The piano accompaniment features a treble clef, a key signature of two flats, and a 3/4 time signature. The target chord is a major triad (G4, B4, D5) with scale degree 5 and Roman numeral V.
- Stimulus 4 (DC):** The piano accompaniment features a treble clef, a key signature of two flats, and a 3/4 time signature. The target chord is a minor triad (F4, A4, C5) with scale degree 6 and Roman numeral vi.
- Stimulus 5 (EV):** The piano accompaniment features a treble clef, a key signature of two flats, and a 3/8 time signature. The target chord is a diminished triad (F4, A4, C5) with scale degree b7 and Roman numeral vii<sup>6</sup>/ii.

Figure 2. Five stimuli representing the five cadence categories. The context passage appears on the left, and the target melodic tone and chord appear on the right with scale degree and Roman numeral annotations.

Köchel index for Mozart's works are indicated with the movement in lowercase Roman numerals and measure numbers. PAC Category: K. 281, i, mm. 5–8. IAC Category: K. 311, i, mm. 1–4. HC Category: K. 333, iii, mm. 60–64. DC Category: K. 457, i, mm. 42–48. EV Category: K. 281, ii, mm. 96–99.

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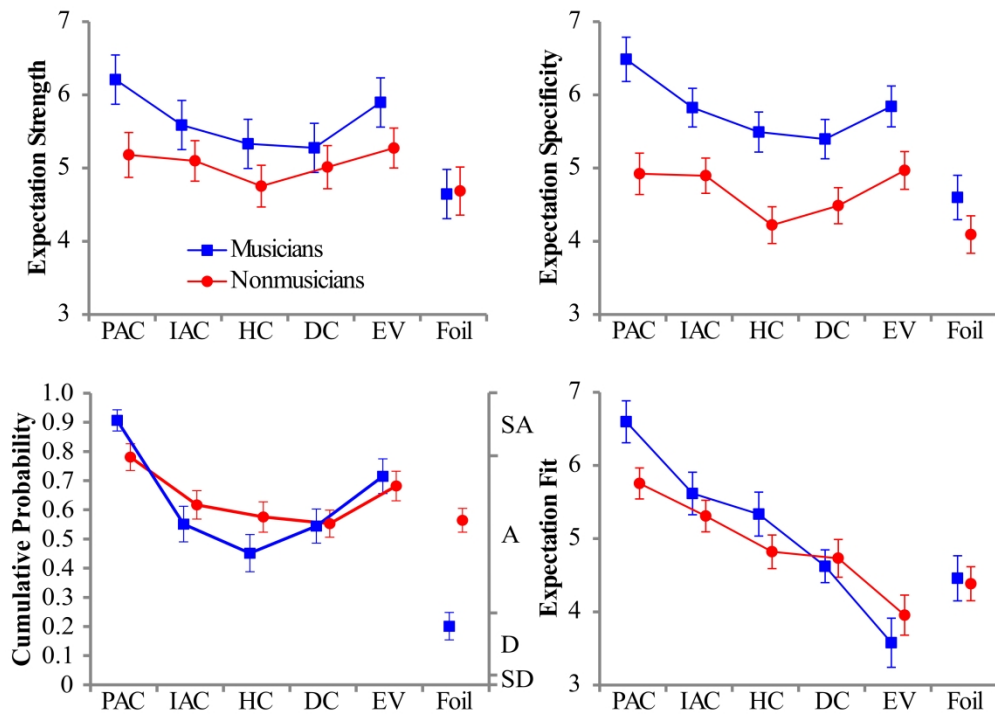


Figure 3. Line plots of the estimated mean expectation strength, specificity, Likert-scale, and fit ratings of musicians (in blue) and nonmusicians (in red) for each cadence category and the foil category. The bottom-left plot presents the estimated mean cumulative probabilities calculated from the Likert-scale ratings for the statement, "the ending is imminent." Right y-axis presents thresholds of the response scale: Strongly Agree (SA), Agree (A), Disagree (D), and Strongly Disagree (SD). Whiskers represent  $\pm 1$  standard error.

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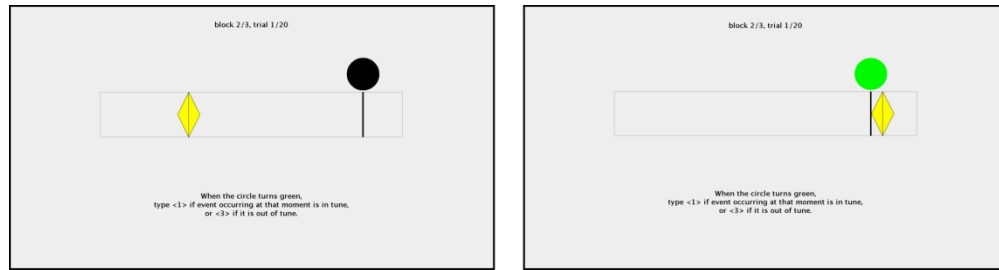


Figure 4. The display used to present the stimuli and collect behavioral responses in Experiment 2.

