Journal of Experimental Psychology:
Human Perception and Performance
2004, Vol. 30, No. 2, 268–286

0096-1523/04/$12.00 DOI: 10.1037/0096-1523.30.2.268

The Perception of Tonal Structure Through the Differentiation and Organization of Pitches

Nicholas A. Smith and Mark A. Schmuckler
University of Toronto at Scarborough

The role of 2 psychological processes, *differentiation* and *organization,* were examined in the perception of musical tonality. Differentiation distinguishes elements from one another and was varied in terms of the distribution of pitch durations within tone sequences. Organization establishes relations between differentiated elements and was varied in terms of either conformity with or deviation from a hierarchical description of tonality. Multiple experiments demonstrated that the perception of tonality depended on a minimal degree of differentiation in the distribution of the duration—but not frequency of occurrence—of pitches and only when pitch distributions were hierarchically organized. Moreover, the mere differentiation of the tonic from nontonic pitches was not sufficient to induce tonal percepts. These results are discussed in relation to tonal strength, musical expressiveness, and principles of auditory pattern processing.

A fundamental aspect of the perception of visual scenes or auditory sequences is the apprehension of their inherent structural information (e.g., Garner, 1974; Gibson, 1979; Koffka, 1935; Kubovy & Pomerantz, 1981; Lockhead & Pomerantz, 1991). Regardless of the specific information being processed, the basic psychological questions are the same: What types of structure(s) are contained in the scene or sequence? What psychological processes are used to apprehend such structure? What is the observer's or listener's sensitivity to this structure? Are different forms of such structure equally accessible, or are some types more easily apprehended? The goal of much of the research in perception and cognition is to explore these basic issues; in the present article, these questions are examined in the context of perceiving music.

Music provides an especially compelling arena for investigating such questions. Along with speech, music represents the most complex form of auditory information with which people interact; thus, it is an ideal candidate for both the discovery of fundamental principles of pattern structure and investigating the parameters of listeners' sensitivity to such information. Moreover, music psychology is in the fortunate position of having entire fields of study devoted to the specification of information available within the musical stimulus itself. For example, work in both musicology and music theory has, over the course of many years, provided elaborate theoretical descriptions of important structural relations existing within music that may or may not be critical in understanding listeners' percepts of such passages (see Schmuckler, 1997, or Schmuckler & Boltz, 1994, for discussion of this point).

The Perception of Tonality and the Probe-Tone Technique

Within the tradition of Western tonal music, one theoretically fundamental component of musical structure is the property of *tonality.* In musical parlance, tonality, or tonal structure, refers to the organization of the complete set of all 12 musical pitch classes (called the *chromatic set*) around a single reference pitch. This reference pitch is called the *tonic,* and the remaining pitch classes are judged in relation to this referent. The tonic pitch denotes the musical key of a piece of music (i.e., in the key of C, the pitch *C* serves as the tonic). Tonality actually induces on the chromatic set a hierarchical organization of importance; this hierarchy is shown at the top of Figure 1. In this hierarchy, the tonic (Pitch Class 0) appears at the top and is seen as the point of maximum stability. Below the tonic are intermediate levels of stability, consisting of the pitches that, along with the tonic, make up the *tonic triad* (Pitch Classes 4 and 7) and the *diatonic set* (Pitch Classes 2, 5, 9, and 11). Finally, at the bottom of the hierarchy are the remaining tones (Pitch Classes 1, 3, 6, 8, and 10), called the *nondiatonic set.* These tones are considered to be outside of the key and thus are seen as the least important tones.

This theoretical hierarchy of importance has also been examined from a psychological point of view. Krumhansl and colleagues, in some now classic tests of this hierarchy (e.g., Krumhansl & Kessler, 1982; Krumhansl & Shepard, 1979), provided evidence of its psychological reality. To explore this question, Krumhansl and Shepard (1979) developed the *probe-tone* procedure (see Krumhansl, 1990a, for a complete description of this method), in which listeners provide a goodness-of-fit rating for each of the 12 pitch classes with reference to a (typically preceding) musical context that instantiates a specific tonality. Using this method, Krumhansl

Nicholas A. Smith and Mark A. Schmuckler, Division of Life Sciences, University of Toronto at Scarborough, Toronto, Ontario, Canada.

The research reported in this article was supported by a Natural Sciences and Engineering Research Council of Canada grant to Mark A. Schmuckler. Parts of this research were included in a master's thesis by Nicholas A. Smith, submitted to the University of Toronto, Toronto, Ontario, Canada. We thank Bruce A. Schneider for comments on an earlier version of this article and Lola L. Cuddy and Michael E. Lantz for discussion and encouragement.

Correspondence concerning this article should be addressed to Nicholas A. Smith, who is now at the Department of Psychology, McMaster University, 1280 Main Street West, Hamilton, Ontario L8S 4K1, Canada. E-mail: nsmith@mcmaster.ca

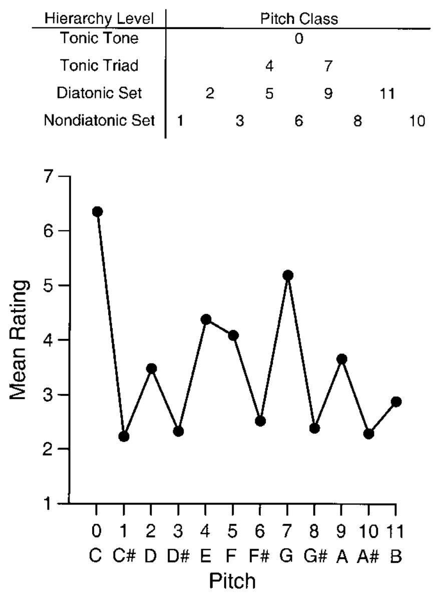

Figure 1. Krumhansl and Kessler's (1982) standardized key profile, which demonstrates the hierarchical structure of the perceived stability of pitches within tonal contexts. Individual pitch classes of the chromatic set are numbered 0–11, with 0 being the tonic tone, and are presented with reference to the tonality of C major.

and colleagues (Krumhansl & Kessler, 1982; Krumhansl & Shepard, 1979) found that listeners' probe-tone ratings matched the music-theoretic hierarchy just described. The bottom part of Figure 1 shows the averaged probe-tone ratings for the chromatic set (found by Krumhansl & Kessler, 1982) in terms of pitch-class numbering and with reference to a given tonality or key (that of C major). These ratings have been called the *tonal hierarchy* (Krumhansl, 1990a), with the tonic receiving the highest rating and functioning as a psychological reference point (e.g., Rosch, 1975; see Krumhansl, 1979) by which the remaining pitch classes of the chromatic set are judged.

Although subjective, the probe-tone technique has proven, over the years, to be a robust way of assessing the relative stability or goodness of fit of the different pitch classes of the chromatic set with reference to the tonality of a musical context. These ratings have been found to be strongly related to objective properties of pitch relations, such as consonance values between pairs of musical tones. Krumhansl (1990a), for example, demonstrated that the tonal hierarchy ratings matched quite well with six different measures of tonal consonance between tone pairs (pp. 50–62). At the same time, these ratings also match strongly with statistical distributions of tone durations and/or the frequency of occurrence of tones within actual musical contexts (Krumhansl, 1990a, pp. 62–76); this latter finding is expanded on below.

Along with correlates of musical structure, the data arising from the probe-tone method have also been found to be robust across a wide array of musical contexts and to be related to a number of psychological processes involved in music perception. For example, the probe-tone procedure, along with variants in which pairs of tones or simultaneous tones (called *chords*) are used as the probes, has been successfully used when the musical context consisted of schematic key-defining passages (e.g., Bharucha & Krumhansl, 1983; Krumhansl, 1979; Krumhansl, Bharucha, & Castellano, 1982; Krumhansl, Bharucha, & Kessler, 1982; Krumhansl & Kessler, 1982; Krumhansl & Shepard, 1979); realistic musical materials, such as short melodies or more complex passages (e.g., Cuddy, 1993; Cuddy & Badertscher, 1987; Cuddy & Smith, 2000; Schmuckler, 1989; Schmuckler & Tomovski, 1997, 2000; Smith & Cuddy, 2003); 20th century musical materials representing either extensions of or alternatives to traditional tonal music (e.g., Krumhansl, Sandell, & Sargent, 1987; Krumhansl & Schmuckler, 1986b); and non-Western musics, such as North Indian (e.g., Castellano, Bharucha, & Krumhansl, 1984) and Balinese (e.g., Kessler, Hansen, & Shepard, 1984) music. In sum, the probe-tone technique provides a very general indicator of perceived tonal structure across a variety of musical contexts.

Furthermore, many studies have demonstrated that the tonal hierarchy, as assessed using the probe-tone technique, is related to many aspects of the psychological processing of music. Studies on recognition memory, for example, have found that the perceived hierarchy of stability effectively predicts memory confusions. Krumhansl (1979), for instance, found that within a tonal context, psychologically unstable tones were more frequently confused with stable tones than vice versa. Similarly, tonality affects memory for musical chords, with psychologically stable chords (quantified using the probe-chord method) being more easily confused with one another (Bharucha & Krumhansl, 1983) and the probability of detecting a change in a chord being predictable from that chord's perceived stability (Krumhansl, Bharucha, & Castellano, 1983; see Justus & Bharucha, 2002, for a review). Finally, tonality and perceived psychological stability affect the speed of processing of tones (Bharucha, 1987; Janata & Reisberg, 1988) and chords (e.g., Bharucha & Stoeckig, 1986, 1987; Schmuckler & Boltz, 1994). Janata and Reisberg (1988), for example, found that reaction times for judgments of tonal membership were related to the perceived psychological stability of the tones, and Schmuckler and Boltz (1994) observed that expectancy judgments of chords were predictable as a function of the chord's role in the tonality of the musical passage. Taken as a whole, these studies provide compelling evidence for the central impact of tonality on musical processing and for the viability of the probe-tone procedure as an indicator of this perceived tonality.

Given the importance of tonality in musical perception, understanding the psychological processes involved in tonal perception is a basic goal of music cognition research (Krumhansl, 1991, 2000). One approach to this issue has explored models of how listeners might determine the tonality of a piece of Western music (e.g., Brown, 1988; Brown & Butler, 1981; Holtzman, 1977; Krumhansl & Schmuckler, 1986a; Leman, 1995; Longuet-Higgins & Steedman, 1971; Shmulevich & Yli-Harja, 2000; Vos & Van Geenen, 1996; Winograd, 1968). Of these models, the best known are Brown and Butler's (1981) *intervallic rivalry theory* and the Krumhansl–Schmuckler *key-finding algorithm* (Krumhansl & Schmuckler, 1986a; described in Krumhansl, 1990a). The former model determines tonality through the identification of rare intervals (i.e., pairs of simultaneous or successive tones) contained in the set of pitches making up a musical passage (see Browne, 1981; Van Egmond & Butler, 1997), whereas the latter model operates by comparing the frequency of occurrence or duration (but see also Huron & Parncutt, 1993) of the component tones of a musical passage with the tonal hierarchy values shown in Figure 1. The efficacy of these models and their abilities to predict listeners' judgments of musical key have been discussed extensively (Brown & Butler, 1981; Butler, 1989, 1990; Cuddy, 1991; Krumhansl, 1990b; Schmuckler & Tomovski, 1997, 2000).

Two fundamental psychological processes can be thought to underlie these models and, presumably, perceptions of tonality as well. The first of these processes is called *differentiation*: the process by which the individual elements or tones of a musical passage are reliably distinguished from one another along some relevant dimension (e.g., perceived importance, psychological stability). The second process, referred to as *organization*, is the process by which relations between these differentiated elements, as well as the nature of these relations themselves, are established. For both of the key-finding models just discussed, and indeed for the perception of tonal structure itself, listeners must differentiate the elements of the musical passage, identifying important and/or psychologically stable pitches, and organize this collection of differentiated pitches into a comprehensive structure (e.g., the tonal hierarchy). It is important to stress that the processes of differentiation and organization are by no means limited to tonality perception but are, rather, two fundamental aspects of theories of perceptual organization and the perception of structure quite generally.