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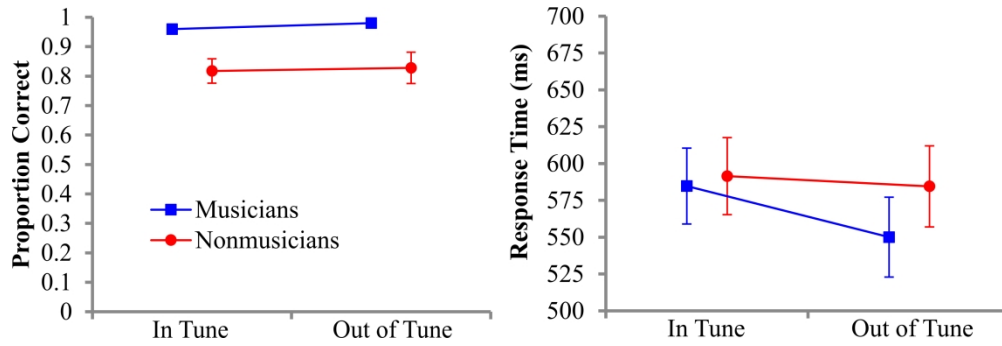


Figure 5. Line plots of the estimated mean proportion correct and correct response times of musicians and nonmusicians for in-tune and out-of-tune trials. Whiskers represent  $\pm 1$  standard error.

1397x461mm (72 x 72 DPI)

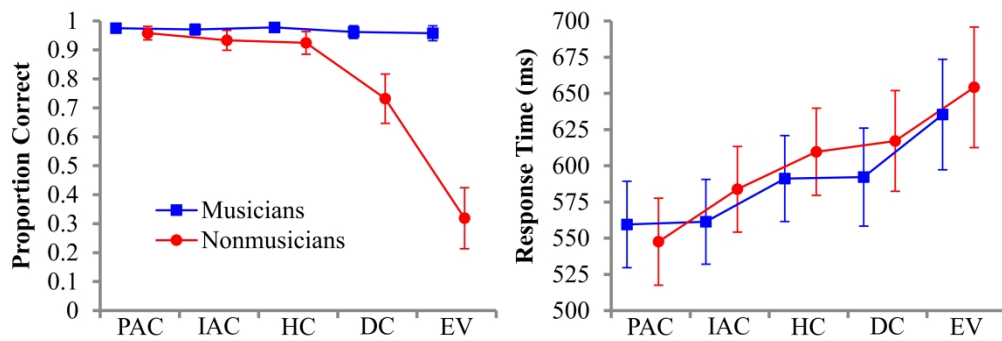
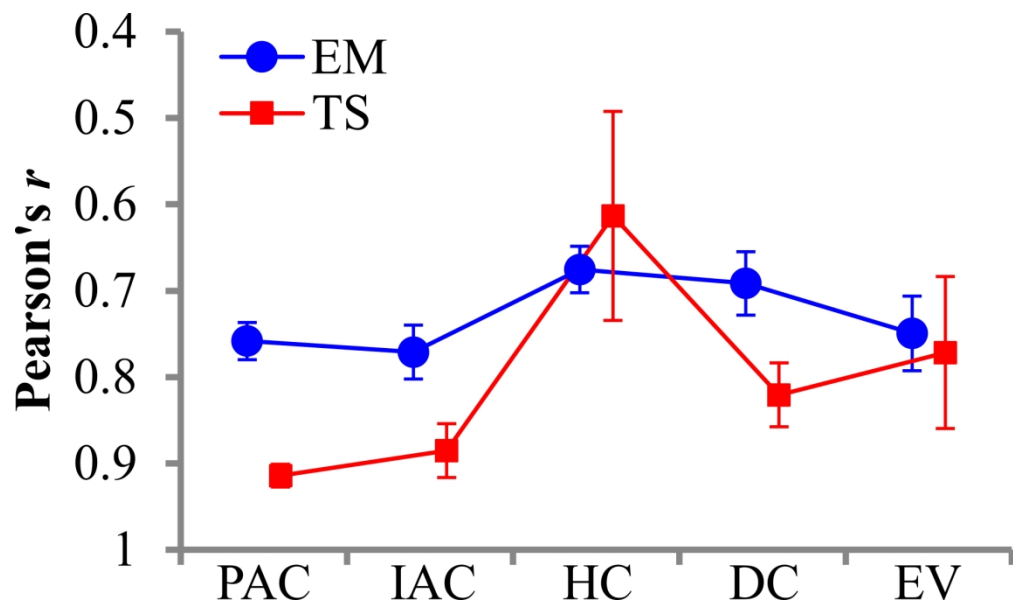