Differentiation

Whereas discrimination refers to a sensitivity to differences along some perceivable stimulus dimension (e.g., pitch, loudness, or timbre in audition), differentiation is a higher order ability to segregate the perceptual scene into elements on the basis of these discriminable differences. Thus, differentiation not only depends on basic sensory discrimination but goes beyond such concerns in transforming the input into perceptual elements. One well-known example of this process of differentiation occurs in auditory scene analysis (Bregman, 1990), which describes how listeners segregate the auditory scene into streams on the basis of frequency (Bregman & Campbell, 1971; Van Noorden, 1975), timbre (McAdams & Bregman, 1979), or discontinuity (Bregman & Dannenbring, 1973). Within this framework, differentiation involves the process by which listeners segregate auditory events into different elements on the basis of some discriminable difference. These elements then combine to form more complex objects; the process underlying this aspect, organization, is discussed below.

Assuming that pitch differentiation is fundamental to the perception of tonality, an obvious question arises as to how pitches might be differentiated. One possible candidate is statistical in nature, with differentiation occurring by notation of the frequency and/or duration of occurrence of the tones within a musical passage. Support for this possibility comes from statistical analyses of music (discussed above) on the relation between psychological stability and the frequency of occurrence and/or duration of pitches within a tonal context.

Organization

Organization is the process of establishing relations between the differentiated elements and, as such, presupposes and complements differentiation. Along with the issue of the specific type of relations among the elements (e.g., more than, less than, similar to), probably the most central issue for organization involves the overall form of these relations. One organizational form is a successive and/or contiguous ordering, such as arranging elements linearly or logarithmically along a perceptual dimension. An example of such organization might be seen in unidimensional models of pitch (e.g., Stevens & Volkman, 1940; Stevens, Volkman, & Newman, 1937; Ward, 1954; see Rasch & Plomp, 1999, for a review). A second organizational form involves the cyclical nature of a set of elements, with elements organized in repeating fashion. Schmuckler (1999), for example, has demonstrated that the melodic contour (the pattern of relative rises and falls in pitch across successive tones) can be characterized by examining its cyclical nature, and Schmuckler and Gilden (1993) have shown that listeners can make use of fractal information in the discrimination of auditory sequences varying in pitch and loudness.

Probably the most common form of organization involves hierarchical structure, with elements at a particular level being subordinate to or subsumed under elements at a higher, presumably more psychologically salient level. Within research on auditory perception, there have been multiple types of hierarchical structure proposed, such as work on serial patterns (Jones, 1981; Martin, 1972; Restle, 1970; Simon & Kotovsky, 1963; Vitz & Todd, 1969), with hierarchical structure applied to multiple dimensions of auditory stimuli, such as pitch, rhythm, and phrase structure (Deutsch, 1982; Deutsch & Feroe, 1981; Jones, 1978; Lerdahl & Jackendoff, 1983; Povel, 1981; Povel & Essens, 1985; Simon & Sumner, 1968). Most important for the current purposes, tonality has been quite thoroughly described in terms of its hierarchical structure, with this structure playing a fundamental role in musical processing, as described earlier.

Tonality, then, provides an ideal arena for studying differentiation and organization, not only because it relies so heavily on these processes but also because it enables a systematic disentangling of these processes. In many domains, differentiation and organization are difficult to study independently because differentiation of elements on the basis of some attribute naturally leads to the organization of these elements. Such is the case with work on auditory streaming (Bregman, 1990), discussed earlier, in which element differentiation (say by frequency) leads to a particular element organization (the formation of high and low tone frequency streams).

In contrast, tonality perception makes it possible to tease apart these processes. For example, differentiation can be examined by comparing how different kinds of duration or frequency of occurrence values for the various pitches might influence listeners' abilities to perceive the psychological stability of these pitches. Additionally, organization can be explored by having the variously differentiated pitches occur in either a typical hierarchical organization or some atypical organization.

What experimental forms might explorations of differentiation and organization take? For differentiation, one manipulation involves varying the durations (or frequencies of occurrence) of the tones relative to one another; as a convenience, we talk in terms of proportional durations (percentages of total sequence length) as opposed to timed durations (e.g., durations in ms or s). For example, take a sequence in which three different tones (say C, F#, and G, or Pitch Classes 0, 6, and 7; Figure 1) have respective durations of 15.2%, 6.0%, and 12.4% of the total sequence length, with the proportion of the remaining total duration of the melody being divided among the remaining 9 pitch classes. This pattern of durations can be changed to either increase or decrease the absolute differences in the proportional durations between tones while at the same time maintaining the relative pattern of durations across tones. Thus, a duration sequence of 11.4%, 7.2%, and 10.3% (for Tones C, F#, and G, respectively) decreases the duration differences of the original (e.g., in the original, the difference in proportional duration between Tones C and F# was 9.2%, and between C and G it was 2.8%, whereas in the new version these differences are now 4.2% and 1.1%, respectively). In contrast, a duration sequence of 35.1%, 2.2%, and 19.2% increases the proportional duration differences between the tones (e.g., the differences between C and F# and between C and G are now 32.9% and 15.9%, respectively). Despite the large absolute differences in proportional durations, however, these sequences are equivalent in a correlational sense, with the differences between elements judged relative to the variance among all values. Accordingly, the correlations between these patterns are, as might be expected, high (rs $\geq$ .97).

Manipulating the absolute degree of differences between elements while holding constant the relative patterning of the differences between the elements has a number of advantages. Most obviously, it provides a means of manipulating the degree of differentiation between elements. Thus, a comparison of listeners' tonal percepts in response to sequences varying in their absolute proportional duration differences (as in the three sequences just described) assesses how strongly elements must be differentiated to produce a perceptibly apprehensible structure (i.e., tonality). Moreover, because all of the sequences contain the same relative pattern of durations, this manipulation holds constant the organizational structure of the sequences.

In the current study, the organizational structure used was based on Krumhansl and Kessler's (1982) tonal hierarchy values, which mirror the duration and frequency of occurrence values found in Western music (as described earlier). To actually manipulate the degree of differentiation, the tonal hierarchy values were raised to exponents varying from 0 (producing a flat, undifferentiated profile) to 1.0 (reproducing the original Krumhansl and Kessler hierarchy) to 4.5 (producing a highly exaggerated profile); we refer to this exponent as *tonal magnitude.* This power transformation preserves, to a high degree, the relative duration pattern while drastically altering the absolute differences between the elements.[1] Examples of profiles differing in tonal magnitude are shown in Figure 2. If percepts of tonal structure systematically vary with changing tonal magnitude, then clearly differentiation is based, in large part, on absolute differences between the elements. In contrast, it might be that past some minimum level, variation in tonal magnitude fails to influence the perception of tonal structure. If so, then differentiation between elements seems primarily to be based on relative differences.

In the current study, organization was manipulated by presenting the differentiated pitches in two ways (compare the first two panels of Figure 2). In one case, listeners heard sequences in which the pitches were arranged hierarchically, mirroring the tonal hierarchy ratings (top panels of Figure 2). In the second case, the sequences contained similarly differentiated pitches, but the hierarchical organization characterizing tonality was disrupted by randomizing the duration pattern (middle panels of Figure 2). Accordingly, these two situations manipulated the presence versus absence of hierarchical organization among comparably differentiated pitches, with any differences in perceptions of tonality between the conditions attesting to the importance of organization independent of differentiation. (The importance of the bottom panels of Figure 2, or the binary hierarchy, is explained in Experiment 3.)

Experiment 1: The Role of Duration Information

Experiment 1 provided an initial test of the role of differentiation and organization in listeners' perceptions of tonality. Differentiation was manipulated via variations in tonal magnitude values, and organization was manipulated by presenting these pitches in either a hierarchical or nonhierarchical fashion. Although these manipulations are equally applicable to either the tone durations or the frequencies of occurrence of tones, in this experiment, durational patterning was manipulated with frequency of occurrence held constant. It is interesting to note that, although the perception of tonality is influenced by both the duration (Coady, 1992) and frequency of occurrence (Oram & Cuddy, 1995) of pitches, which are in fact naturally correlated in music, these two parameters are not equivalent in their ability to induce a tonal percept. Lantz and Cuddy (1996, 1998) teased these parameters apart by systematically varying the sounded duration of different pitches while holding their frequency of occurrence constant or varying frequency of occurrence while controlling total duration. Tonal stability ratings indicated that variations in tone duration, but not frequency of occurrence, led to percepts of tonality in listeners. Given this work, these initial tests focused on durational patterning.

Method

Participants. Forty students (with normal hearing) at the University of Toronto at Scarborough, Toronto, Ontario, Canada, participated in this experiment in exchange for $7 (U.S.$10) or bonus credit in their introductory psychology course. These students were assigned to either the hierarchical (n = 20) or the nonhierarchical (n = 20) condition; the decision to use a between-subjects design was based on practical time limitations. All of these participants met a 3-year minimum musical training requirement. On average, the two groups of listeners did not differ significantly in

[1] Correlations between Krumhansl and Kessler's (1982) tonal hierarchy values and duration profiles with tonal magnitudes of 0.5 to 4.5 ranged from .90 to 1.00 (M = .96, SD = .04).

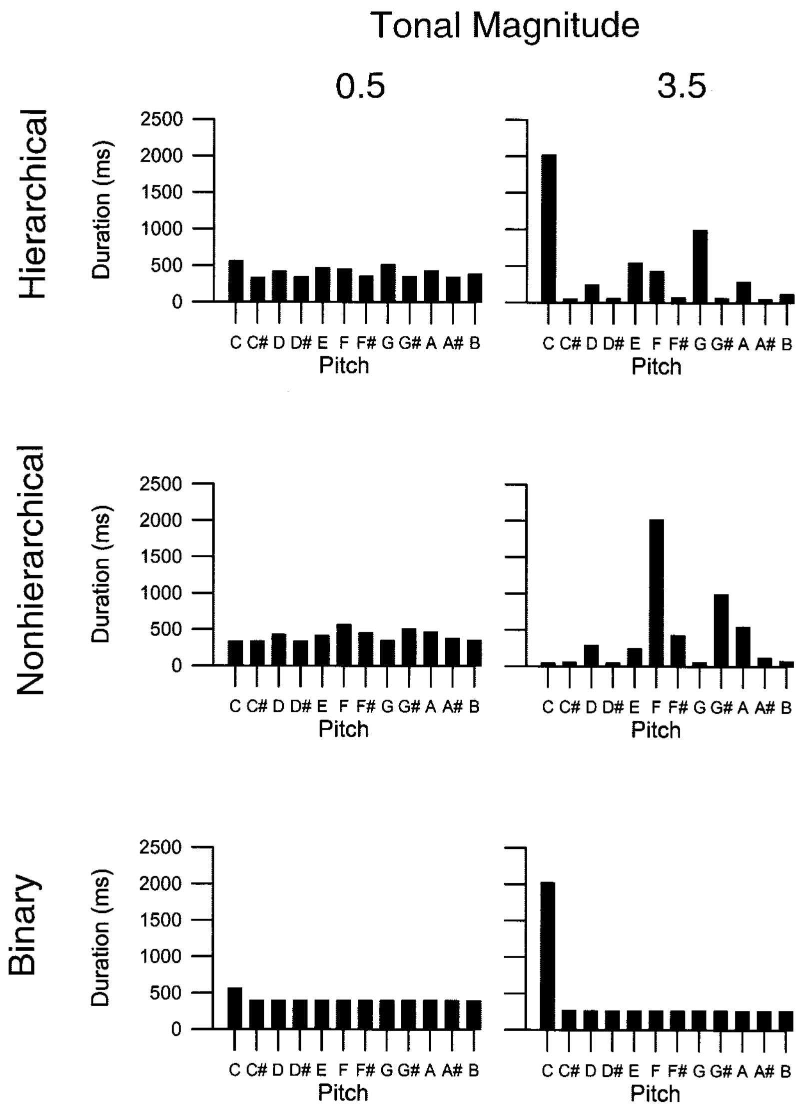

Figure 2. Examples of duration profiles differing in their tonal magnitude and hierarchical structuring. Hierarchical duration profiles are those based on Krumhansl and Kessler's (1982) tonal hierarchy. Nonhierarchical profiles were created by randomizing these same duration profiles. Binary profiles differentiate the tonic tone (Pitch Class 0) from the remaining tones.