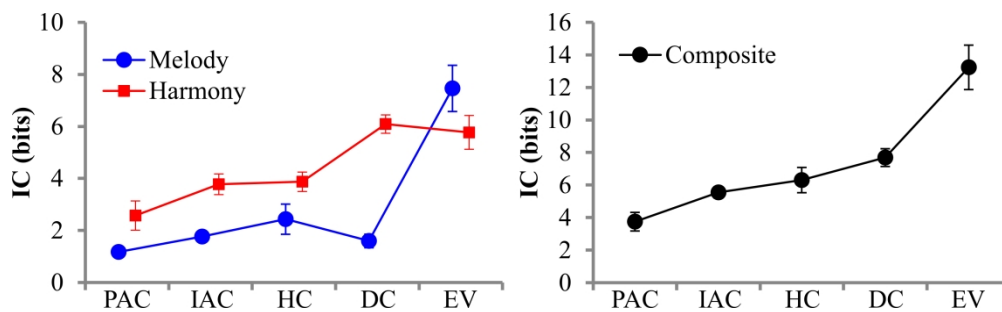
Figure 6. Line plots of the estimated mean proportion correct and correct response times of musicians and nonmusicians for each cadence category. Whiskers represent  $\pm 1$  standard error.

1399x465mm (72 x 72 DPI)

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687x403mm (72 x 72 DPI)



1376x406mm (72 x 72 DPI)

Table 1

Analysis of deviance table for maximal linear mixed effects models predicting ratings of expectation strength, specificity, and fit.

	<i>df</i> <sup>a</sup>	Wald <i>F</i>	<i>p</i>
<b>Expectation Strength</b>			
Cadence Category	41.88	3.01	.028*
Training	38.00	2.77	.104
Cadence Category × Training	27.25	1.57	.210
<b>Expectation Specificity</b>			
Cadence Category	40.70	3.57	.014*
Training	39.23	17.38	<.001***
Cadence Category × Training	32.02	3.01	.032*
<b>Expectation Fit</b>			
Cadence Category	8.62	10.44	.002**
Training	44.43	1.54	.222
Cadence Category × Training	51.82	2.12	.091

*Note.*  $N = 1600$  (40 stimuli × 40 participants). Independent variables are factor variables with sum coding (e.g., *musicians* = 1, *nonmusicians* = -1). A maximum random effects structure was included, with a random intercept for participants and by-participant slopes for cadence category, and a random intercept for musical stimuli and by-stimulus slopes for musical training.

\*  $p < .05$  \*\*  $p < .01$  \*\*\*  $p < .001$ .

<sup>a</sup>Denominator degrees of freedom for Type III Wald *F* tests reported with Kenward-Roger approximation.

Table 2

Intercorrelations between the model simulations and the fit ratings (Experiment 1) and correct RTs (Experiment 2) of musicians and nonmusicians.

	Fit Ratings			RTs			EM	TS	Simulations		
	Mus.	Nonmus.	Pooled	Mus.	Nonmus.	Pooled			Mel.	IDyOM Harm.	Comp.
<b>Fit Ratings</b>											
Musicians		.86***	.98***	-.59**	-.34	-.55**	.15	.16	-.64***	-.72***	-.78***
Nonmusicians			.95***	-.39	-.30	-.38	.14	.14	-.60**	-.66***	-.73***
Pooled				-.54*	-.33	-.51*	.15	.16	-.64***	-.72***	-.79***
<b>RTs</b>											
Musicians					.60**	.92***	-.28	-.33	.71***	.46~	.71***
Nonmusicians						.88***	.18	.13	.41	.34	.46~
Pooled							-.18	-.24	.63***	.50*	.67***
<b>Simulations</b>											
Echoic Memory								.66***	-.10	-.16	-.14
Tonal Space									-.30	-.12	-.27
IDyOM											
Melody										.45~	.91***
Harmony											.79***
Composite											

Note.  $N = 40$ . 'Pooled' computes the average ratings or correct RTs across the corresponding ratings or RTs from musicians and nonmusicians.  $P$ -values were adjusted with the Holm method.

~  $p < .10$  \*  $p < .05$  \*\*  $p < .01$  \*\*\*  $p < .001$ , two-tailed.