their years of musical training (*M*s = 9.85 and 8.15, *SD*s = 4.13 and 3.17, respectively), $t(19) = 1.38$.[2]

Materials. The stimuli for this study consisted of a series of algorithmically composed pitch sequences, 10 s in length and all containing 24 tones. The pitches for each sequence were drawn from 1 of 10 adjacent chromatic sets within the pitch range from C_4 (262 Hz) to A_5 (880 Hz), with each pitch occurring twice. To produce the patterns of relative durations, the values for the 12 chromatic pitches in the standardized major key profile of Krumhansl and Kessler (1982) were raised to 1 of 10 exponents (0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, and 4.5), thereby producing the tonal magnitude manipulation described earlier. These transformed values were then expressed as a percentage of the sum of all 12 values, multiplied by 10,000 (the duration of the sequence in ms), and divided by 2 (the number of times each pitch occurs in the sequence). The resulting durations, shown in Appendix A, were then used to create sequences by randomly permuting the order of all 24 tones. Because these duration profiles were based on the Krumhansl and Kessler (1982) tonal hierarchy, the sequences produced by this method constitute the *hierar-*

[2] Differentiation and organization are presumably general perceptual processes and, hence, operative in all (musically trained and untrained) listeners. Accordingly, the decision to use trained listeners was based on the fact that, although both trained and untrained listeners can perceive tonality (e.g., Cuddy & Badertscher, 1987; Hébert, Peretz, & Gagnon, 1995), musically trained listeners nevertheless show greater sensitivity to more subtle aspects of the hierarchical structure of tonality (e.g., Cuddy & Badertscher, 1987; Krumhansl & Shepard, 1979). As such, we felt that using musically trained listeners would provide the strongest possible test of sensitivity to tonality in the somewhat unusual sequences used in this study.

chically organized sequences of this study. To produce the *nonhierarchical* sequences, the durations based on the tonal hierarchy values were randomly assigned to different pitches.

All sequences were played on a Yamaha DX7 synthesizer, set to an electric piano timbre, which was connected to a Macintosh 8100 AV computer via a MIDI interface. Audio output from the synthesizer was fed into a Mackie 1202 mixer and was presented to listeners at a comfortable listening level through two Boss MA-12 micro monitors.

Design and procedure. The study used the probe-tone method of Krumhansl and Shepard (1979). Each trial consisted of a presentation of a pitch sequence, followed by a 1-s silent interval and then a 2-s probe tone. The probe tone was 1 of the 12 pitches of the chromatic scale and was played with the same timbre and loudness, and in the same octave, as the sequence. After each probe tone, listeners rated on a 7-point scale how well they felt the probe tone fit into the context of the sequence they heard. It was stressed that they were to judge how well the probe tone fit into the sequence in general, not as a continuation of the sequence.

Each block of the experiment contained 14 trials, with the listener hearing the same sequence on all trials within a given block. The first 2 trials in the block were practice, used to familiarize the listener with the pitch sequence for that block. The following 12 trials contained the 12 probe tones, presented in a different random order for each listener. Each listener completed 10 blocks of trials, corresponding to the 10 tonal magnitude values of 0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, and 4.5. The order of the tonal magnitudes across blocks was also randomized for each listener. In the nonhierarchical condition, a different randomized version of the key profile was used for each block and listener. To avoid carry-over effects between blocks, the sequences were drawn from different chromatic sets, suggesting different tonics, on successive blocks of trials. An entire experimental session lasted approximately 45 min, after which each listener filled out a participant information form and was debriefed.

Results and Discussion

Prior to analyses, listeners' probe-tone ratings across the different blocks were transposed back to a common key; for convenience, these ratings are presented with reference to C major. For the nonhierarchical condition, in which tone durations were randomized across the pitches, the probe-tone ratings were assigned to scale degrees according to each pitch's duration rather than its name. Thus, the rating for the probe tone whose pitch had the longest duration in the melody was assigned to the pitch C (Pitch Class 0), the rating for the probe tone with the second longest duration was assigned to the pitch G (Pitch Class 7), and so forth. By this operation, the hierarchical structure that was destroyed in the nonhierarchical condition was mimicked, enabling comparisons with the hierarchical condition.

Preliminary analyses investigated the degree of consistency in probe-tone ratings at each level of tonal magnitude for hierarchical and nonhierarchical conditions. Accordingly, each listener's set of probe-tone ratings (for each tonal magnitude level individually) was correlated with the ratings of all other individual listeners, and the average correlation within the resulting half matrix of all possible intercorrelations was computed. For the hierarchical condition, the mean intersubject correlation increased systematically with increasing tonal magnitude, from −.09 at a tonal magnitude of 0 up to .41 and .35 at tonal magnitudes of 4.0 and 4.5, respectively. Supporting this increase, the mean intersubject correlations were positively correlated with tonal magnitude, $r(8) = .88$, $p < .01$. In contrast, for the nonhierarchical condition, the mean intersubject correlations at all tonal magnitudes were quite low, varying between .02 and .09. Additionally, there was no significant relation between tonal magnitude and the mean intersubject correlation, $r(8) = .53$. Generally, these patterns suggest that increases in tonal magnitude systematically add some common structure that is perceived by listeners, but only when this structure is organized hierarchically.

The next step in the analyses investigated the degree of differentiation in the probe-tone profiles as a function of tonal magnitude and organization type. Toward this end, ratings were analyzed in a three-way analysis of variance (ANOVA), with the within-subject variables of tonal magnitude (0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5) and probe tone (C, C#, D, D#, E, F, F#, G, G#, A, A#, B) and the between-subjects variable of organization type (hierarchical vs. nonhierarchical).[3] Of particular relevance were the significant main effects of probe tone, $F(11, 418) = 13.03$, $MSE = 3.52$, $p < .01$, and tonal magnitude, $F(9, 342) = 3.44$, $MSE = 3.08$, $p < .01$, as well as the significant Probe Tone × Organization Type, $F(11, 418) = 7.08$, $MSE = 3.52$, $p < .01$, Probe Tone × Tonal Magnitude, $F(99, 3762) = 1.79$, $MSE = 2.31$, $p < .01$, and Probe Tone × Organization Type × Tonal Magnitude, $F(99, 3762) = 1.32$, $MSE = 2.31$, $p < .05$, interaction effects. No significant effects were found for organization type, $F(1, 38) = 0.63$, $MSE = 29.30$, or the Tonal Magnitude × Organization Type interaction, $F(9, 342) = 1.35$, $MSE = 3.08$.

These effects were further explored in a series of one-way ANOVAs for each level of tonal magnitude and organization type (see Table 1).[4] An intriguing pattern was found, such that for the hierarchical condition, the probe tones became more differentiated with increasing tonal magnitude. For example, there were no differences in ratings at tonal magnitudes of 0 and 0.5, but at 1.0 and above, these ratings became significantly differentiated. In contrast, in the nonhierarchical condition, listeners failed to differentiate probe tones at any tonal magnitude.

The next step in the analyses involved determining the degree to which the differentiated pitches were organized. Toward this end, the mean probe-tone ratings for each tonal magnitude were corre-

[3] One issue with repeated measures ANOVAs involves a concern over violations of sphericity for one or more of the repeated measures variables, with such a violation indicating that the assumptions of equal variances and covariances are not justified, and thus the value of the F ratio is compromised. When such a situation occurs, the more conservative Greenhouse–Geisser correction be applied to the repeated measures effects. In this experiment, as well as the subsequent experiments, we examined our data for sphericity violations, and when such violations were detected (as occurred in all three experiments), the affected effects were reexamined using the correction. In every case in which sphericity was violated, these more conservative tests replicated the pattern of significances observed with the more standard ANOVA procedure. Accordingly, to simplify our explication of what are already complicated results, we do not present these additional tests, and we report the uncorrected degrees of freedom.

[4] Given the large number of analyses conducted here, one might argue that it would be more appropriate to adopt a stricter level of statistical significance (say the .01 level) than is typically used. Although we did consider this, one concern with this procedure is that such a conservative approach eliminates some effects in later experiments that are actually problematic for (as opposed to supportive of) the arguments we make in this article. Thus, even though removal of these results would strengthen our arguments, in a spirit of conservativism, we chose to maintain the more traditional significance values.

Table 1
Mean Probe-Tone Ratings for Each Pitch at Each Tonal Magnitude for Listeners in the Hierarchical and Nonhierarchical Conditions of Experiment 1

Pitch	Tonal magnitude 0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5
Hierarchical										
C	4.85	4.60	5.10	4.95	5.45	4.90	5.70	5.25	5.30	5.40
C#/D♭	4.45	4.35	3.90	4.40	4.20	3.95	3.90	3.10	2.95	3.55
D	4.40	4.75	4.15	4.00	4.80	4.15	4.20	3.50	4.65	4.50
D#/E♭	4.35	4.15	4.40	5.00	4.10	4.35	4.45	3.60	3.10	3.10
E	4.40	4.35	5.40	4.45	4.60	4.90	4.90	4.25	4.95	5.50
F	4.60	4.25	4.15	4.50	4.75	4.95	4.60	4.55	4.45	5.35
F#/G♭	4.75	4.15	4.10	4.45	4.15	4.30	4.25	3.80	3.55	3.35
G	5.20	4.35	4.90	5.25	6.05	5.70	5.25	4.95	5.55	5.60
G#/A♭	4.95	4.40	5.35	4.65	4.65	3.85	4.10	3.60	4.00	3.40
A	4.35	5.00	5.05	4.90	4.05	4.00	4.55	4.25	4.75	5.15
A#/B♭	3.70	4.75	3.15	3.20	3.65	3.35	3.15	3.10	2.45	2.80
B	4.80	4.25	4.40	3.95	3.85	3.15	3.05	3.50	3.20	3.50
$F(11, 209)$[a]	1.71	0.73	4.81***	3.35***	5.34***	5.20***	5.78***	4.57***	11.25***	10.37***
MSE	1.73	1.99	1.87	1.87	1.77	2.02	2.04	2.13	1.82	2.18
Nonhierarchical										
C	4.20	4.00	3.55	4.30	4.95	4.05	4.15	4.80	4.60	3.45
C#/D♭	4.45	3.90	4.10	4.25	4.05	4.00	3.60	4.25	3.65	3.00
D	3.80	4.25	4.30	4.10	4.20	4.35	3.45	4.30	4.25	4.50
D#/E♭	5.05	4.20	4.70	4.65	4.10	3.90	4.10	4.00	4.00	4.35
E	4.35	4.65	4.00	4.45	3.95	5.10	4.65	4.95	4.10	3.95
F	4.65	4.25	4.30	4.55	3.80	4.00	4.40	4.55	3.45	4.30
F#/G♭	4.20	4.55	4.30	4.35	3.65	4.70	4.40	4.40	4.70	4.00
G	4.20	4.55	4.40	4.40	5.10	4.25	4.40	4.20	4.95	4.15
G#/A♭	4.35	3.80	4.40	3.90	4.60	4.40	3.90	4.25	3.70	4.35
A	4.85	4.10	4.65	4.55	4.50	4.70	4.10	4.25	4.05	3.70
A#/B♭	4.45	4.70	4.30	4.15	4.65	4.25	4.25	3.80	4.10	3.75
B	3.90	3.80	4.80	4.35	4.40	3.95	3.05	3.45	3.40	4.05
$F(11, 209)$[a]	0.96	0.81	0.84	0.35	1.37	1.09	1.33	1.08	1.42	1.04
MSE	2.69	2.60	2.69	2.59	2.95	2.50	3.23	3.06	3.38	3.57

[a] The results of a one-way analysis of variance for the main effect of pitch of the probe tone.
*** $p < .001$.

lated with the tonal hierarchy values of Krumhansl and Kessler (1982). This analysis assessed the degree to which the tonal structure underlying the sequences (be it hierarchical or nonhierarchical) was present in listeners' ratings. Figure 3 presents these correlations as a function of tonal magnitude for the two organizational conditions. For the hierarchical sequences, tonal structure was present as a function of increasing tonal magnitude with tonal magnitudes of 2.0 and above, demonstrating significant relations. Moreover, these correlations were themselves significantly related to tonal magnitude, $r(8) = .88$, $p < .01$. In contrast, for the nonhierarchical condition, there was no systematic increase. Only one of the correlations (for tonal magnitude of 3.5) was significant, and there was no reliable relation between increasing tonal magnitude and perceived tonality, $r(8) = .48$. Thus, for only the hierarchical condition, as tonal magnitude increased, listeners' ratings more closely matched a standard description of tonal structure.

In general, this experiment explored the importance of differentiation and organization in the perception of tonality. One of the primary results of this experiment was that, without a sufficient degree of distinction between tone durations, listeners did not differentiate the tonal implications of the various probe tones and, thus, failed to apprehend the implied tonality of the sequences. Moreover, percepts of tonality increased systematically with increasing duration differences. Together, these findings imply that it is not just the relative pattern of tone durations that is important in differentiating the tonal implications of these elements, but instead, there may be some absolute level of duration difference necessary for element differentiation. Such a result has implications for musical key finding; this topic is addressed in the General Discussion.

The perception of tonality was not wholly dependent on simple element differentiation, however. Just as important for this percept was the fact that the differentiated elements were organized in a hierarchical fashion, mirroring the structure described by Krumhansl and colleagues (Krumhansl & Kessler, 1982; Krumhansl & Shepard, 1979); when durations were organized in a nonhierarchical fashion, no tonal perception was evident. It is interesting to

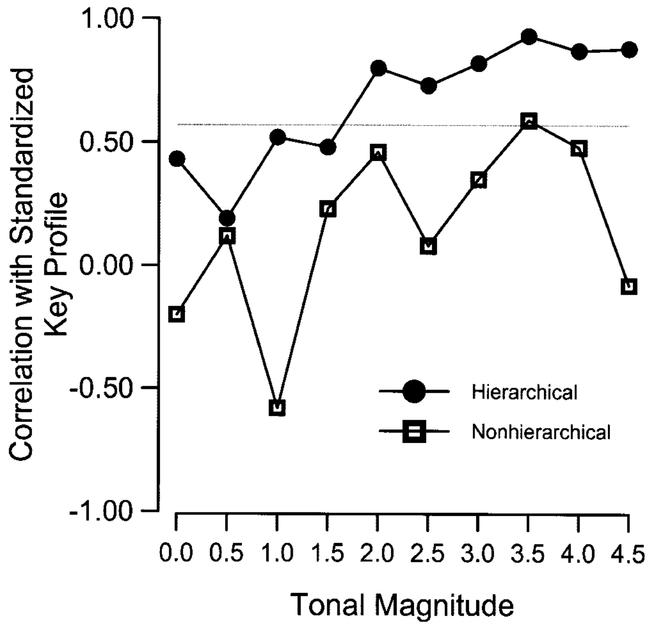

Figure 3. Correlations between mean probe-tone ratings and standard tonal hierarchy ratings (Krumhansl & Kessler, 1982) for the hierarchical and nonhierarchical conditions of Experiment 1 as a function of tonal magnitude. The dashed line at $r = .57$ represents the $p < .05$ significance level for $df = 10$.

note that, because we reorganized the actual ratings in the nonhierarchical condition such that the rating for the longest duration tone was compared to the value of the highest rated element in the tonal hierarchy (and thus the longest duration tone in the hierarchical condition), one important implication of this result is that the production of the goodness-of-fit ratings does not occur simply by giving the highest rating to the element heard for the longest period of time. If this were the strategy employed by listeners, then the correlations between the probe-tone ratings in the nonhierarchical condition and the tonal hierarchy values should have been significant at some level of tonal magnitude. The fact that this did not occur suggests that the relative duration pattern acted as a cue to allow listeners to recognize a tonal hierarchy and, thus, to apprehend the musically important relations inherent in the structure of this hierarchy (e.g., the structural importance of Pitch Classes 0, 4, and 7; the relative unimportance of the pitch classes of the nondiatonic set). This idea that the pattern induced a particular analytical set on the perception of the individual tones is intriguing and is also returned to in the General Discussion.

One limitation to the current results is that the stimuli of this experiment broke the natural correlation that exists between tone duration and frequency of occurrence, using sequences in which the elements were completely undifferentiated in terms of this latter factor (i.e., every pitch occurred twice). Recognizing this limitation raises the obvious question of whether differentiation of elements will occur if the elements are distinguished by variation in frequency of occurrence (with total duration held constant). Exploring issues related to this question was the goal of Experiment 2.

Experiment 2: The Role of Frequency-of-Occurrence Information

Experiment 2 examined a number of questions related to the importance of tone duration, frequency of tone occurrence, and the relation between the two on listeners' percepts of tonality. The most straightforward issue involved whether changing tonal magnitude has the same impact on the percept of tonality when element differentiation occurs via frequency of occurrence (holding duration constant) as it does when differentiation occurs via tone duration (holding frequency of occurrence constant). Given the results of Lantz and Cuddy (1996, 1998) described earlier, in which percepts of tonality mirrored duration and not frequency of occurrence information, it was anticipated that this situation would fail to instantiate tonal percepts for both hierarchical and nonhierarchical organizations, irrespective of tonal magnitude.

An additional, and more subtle, issue involved examining the impact on tonal percepts of breaking the natural relation between frequency of occurrence and duration. One reason that listeners may have failed to either differentiate or organize the nonhierarchical stimuli of Experiment 1 is that these stimuli violated this typical relation, which may have been especially disruptive given the fact that these stimuli were presented in a nonstandard organizational pattern (i.e., randomized tonal hierarchy relations). The current experiment explored whether elements can be differentiated and organized (both hierarchically and nonhierarchically) when duration and frequency of occurrence information retain their natural correlation.

Method

Participants. Forty students at the University of Toronto at Scarborough participated in this experiment in exchange for $7 (U.S.$10) or bonus credit in their introductory psychology course. They were assigned to one of two conditions, hierarchical ($n = 20$) or nonhierarchical ($n = 20$). On average, the two groups did not differ significantly in their years of musical training (*M*s = 7.8 and 8.8, *SD*s = 2.62 and 3.54, respectively), $t(35) = 0.99$, *ns.*

Materials. Pitch sequences were created that varied systematically in terms of the frequency of occurrence and total duration of their constituent pitches. All sequences were approximately 10 s in length and contained between 98 and 100 tones, with the proportion of these tones assigned to a given pitch determined by a tonal-magnitude calculation. The variation in the exact number of notes arose because of a rounding error in moving from decimal percentages representing tonal magnitude values to integer values for frequency-of-occurrence values. In contrast to the previous experiment, this experiment used a more limited range of tonal magnitude values (0.5, 1.0, 1.5, 2.0, and 2.5). This reduced range was adopted to keep the duration of the experiment to a reasonable length, as well as to avoid the situation at higher tonal magnitudes in which the proportion of occurrences for a pitch would equal less than 1%–2% (i.e., less than one or two occurrences). The tone durations were calculated in one of two ways. In the *uncontrolled* total duration condition, all tones were sounded for 100 ms regardless of their pitch, with the consequence that the total duration of each pitch increased with its frequency of occurrence. In the *controlled* total duration condition, the total duration for each pitch was set a priori to 833 ms, with the duration of each individual occurrence of that pitch determined by dividing this total duration by its frequency of occurrence. Thus, this condition not only broke the natural correlation between frequency of occurrence and total duration, it in fact reversed this relation. The frequency-of-occurrence and duration values for uncontrolled and controlled total duration conditions, as a function of tonal magnitude, appear in Appendix B.[5] As in Experiment 1, sequences were either hierarchical or nonhierarchical, with the relation between the frequency-of-occurrence and duration values and pitches either preserving or destroying the hierarchical structure of tonality.

Procedure. The procedure of this experiment was identical to that of Experiment 1.

Results and Discussion

As in Experiment 1, probe-tone ratings were transposed to the common key of C major, and the nonhierarchical condition was organized hierarchically on the basis of tone duration (e.g., the rating for the longest pitch was assigned to Pitch Class 0). Preliminary analyses investigated the degree of consistency in probe-tone ratings at each level of tonal magnitude for hierarchical and nonhierarchical conditions by intercorrelating listeners' ratings. For listeners in the uncontrolled total duration hierarchical condition, mean intersubject correlations increased with increasing tonal magnitude, with a range of −.01 at a tonal magnitude of 0.5 to .18 at a tonal magnitude of 2.5; these mean intersubject correlations were themselves significantly correlated with tonal magnitude, $r(3) = .97$, $p < .01$. However, the relation between tonal magnitude and mean intersubject correlation was not significant for controlled total duration hierarchical sequences. In this case, correlations ranged from .01 to .04 at tonal magnitudes of 0.5 and 2.5, respectively, with no significant relation between the two variables, $r(3) = .79$. For the nonhierarchical sequences, there was similarly no relation between intersubject correlations and tonal magnitude for either the controlled total duration, $r(3) = .73$, or the uncontrolled total duration, $r(3) = .58$, conditions, with the mean intersubject correlations ranging from .02 to .05 and .00 to .02 for tonal magnitudes between 0.5 and 2.5, respectively. This pattern of results suggests that only in the hierarchical, uncontrolled total duration condition did a common perceptible structure emerge with increasing tonal magnitude.

The next analytical step investigated the degree of differentiation in probe-tone ratings as a function of the different experimental variables. Toward this end, listeners' ratings were submitted to a four-way ANOVA with the within-subject variables of tonal magnitude (0.5, 1.0, 1.5, 2.0, 2.5), probe tone (C, C#, D, D#, E, F, F#, G, G#, A, A#, B), and duration (controlled vs. uncontrolled) and the between-subjects variable of organization (hierarchical vs. nonhierarchical). There were significant main effects of probe tone, $F(11, 418) = 2.36$, $MSE = 3.90$, $p < .01$, and duration type, $F(1, 38) = 10.49$, $MSE = 8.97$, $p < .01$; significant Probe Tone × Organization, $F(11, 418) = 2.30$, $MSE = 3.90$, $p < .01$, Probe Tone × Duration Type, $F(11, 418) = 3.06$, $MSE = 2.77$, $p < .01$, Probe Tone × Tonal Magnitude, $F(44, 1672) = 2.04$, $MSE = 2.61$, $p < .01$, and Duration Type × Tonal Magnitude, $F(4, 152) = 5.27$, $MSE = 3.63$, $p < .01$, interactions; and significant Probe Tone × Duration Type × Organization, $F(11, 418) = 2.91$, $MSE = 2.77$, $p < .01$, Probe Tone × Organization × Tonal Magnitude, $F(44, 1672) = 1.53$, $MSE = 2.61$, $p < .05$, and Probe Tone × Duration Type × Tonal Magnitude, $F(44, 1672) = 1.72$, $MSE = 2.55$, $p < .01$, interactions. The main effects of organization type, $F(1, 38) = 1.69$, $MSE = 36.42$, and tonal magnitude, $F(4, 152) = 0.30$, $MSE = 4.27$, were not significant; nor were the Organization Type × Duration Type, $F(1, 38) = 0.12$, $MSE = 8.97$, Organization Type × Tonal Magnitude, $F(4, 152) = 0.68$, $MSE = 4.27$, and Organization Type × Duration Type × Tonal Magnitude, $F(4, 152) = 0.83$, $MSE = 3.63$, interaction effects. The Probe Tone × Duration Type × Tonal Magnitude interaction effect was not significant, $F(44, 1672) = 1.29$, $MSE = 2.55$. Although complex, these interactions suggest that ratings of the probe tones varied systematically with changes in duration type, organization, and tonal magnitude. Subsequent analyses attempted to disentangle these effects.

Specifically, probe-tone ratings were analyzed in a series of one-way ANOVAs at each level of tonal magnitude, organization type, and duration type; these ratings and the results of these ANOVAs appear in Table 2. In the uncontrolled total duration hierarchical condition, the probe tones became increasingly differentiated with increasing tonal magnitude, with significant differences between probe-tone ratings at tonal magnitudes of 1.5 and higher. In contrast, no differentiation was found at any level of tonal magnitude in the controlled total duration hierarchical condition. Similarly, in the two nonhierarchical conditions (controlled and uncontrolled total duration), the only significant effect observed was at a tonal magnitude of 2.0 for the uncontrolled total durations; other than this isolated effect, ratings did not vary. Thus, differentiation of probe tones was restricted to sequences containing hierarchically organized tones in which tone duration varied in accordance with frequency of occurrence.

The next series of analyses investigated the degree of organization of the differentiated pitches. As in Experiment 1, the mean probe-tone ratings for each tonal magnitude, organization, and duration type were correlated with the Krumhansl and Kessler (1982) tonal hierarchy values to assess the degree of tonal structure. Figure 4 presents these correlations as a function of tonal magnitude for the two organization and duration types. In the hierarchical conditions, uncontrolled total duration led to increasing tonal structure with greater tonal magnitude, with significant correlations at tonal magnitudes of 1.5 and above. In contrast, controlled total duration failed to produce any significant correlations. Similarly, in both nonhierarchical conditions, there was no evidence of tonal structure at any tonal magnitude. Thus, just as with differentiation, it was only when the sequences contained hierarchically organized tones varying in total tone duration that listeners apprehended any degree of tonality.

Along with assessing the role of frequency-of-occurrence information, the controlled total duration condition also disentangled

[5] In the uncontrolled total duration condition in particular, the length of some of these tones was quite short, raising questions about whether listeners could actually perceive the pitch of these tones in the first place. Work on pitch perception (e.g., Patterson, Peters, & Milroy, 1983; Robinson & Patterson, 1995) has found that for complex tones, 8–10 cycles of the waveform are required for stable pitch perception. On the basis of this estimate, virtually all of the tones employed in this experiment should have produced a recognizable pitch. The only possible concern here is that, at a tonal magnitude of 2.5, if the tonic tone was either C_4 (262 Hz) or $C\#_4$ (277 Hz), a 28-ms duration would result in 7.34 and 7.76 cycles (respectively), which are just below the border of pitch perceptible. Although this is potentially worrisome, because random tonics were chosen throughout this experiment, our feeling is that the possibility of this being a significant factor is, in all likelihood, small at best.

Table 2
Mean Probe-Tone Ratings for Each Pitch at Each Tonal Magnitude for Listeners in the Hierarchical and Nonhierarchical Conditions of Experiment 2 as a Function of Duration Condition

	Tonal magnitude									
	Uncontrolled total duration (ms)					Controlled total duration (ms)				
Pitch	0.5	1.0	1.5	2.0	2.5	0.5	1.0	1.5	2.0	2.5
Hierarchical										
C	3.45	4.70	4.70	4.90	5.65	3.70	3.80	4.20	4.20	4.40
C#/D♭	4.20	3.40	3.60	2.70	4.20	4.00	4.15	3.75	4.00	4.95
D	4.00	3.35	3.50	4.05	3.55	3.95	4.15	3.25	3.65	4.05
D#/E♭	4.35	4.20	3.60	2.80	3.25	4.40	3.70	4.45	4.40	3.95
E	4.65	4.30	3.80	4.00	4.70	4.30	4.10	3.90	3.55	4.20
F	4.45	4.20	4.05	3.95	3.75	4.45	4.10	4.40	4.90	4.90
F#/G♭	3.95	3.65	4.00	3.65	3.55	4.05	4.00	4.95	4.30	4.25
G	4.20	4.30	4.95	5.45	4.55	3.55	3.80	4.75	4.70	5.15
G#/A♭	4.05	4.55	4.15	3.20	3.45	4.15	4.25	4.55	4.85	5.10
A	4.50	4.35	4.95	4.35	3.40	4.90	4.60	4.45	4.60	4.40
A#/B♭	4.75	3.45	3.05	3.25	2.40	4.45	4.20	4.85	5.25	4.25
B	3.80	4.10	3.60	3.50	2.90	4.00	4.45	3.95	4.10	3.85
$F(11, 209)^{a}$	0.87	1.54	2.57**	4.71***	5.77***	0.99	0.42	1.96	1.69	1.67
MSE	3.20	2.80	2.82	2.83	2.66	2.73	3.29	2.54	3.10	2.49
Nonhierarchical										
C	4.50	4.00	3.90	4.70	4.60	4.10	4.20	4.60	4.90	4.95
C#/D♭	4.40	3.90	5.20	4.95	4.70	4.85	4.45	4.65	4.60	4.50
D	4.60	3.75	4.05	4.15	4.15	4.15	4.90	4.15	4.70	4.95
D#/E♭	4.75	4.60	4.10	3.65	4.00	4.05	4.70	4.95	4.40	4.75
E	4.40	4.50	4.25	4.00	3.80	4.50	3.85	4.45	4.70	4.80
F	3.20	4.40	3.15	4.10	4.50	4.35	4.60	4.35	3.75	5.30
F#/G♭	4.20	4.50	3.90	4.20	3.50	4.85	4.50	4.65	4.10	5.00
G	4.70	5.40	4.60	4.65	4.30	4.05	4.45	4.65	4.25	4.90
G#/A♭	4.10	4.75	4.15	3.85	3.40	4.70	3.90	3.90	3.90	4.55
A	3.70	4.35	5.25	3.35	3.35	4.60	4.40	4.30	4.35	4.95
A#/B♭	4.20	5.30	3.75	5.20	3.50	4.50	4.05	3.80	4.30	4.85
B	4.05	3.85	3.75	3.70	4.95	3.55	5.20	4.45	4.20	4.40
$F(11, 209)^{a}$	1.32	1.94	2.48	2.56*	2.46	1.27	1.25	0.83	0.91	0.54
MSE	2.97	2.91	2.92	2.46	2.51	2.37	2.54	2.66	2.54	2.27

[a] The results of a one-way analysis of variance for the main effect of pitch of the probe tone.
* $p < .05$. ** $p < .01$. *** $p < .001$.

the influences of the total duration of a tone and the duration of an individual occurrence of that tone. In Experiment 1, the total pitch duration was varied by manipulating the duration of each pitch's occurrence; because all pitches occurred equally often, total duration and individual pitch duration were perfectly correlated. In contrast, in the current controlled total duration condition, individual durations were manipulated independently of their total duration. One consequence of this procedure is that the duration profile of the individual pitches within the controlled total duration condition (assuming a hierarchical structure) exhibits a high degree of tonal structure but of a very different key.

Take a controlled total duration profile that implies the key of C major in terms of the frequency of occurrence of pitches. Hierarchically important pitches (i.e., C, E, and G; Pitch Classes 0, 4, and 7) occur frequently, but because total duration is controlled, these tones have short individual durations. If one examines the pattern of individual durations across pitches (see Appendix B), one finds that these durations actually imply tonalities of F# major and C# major (two maximally dissimilar keys from C major).[6] This produces the very interesting situation in which two different aspects of the same profile make competing predictions about which key could be perceived by listeners. To examine the possibility that listeners might be sensitive to the alternative tonal implications of the individual durations, we correlated probe-tone ratings with standardized key profiles for these alternative keys. No significant correlations were found between listeners' ratings and alternative keys, suggesting that despite significant correlations between individual note durations and alternative keys, it was only the total duration of pitches that drove the perception of tonal structure.

Together, Experiments 1 and 2 demonstrate that for a tonal organization to be perceived, the pitches of the chromatic scale

[6] Correlations between the individual duration profiles, shown in Appendix B, and tonal hierarchy values, ranged from .70 to .78 for F# major and from .58 to .64 for C# major.

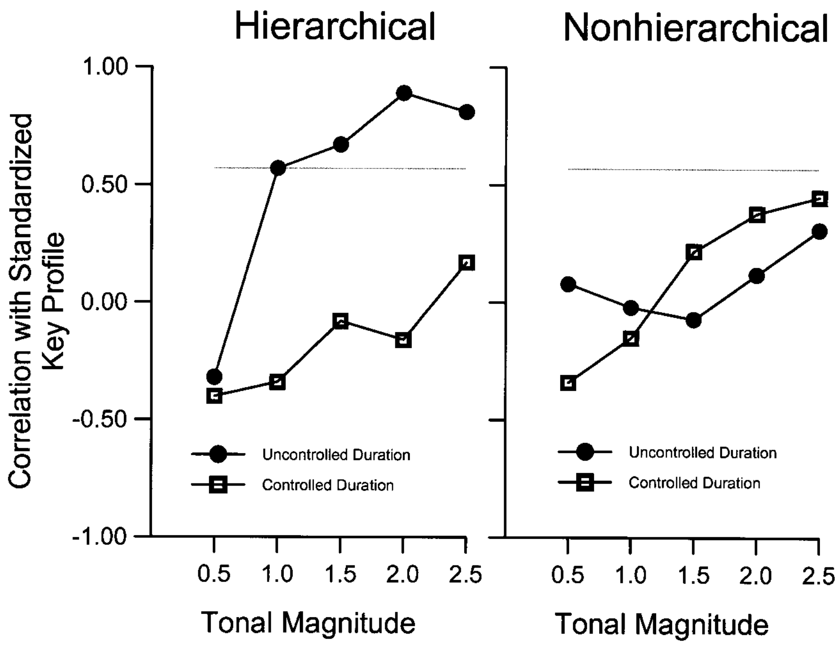

Figure 4. Correlations between mean probe-tone ratings and standard tonal hierarchy ratings (Krumhansl & Kessler, 1982) for the hierarchical and nonhierarchical controlled and uncontrolled total duration conditions of Experiment 2 as a function of tonal magnitude. The dashed line at $r = .57$ represents the $p < .05$ significance level for $df = 10$.

must be sufficiently differentiated in their total duration, and they must be hierarchically organized, embodying the structure outlined in Krumhansl's classic work (Krumhansl, 1979, 1990a, 2000; Krumhansl & Kessler, 1982; Krumhansl & Shepard, 1979) on the perception of tonality. One potential limitation to this result is the fact that it is unclear whether listeners' failure to perceive tonal structure in the nonhierarchical conditions was due to the absence of information supporting a consistent tonal interpretation of the sequence or the presence of information contradicting a tonal interpretation. For example, if a sequence has C as the longest pitch, a likely candidate for the tonality of the sequence is C major. In the hierarchical condition, the second and third longest pitches, G and E, support this interpretation. However, in the nonhierarchical condition, the second and third longest pitches might be C# and B, whereas G and E have short durations. In this case, C major is not supported by the short G and E pitches, and it is contradicted by the long C# and B pitches. Recognition of this limitation thus raises the question of which pitch relations are important. Must listeners hear all of the pitches in their appropriate hierarchical position to perceive the underlying tonal structure, or are some pitch relations, such as the distinction between the tonic and nontonic pitches, more important than others?

Experiment 3: Binary Hierarchical Information

Experiment 3 addressed the question of whether the failure of tonal perception in the nonhierarchical condition was due to a lack of supportive information or to the presence of contradictory information by introducing a modified hierarchical structure. This modification preserved the differentiation between the tonic (e.g., Pitch Class 0; Figure 1) and nontonic pitches (Pitch Classes 1–11; Figure 1) but eliminated any differentiation among nontonic pitches by equating their durations. In relation to this two-level binary hierarchy (as opposed to the multilevel tonal hierarchy shown in Figure 1, top), the real difference between the hierarchical and nonhierarchical structures in Experiments 1 and 2 is whether the key implication of the longest pitch, the tonic, is supported or contradicted by the remaining pitches.

If, on the one hand, listeners' failure to perceive tonality in the nonhierarchical conditions of Experiments 1 and 2 was due to contradictory information, then eliminating all differentiation among the nontonic pitches should reduce this influence and, thus, allow listeners to perceive the key implied by the tonic. If, on the other hand, it was the absence of evidence supporting the key implied by the tonic that prevented listeners from perceiving tonality, then this implied key will remain unperceived, because the supportive information is equally absent in the binary condition.

Method

Twenty students at the University of Toronto at Scarborough participated in this experiment in exchange for $7 (U.S.$10) or bonus credit in their introductory psychology course. They all met the 3-year minimum musical training prerequisite, having an average 8.15 years of training ($SD = 2.83$). The stimuli were identical to the sequences of Experiment 1, with total tone duration manipulated as a function of tonal magnitude (from 0 to 4.5). In this case, though, changes in tonal magnitude were indicated solely by differences in duration between the tonic and remaining pitches. The duration of the 11 nontonic pitches was set to a single value, determined by averaging the duration of the remaining values used in Experiment 1. Examples of binary profiles differing in their tonal magnitudes are shown in the bottom panels of Figure 2, and the actual durations appear in Appendix C. Other than the averaging of tone durations for nontonic pitches, all aspects of Experiment 3 were identical to Experiment 1.

Results and Discussion

As in the previous experiments, consistency was examined by intercorrelating listeners' ratings and calculating the mean intersubject correlation at each level of tonal magnitude. These mean intersubject correlations ranged from −.02 to .13 and showed a general increase with increasing tonal magnitude, $r(8) = .73$, $p < .05$. This increase suggests that some common structure was perceived by listeners at higher tonal magnitudes, although it is worth noting that this consistency is lower than that for the hierarchical condition of Experiment 1.

Next, the degree of differentiation of probe-tone ratings was examined in a two-way ANOVA with the within-subject variables of tonal magnitude (0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, and 4.5) and probe tone (C, C#, D, D#, E, F, F#, G, G#, A, A#, and B). There was a significant effect of probe tone, $F(11, 209) = 6.87$, $MSE = 2.34$, $p < .01$. The main effect of tonal magnitude, $F(9, 171) = 1.78$, $MSE = 2.15$, and the Tonal Magnitude × Probe Tone interaction, $F(99, 1881) = 1.17$, $MSE = 2.11$, were not significant.

For comparison with the previous studies, a series of one-way ANOVAs was performed, examining the probe-tone ratings at each level of tonal magnitude. Table 3 presents the mean probe-tone ratings as a function of tonal magnitude, along with the results of these analyses. At low levels of tonal magnitude, there were no differences in probe-tone ratings; however, for tonal magnitudes of 2.5 and over, there were significant differences in these ratings. To determine whether these effects were due to the differentiation of all the pitches or solely to differentiation of the tonic from nontonic pitches, a second series of ANOVAs was performed on the nontonic pitches alone; the results of these analyses also appear in Table 3. Although some tonal magnitudes (2.5 and 3.0) produced significant differences, by and large there was no differentiation of probe-tone ratings once the tonic was removed. As such, this result suggests that listeners primarily differentiated the tonic from the nontonic pitches only and did not differentiate between the remaining pitches themselves.

Finally, the degree of organization was assessed by correlating the mean probe-tone ratings with the tonal hierarchy values, $r(10) = -.02$ to .72 (shown in Figure 5). Although there was not as strong a linear increase with increases in tonal magnitude, $r(8) = .38$, *ns*, it is notable that the only two significant correlations with the tonal hierarchy were for the highest tonal magnitudes, suggesting that increasing relative tone duration differences drives perceptual organization for binary profiles, just as it did for the fully differentiated profiles of Experiments 1 and 2.

Before much is made of this result, however, it is important to evaluate the impact of the high tonic rating on the correlations with the tonal hierarchy, to assess whether differentiation of the tonic induced the complete pattern of stability relations of the tonal hierarchy. To evaluate this possibility, these correlations were calculated after removal of the tonic value. Overall, this analysis produced lower correlations, ranging from −.54 to .48, with none of the correlations statistically significant. Moreover, the weak

Table 3
Mean Probe-Tone Ratings for Experiment 3

	Tonal magnitude									
Pitch	0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5
C	4.65	4.30	4.80	4.65	4.70	5.15	5.25	5.00	5.15	5.85
C#/D♭	4.65	4.00	4.45	3.80	5.10	4.75	5.05	4.75	4.35	4.35
D	4.65	3.65	4.05	3.30	4.20	4.15	3.90	3.95	4.60	4.00
D#/E♭	4.25	4.15	3.80	3.80	4.50	4.45	4.40	4.05	3.75	3.90
E	4.40	4.15	4.05	4.05	4.55	4.55	4.45	3.95	4.65	3.60
F	4.70	4.30	4.05	4.00	4.10	4.55	3.80	4.15	3.90	4.45
F#/G♭	4.95	4.25	4.40	4.45	3.85	4.40	4.00	3.95	4.00	3.60
G	4.50	4.00	4.60	4.40	3.85	4.40	3.20	4.15	4.20	3.85
G#/A♭	4.25	4.05	3.85	4.05	4.35	3.50	3.90	4.20	3.85	3.95
A	4.25	4.55	3.95	4.20	4.00	3.50	3.40	3.65	4.00	3.70
A#/B♭	4.35	3.70	4.35	4.25	4.10	3.75	3.85	4.50	3.50	3.70
B	4.35	4.80	4.35	4.05	4.20	4.40	4.20	5.00	3.80	4.25
Tonic and nontonic pitches										
$F(11, 209)$[a]	0.53	0.97	0.86	0.95	1.34	2.58**	3.44**	1.90*	1.98*	3.63**
MSE	1.91	2.15	2.26	2.65	2.03	1.91	2.11	2.03	2.20	2.12
Nontonic pitches alone										
$F(10, 190)$[a]	0.58	1.08	0.64	0.77	1.34	1.95*	2.47**	1.52	1.22	0.80
MSE	1.82	2.08	2.24	2.67	1.96	1.96	2.09	2.04	2.13	2.20

[a] The results of a one-way analysis of variance for the main effect of pitch of the probe tone.
* $p < .05$. ** $p < .01$.

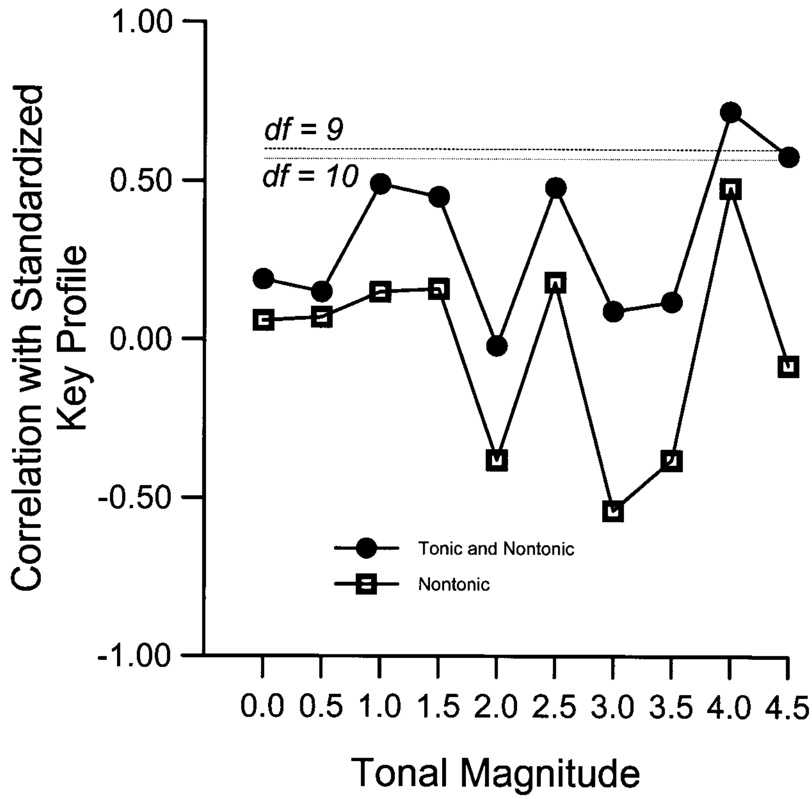

Figure 5. Correlations between mean probe-tone ratings for both all tonic and nontonic pitches, and for the nontonic pitches alone, and standard tonal hierarchy ratings (Krumhansl & Kessler, 1982) for the binary sequences of Experiment 3 as a function of tonal magnitude. The dashed lines at r = .57 and .60 represent the $p < .05$ significance levels for df = 10 and 9, respectively.

linear trend with tonal magnitude was now eliminated, $r(8) = -.15$, *ns.* Thus, although auditory sequences containing a differentiated tonic rendered the tonic at least recognizable as an important pitch, simple tonic identification did not induce a full-blown hierarchical organization on the complete set of pitches.

Listeners' failure to recover the tonal hierarchy in these sequences shows that the binary hierarchy is not sufficient to induce tonal perception. This suggests that the failures of tonality perception in the nonhierarchical conditions of Experiments 1 and 2 were most likely due to the absence of information supporting a tonal interpretation of the sequence and not to the presence of contradictory information. Given the fact that supporting information appears to be critical, and that the binary sequences do not provide enough of such support, the question immediately arises as to exactly how much and what type of supporting hierarchical information is required to induce tonal perception. One possible way of addressing this question might be to retain a two-level hierarchy but add more discriminating information within these levels, with the top level containing multiple structurally important tones (i.e., the pitch classes of the tonic triad, as shown in the first two levels of Figure 1, top) and the bottom level containing the remaining tones (as outlined in Figure 1, top). Or, alternatively, it would be possible to include additional hierarchical levels without discriminating within each level. Thus, one could use a trinary hierarchy, with the top level containing a long duration tonic, the next level containing the remaining diatonic tones played with an intermediate duration, and the bottom level containing the nondiatonic tones presented with a short duration. Eventually, of course, with the addition of more hierarchical levels, the typical tone profile will emerge; nevertheless, such systematic additions of structure would provide insight into the nature of the information necessary to invoke more abstract, internal representations of musical structure in listeners.

Manipulating the number and content of the hierarchical levels also allows for exploration of one of the more curious, and admittedly contradictory, findings of this experiment, which is that in contrast to the previous studies, listeners in this experiment could track the most prevalent tone in the auditory sequence and use this information as the basis for their stability ratings. The obvious difference between the present experiment and Experiments 1 and 2, of course, is that in the current experiment, listeners only had to track one duration difference with a single tone as opposed to the multiple differences with multiple tones in the earlier experiments. In this case, use of randomized versions of the multileveled profiles (described above) would enable determination of the degree to which listeners can use patterns of novel duration differences to drive percepts of psychological stability. As an aside, Lantz (2002) has recently demonstrated that listeners can, under some circumstances, use relative duration differences as a cue to differentiation of pitches in up to a three- to four-level hierarchy with nontonal sequences. On a more general level, the findings of Lantz (2002), as well as those of this study, provide insight into how listeners might actually internalize the hierarchical structure of tonality during musical learning and development.

General Discussion

The present experiments examined two complementary processes of perceptual organization—differentiation and organization—within the context of perceiving tonality. Overall, it was found that these two principles played a conjunctive role, with the apprehension of tonality requiring both a sufficient degree of differentiation among pitches, characterized by tonal magnitude, and hierarchical organization of these differentiated pitches, characterized by adherence to a prototypical schema for musical tonality (Krumhansl, 1990a; Krumhansl & Kessler, 1982; Krumhansl & Shepard, 1979). These findings have a host of implications for the understanding of how listeners come to apprehend tonality, as well as aspects of auditory processing more generally. Here, we explore some of these implications.

One of the first issues with which we can grapple is the relation between our conception of tonal magnitude and the more standard psychomusicological concept of *tonal strength.* Although we have derived tonal magnitude as a power transformation of the standardized key profile, on reflection it is clear that tonal magnitude is in many ways comparable to the more familiar concept of tonal strength. Research on tonal strength has occupied a central place in work on musical cognition, with such investigations extensively studying, for example, the consequences of varying tonal strength on the processing of and memory for musical passages (e.g., Croonen, 1994, 1995; Cuddy, Cohen, & Mewhort, 1981; Cuddy, Cohen, & Miller, 1979; Cuddy & Lyons, 1981; Dowling, 1978, 1991). In addition, this work has identified characteristics that make a passage tonally strong, with music heard as tonally strong if it (a) is diatonic, in that it is composed primarily of pitches of the diatonic set; (b) begins and ends on the tonic; and (c) exhibits cadential structure (e.g., contains a sequence of chords built on Pitch Class 0, followed by Pitch Class 7, and ending on Pitch Class 0). It is interesting to note that our manipulation of tonal magnitude is linked to variation in many of these parameters. For example, increases in tonal magnitude result in increased diatonicism, in that diatonic and nondiatonic tones become more frequent and infrequent, respectively. Similarly, the prescriptions that tonal music begin and end on the tonic and exhibit cadential structure have the effect that hierarchically important tones become more frequent, thus producing duration distributions with greater tonal magnitudes.

As conceptualized in the current article, tonal magnitude provides a viable means of assessing the tonal strength of musical passages, one that goes beyond previous attempts to quantify this aspect of musical structure. For example, one earlier method of tonal strength assessment was described by Takeuchi (1994), who, using the Krumhansl–Schmuckler key-finding algorithm (described earlier; Krumhansl & Schmuckler, 1986a), suggested that the value of the highest correlation produced by the algorithm (called the *maximum key correlation,* or MKC) could index the tonal strength of a passage. In keeping with her hypothesis, Takeuchi found that the MKC was indeed predictive of perceived tonal strength, with high-MKC melodies perceived by listeners as having greater tonal strength than low-MKC melodies.

Of course, one of the main points of the research reported in the present article is that assessing tonal strength by correlational pattern matching, as occurs with the key-finding algorithm, has some important limitations. These limitations are illustrated by the duration profiles in the top panels of Figure 2. According to the key-finding algorithm and the MKC, sequences based on either distribution should be essentially comparable in instantiating tonality (e.g., have comparable tonal strengths) because the two distributions correlate to a similar degree with the tonal hierarchy. Clearly, however, this is not the case, with these two duration distributions giving rise to sequences differing dramatically in their perceived tonality.

As such, tonal magnitude estimates could provide a reasonable conjunct measure of tonal strength, to be used with the key-finding algorithm to produce a more complete description of the tonal implications of a passage. Along these lines, the key-finding algorithm could be used to determine the candidate key(s) for a given musical passage, and a tonal magnitude estimate of the passage could be calculated to provide a sense of how strongly tonal structure is instantiated (note that tonal magnitude estimates for a given passage do not vary with different keys, meaning that this measure is not a key-finding measure per se).[7] Thus, it is conceivable that a musical passage might produce a high maximum key correlation with a particular tonality while containing a relatively low tonal magnitude value; such a situation would suggest that this passage, although unambiguous in its tonal structure, nevertheless induces this key only somewhat weakly. How much to weight a judgment of key determination on the basis of variation in tonal magnitude is an open question at the moment, but it does suggest an interesting avenue for future work.

Of course, critical to the use of tonal magnitude in key finding is some estimate of the minimum level of tonal magnitude necessary for a passage to induce a tonal percept. On the basis of the results of the current study, it seems that duration differences produced in accordance with the standardized key profile of Krumhansl and Kessler (1982; see Figure 1) having a tonal magnitude of 1.0 might in fact not be sufficient to produce reliable tonal percepts. Instead, Experiment 1 suggests that tonal magnitude values of about 2.0 might be required, whereas Experiment 2 drops this value to about 1.5. The obvious reason for the somewhat lower estimate in the latter case is that, in Experiment 2, both duration and frequency-of-occurrence values were hierarchically organized, whereas in Experiment 1 only duration values were organized in

[7] One way of assessing the tonal magnitude of a passage would be to compare the duration profile of the passage in question with a range of tonal magnitude profiles, say from 0 to 4.0 (in steps of 0.1) and look for the tonal magnitude value producing the smallest squared mean difference scores. If one were to then take a tonal magnitude estimate of 1.5 as the ideal tonal magnitude value (based, for example, on the hierarchical uncontrolled total duration condition of Experiment 2), a measure of tonal strength could be derived by comparing the observed tonal magnitude of a passage with this ideal value. Although speculative, such a procedure suggests an intriguing avenue for future investigation.

this fashion. It should be remembered, though, that all three experiments used randomized, nonmetrical pitch sequences. Accordingly, embedding tonal magnitude variation into more realistic melodies might lead to the perception of tonality at even lower tonal magnitudes. Future work could, and should, examine this issue more closely. (This comparison across experiments is intriguing because it suggests that the redundancy of information from duration and frequency of occurrence in musical passages is important in inducing tonal percepts in that passages containing such redundancy might not need to contain overly exaggerated duration differences between tones. This, then, might partially explain why highly chromatic musical passages—e.g., music making frequent use of nondiatonic pitches along with diatonic ones—such as those found in Western classical works of the late 19th to early 20th century, can nevertheless induce reasonably strong tonal percepts.)

The current results also have implications for musical key finding in their use of random orderings of tones. Up to now, the literature in musical cognition has been rather pessimistic as to the efficacy of random sequences of tones in producing strong tonal percepts. West and Fryer (1990), for example, found that after hearing random orderings of the diatonic set, listeners were unable to identify the tonic of the sequence, indicative of a failure of tonal perception. The current findings suggest that West and Fryer's finding of lack of tonal perception might have been due to insufficient differentiation among the scale pitches, given that all tones in their work were played with equal durations.

In fact, one of the most striking findings of the current study, and one having broader implications for key finding, is the fact that random sequences of tones in any fashion could result in percepts of tonality. Within musical lore, it is axiomatic that a controlled serial ordering of tones (e.g., tones occurring in a particular order) is critical for both the informal enjoyment and appreciation of music and for formal analyses of musical structure. In fact, the central role played by serial order information underlies one of the most fundamental distinctions between the Krumhansl–Schmuckler key-finding algorithm (Krumhansl & Schmuckler, 1986a) and Brown and Butler's (1981) intervallic rivalry theory key-finding model (described earlier). One of the most important and potentially devastating criticisms leveled at the key-finding algorithm by the intervallic rivalry theory has concerned the former's failure to incorporate serial order information. In this context, the present experiments lend strong support to the key-finding algorithm by demonstrating that appropriate serial order information is not a prerequisite for key finding, provided that the chromatic set is sufficiently differentiated and organized.

Looked at more generally, the current experiments could be seen as quite damaging to the intervallic rivalry theory. According to that approach, key finding arises because of listeners' identification of rare versus ubiquitous intervals that simply fall out of the interval content of the diatonic set. Because, however, the current experiments based their sequences on the chromatic (and not the diatonic) set, there is no rare interval information available by which key finding might occur. Nevertheless, listeners could identify the tonal structure of these sequences; such findings are, at the least, problematic for a rare interval account.[8]

In a different vein, the current manipulations of tonal magnitude also have implications regarding the relation between tonal instantiation and the expressive performance of music. According to some researchers (e.g., Sundberg, Askenfelt, & Frydén, 1983; Sundberg, Frydén, & Askenfelt, 1983), one means for producing musically expressive renditions of musical scores is the systematic application of rules that (among other things) sharpen durational contrasts by shortening short tones and lengthen the durations of tones terminating melodic leaps. In keeping with this hypothesis, perceptual experiments (e.g., Thompson, Sundberg, Friberg, & Frydén, 1989) have shown that applying these rules transforms an automated performance into one that is heard as much more expressive. Because the note durations of musical scores mimic the standardized key profiles, such rules have the effect of increasing the tonal magnitude of a piece in its performed tone durations relative to the notated durations in the musical score.[9] One implication of these results is that total tone durations taken from a musically expressive performance might exhibit a higher tonal magnitude than a less expressive performance of the same piece; ongoing work is examining this possibility. Such a finding would be especially intriguing given the current results suggesting that increased tonal magnitude facilitates the apprehension of tonal structure. Accordingly, one consequence of performance expression might be the more effective communication of tonal structure to listeners.

Finally, and much more generally, the role of tonal magnitude in the perception of tonality may reflect very basic principles of auditory pattern perception. For example, the finding that the tonal stability of a pitch is related to its proportional duration is closely related to the proportion-of-the-total-duration rule (Kidd, 1995; Kidd & Watson, 1992), which proposes that the allocation of attention to elements of a given frequency in an auditory pattern is a function of its total duration proportional to those of other frequencies. Kidd and Watson's finding, among others, has been incorporated into Lutfi's (1993) more general component-relative-entropy model of auditory pattern analysis, which argues that the discriminability of an element in a pattern is a function of how much that element's duration (or some other parameter) contributes to the overall variance in duration among all elements. It is interesting to note that increasing tonal magnitude has precisely the effect of increasing the tonic's and other hierarchically impor-

[8] In truth, this criticism is valid for any analysis of real music by the intervallic rivalry model, given the fact that composers obviously take advantage of the entire chromatic set in their compositions. How the intervallic rivalry theory addresses this problem is unclear. One possibility is that the diatonic set is in some way abstracted out of the actual musical surface. Of course, such a supposition leads to the question of how such an abstraction procedure occurs, with the most obvious solution being the abstraction out of those pitches that occur most frequently. This, of course, leads directly to the Krumhansl–Schmuckler key-finding algorithm (Krumhansl & Schmuckler, 1986a).

[9] Consistent with this idea are data regarding tone deviations in musically expressive performances (see Palmer, 1997, for a review). One finding in this work is the occurrence of decreased tempo at phrase endings. Because phrase endings contain a high proportion of hierarchically important notes, such changes in tempo would selectively increase durations of tonally important pitches and thus increase the tonal magnitude of the music.

tant pitches' contributions to the variance in duration among all pitches.

In sum, the current experiments set out to investigate how two fundamental processes—the differentiation of elements in an array and the organization of these elements into a recognizable hierarchy—function in the perception of musical materials. Toward this goal, music has provided an excellent arena for investigating these basic processes, affording insights into the operation of both processes. Such insights have the potential to cut across individual domains of study within a modality (e.g., music and speech in audition) and even across modalities themselves (e.g., differentiation in audition vs. vision). Further work on the topic will, it is hoped, shed more light on such basic aspects of perceptual organization.

References

Bharucha, J. J. (1987). Music cognition and perceptual facilitation: A connectionist framework. *Music Perception, 5,* 1–30.

Bharucha, J. J., & Krumhansl, C. L. (1983). The representation of harmonic structure in music: Hierarchies of stability as a function of context. *Cognition, 13,* 63–102.

Bharucha, J. J., & Stoeckig, K. (1986). Reaction time and musical expectancy: Priming of chords. *Journal of Experimental Psychology: Human Perception and Performance, 12,* 403–410.

Bharucha, J. J., & Stoeckig, K. (1987). Priming of chords: Spreading activation or overlapping frequency spectra. *Perception & Psychophysics, 41,* 519–524.

Bregman, A. S. (1990). *Auditory scene analysis.* Cambridge, MA: MIT Press.

Bregman, A. S., & Campbell, J. (1971). Primary auditory stream segregation and perception of order in rapid sequences of tones. *Journal of Experimental Psychology, 89,* 244–249.

Bregman, A. S., & Dannenbring, G. (1973). The effect of continuity on auditory stream segregation. *Perception & Psychophysics, 13,* 308–312.

Brown, H. (1988). The interplay of set content and temporal context in a functional theory of tonality perception. *Music Perception, 5,* 219–250.

Brown, H., & Butler, D. (1981). Diatonic trichords as minimal tonal cue-cells. *In Theory Only, 5,* 37–55.

Browne, R. (1981). Tonal implications of the diatonic set. *In Theory Only, 5,* 3–21.

Butler, D. (1989). Describing the perception of tonality in music: A critique of the tonal hierarchy theory and a proposal for a theory of intervallic rivalry. *Music Perception, 6,* 219–242.

Butler, D. (1990). Response to Carol Krumhansl. *Music Perception, 7,* 325–338.

Castellano, M. A., Bharucha, J. J., & Krumhansl, C. L. (1984). Tonal hierarchies in the music of North India. *Journal of Experimental Psychology: General, 113,* 394–412.

Coady, L. (1992). *Perception of tonality as a function of note duration in novel melodic sequences.* Unpublished honors thesis, Queen's University, Kingston, Ontario, Canada.

Croonen, W. L. M. (1994). Effects of length, tonal structure, and contour in the recognition of tone series. *Perception & Psychophysics, 55,* 623–632.

Croonen, W. L. M. (1995). Two ways of defining tonal strength and implications for recognition of tone series. *Music Perception, 13,* 109–119.

Cuddy, L. L. (1991). Melodic patterns and tonal structure: Converging evidence. *Psychomusicology, 10,* 107–126.

Cuddy, L. L. (1993). Melody comprehension and tonal structure. In T. J. Tighe & W. J. Dowling (Eds.), *Psychology and music: The understanding of melody and rhythm* (pp. 19–38). Hillsdale, NJ: Erlbaum.

Cuddy, L. L., & Badertscher, B. (1987). Recovery of the tonal hierarchy: Some comparisons across age and levels of musical experience. *Perception & Psychophysics, 41,* 609–620.

Cuddy, L. L., Cohen, A. J., & Mewhort, D. J. K. (1981). Perception of structure in short melodic sequences. *Journal of Experimental Psychology: Human Perception and Performance, 7,* 869–883.

Cuddy, L. L., Cohen, A. J., & Miller, J. (1979). Melody recognition: The experimental application of musical rules. *Canadian Journal of Psychology, 33,* 148–157.

Cuddy, L. L., & Lyons, H. I. (1981). Musical pattern recognition: A comparison of listening to and studying tonal structures and tonal ambiguities. *Psychomusicology, 1,* 15–33.

Cuddy, L. L., & Smith, N. A. (2000). Perception of tonal pitch space and tonal tension. In D. Greer (Ed.), *Musicology and sister disciplines* (pp. 47–59). Oxford, England: Oxford University Press.

Deutsch, D. (1982). Internal representation of information in the form of hierarchies. *Perception & Psychophysics, 31,* 596–598.

Deutsch, D., & Feroe, J. (1981). The internal representation of pitch sequences in tonal music. *Psychological Review, 88,* 503–522.

Dowling, W. J. (1978). Scale and contour: Two components of a theory of memory for melodies. *Psychological Review, 76,* 300–307.

Dowling, W. J. (1991). Tonal strength and melody recognition after long and short delays. *Perception & Psychophysics, 50,* 305–313.

Garner, W. R. (1974). *The processing of information and structure.* New York: Wiley.

Gibson, J. J. (1979). *The ecological approach to visual perception.* Boston: Houghton Mifflin.

Hébert, S., Peretz, I., & Gagnon, L. (1995). Perceiving the tonal ending of tune excerpts: The roles of pre-existing representation and musical expertise. *Canadian Journal of Experimental Psychology, 49,* 193–209.

Holtzman, S. R. (1977). A program for key determination. *Interface, 6,* 29–56.

Huron, D., & Parncutt, R. (1993). An improved model of tonality perception incorporating pitch salience and echoic memory. *Psychomusicology, 12,* 154–171.

Janata, P., & Reisberg, D. (1988). Response-time measures as a means of exploring tonal hierarchies. *Music Perception, 6,* 161–172.

Jones, M. R. (1978). Auditory patterns: Studies in the perception of structure. In E. C. Carterette & M. P. Friedman (Eds.), *Handbook of perception, Vol. 8: Perceptual coding* (pp. 255–288). New York: Academic Press.

Jones, M. R. (1981). A tutorial on some issues and methods in serial pattern research. *Perception & Psychophysics, 30,* 492–504.

Justus, T. C., & Bharucha, J. J. (2002). Music perception and cognition. In H. Pashler (Series Ed.) & S. Yantis (Vol. Ed.), *Stevens' handbook of experimental psychology, Vol. 1: Sensation and perception* (3rd ed., pp. 453–492). New York: Wiley.

Kessler, E. J., Hansen, C., & Shepard, R. N. (1984). Tonal schemata in the perception of music in Bali and in the West. *Music Perception, 2,* 131–165.

Kidd, G. R. (1995). Proportional duration and proportional variance as factors in auditory pattern discrimination. *Journal of the Acoustical Society of America, 97,* 1335–1338.

Kidd, G. R., & Watson, C. S. (1992). The "proportion-of-the-total-duration rule" for the discrimination of auditory patterns. *Journal of the Acoustical Society of America, 92,* 3109–3118.

Koffka, K. (1935). *Principles of Gestalt psychology.* New York: Harcourt Brace.

Krumhansl, C. L. (1979). The psychological representation of musical pitch in a tonal context. *Cognitive Psychology, 11,* 346–374.

Krumhansl, C. L. (1990a). *Cognitive foundations of musical pitch.* New York: Oxford University Press.
Krumhansl, C. L. (1990b). Tonal hierarchies and rare intervals in music cognition. *Music Perception, 7,* 309–324.
Krumhansl, C. L. (1991). Music psychology: Tonal structures in perception and memory. *Annual Review of Psychology, 42,* 277–303.
Krumhansl, C. L. (2000). Tonality induction: A statistical approach applied cross-culturally. *Music Perception, 17,* 461–479.
Krumhansl, C. L., Bharucha, J. J., & Castellano, M. A. (1982). Key distance effects on perceived harmonic structure in music. *Perception & Psychophysics, 32,* 96–108.
Krumhansl, C. L., Bharucha, J. J., & Kessler, E. J. (1982). Perceived harmonic structure of chords in three related musical keys. *Journal of Experimental Psychology: Human Perception and Performance, 8,* 24–36.
Krumhansl, C. L., & Kessler, E. J. (1982). Tracing the dynamic changes in perceived tonal organization in a spatial representation of musical keys. *Psychological Review, 89,* 334–368.
Krumhansl, C. L., Sandell, G. J., & Sargeant, D. C. (1987). The perception of tone hierarchies and mirror forms in twelve-tone serial music. *Music Perception, 5,* 31–78.
Krumhansl, C. L., & Schmuckler, M. A. (1986a, August). *Key-finding in music: An algorithm based on pattern matching to tonal hierarchies.* Paper presented at the 19th Annual Meeting of the Society for Mathematical Psychology, Cambridge, MA.
Krumhansl, C. L., & Schmuckler, M. A. (1986b). The *Petroushka* chord: A perceptual investigation. *Music Perception, 4,* 153–184.
Krumhansl, C. L., & Shepard, R. N. (1979). Quantification of the hierarchy of tonal functions within a diatonic context. *Journal of Experimental Psychology: Human Perception and Performance, 5,* 579–594.
Kubovy, M., & Pomerantz, J. R. (Eds). (1981). *Perceptual organization.* Hillsdale, NJ: Erlbaum.
Lantz, M. E. (2002). *The role of duration and frequency of occurrence in perceived pitch structure.* Unpublished doctoral dissertation, Queen's University, Kingston, Ontario, Canada.
Lantz, M. E., & Cuddy, L. L. (1996, August). *The effects of surface cues in the perception of pitch structure: Frequency of occurrence and duration.* Paper presented at Fourth International Conference on Music Perception and Cognition, Montreal, Quebec, Canada.
Lantz, M. E., & Cuddy, L. L. (1998). Total and relative duration as cues to surface structure in music. *Canadian Acoustics, 26*(3), 56–57.
Leman, M. (1995). A model of retroactive tone-center perception. *Music Perception, 12,* 430–471.
Lerdahl, F., & Jackendoff, R. (1983). *A generative theory of tonal music.* Cambridge, MA: MIT Press.
Lockhead, G. R., & Pomerantz, J. R. (1991). *The perception of structure.* Washington, DC: American Psychological Association.
Longuet-Higgins, H. C., & Steedman, M. J. (1971). On interpreting Bach. *Machine Intelligence, 6,* 221–241.
Lutfi, R. A. (1993). A model of auditory pattern analysis based on component-relative-entropy. *Journal of the Acoustical Society of America, 94,* 748–758.
Martin, J. (1972). Rhythmic (hierarchical) versus serial structure in speech and other behavior. *Psychological Review, 79,* 487–509.
McAdams, S., & Bregman, A. S. (1979). Hearing musical streams. *Computer Music Journal, 3*(4), 26–43.
Oram, N., & Cuddy, L. L. (1995). Responsiveness of Western adults to pitch-distributional information in melodic sequences. *Psychological Research/Psychologische Forschung, 57,* 103–118.
Palmer, C. (1997). Music performance. *Annual Review of Psychology, 48,* 115–138.
Patterson, R. D., Peters, R. W., & Milroy, R. (1983). Threshold duration for melodic pitch. In W. Klinke & W. M. Hartmann (Eds.), *Hearing: Physiological bases and psychophysics* (pp. 321–325). Berlin, Germany: Springer-Verlag.
Povel, D. (1981). Internal representations of simple temporal patterns. *Journal of Experimental Psychology: Human Perception and Performance, 7,* 3–18.
Povel, D., & Essens, P. (1985). The perception of temporal patterns. *Music Perception, 2,* 411–440.
Rasch, R., & Plomp, R. (1999). The perception of musical tones. In D. Deutsch (Ed.), *The psychology of music* (2nd ed., pp. 89–112). San Diego, CA: Academic Press.
Restle, F. (1970). Theory of serial pattern learning: Structural trees. *Psychological Review, 77,* 481–495.
Robinson, K., & Patterson, R. D. (1995). The duration required to identify the instrument, the octave, or the pitch chroma of a musical note. *Music Perception, 13,* 1–15.
Rosch, E. (1975). Cognitive reference points. *Cognitive Psychology, 7,* 532–547.
Schmuckler, M. A. (1989). Expectation in music: Investigation of melodic and harmonic processes. *Music Perception, 7,* 109–150.
Schmuckler, M. A. (1997). Expectancy effects in memory for melodies. *Canadian Journal of Experimental Psychology, 51,* 292–305.
Schmuckler, M. A. (1999). Testing models of melodic contour similarity. *Music Perception, 16,* 295–326.
Schmuckler, M. A., & Boltz, M. G. (1994). Harmonic and rhythmic influences on musical expectancy. *Perception & Psychophysics, 56,* 313–325.
Schmuckler, M. A., & Gilden, D. L. (1993). Auditory perception of fractal contours. *Journal of Experimental Psychology: Human Perception and Performance, 19,* 641–660.
Schmuckler, M. A., & Tomovski, R. (1997, November). *Perceptual tests of musical key-finding.* Paper presented at the 38th Annual Meeting of the Psychonomic Society, Dallas, TX.
Schmuckler, M. A., & Tomovski, R. (2000, November). *Tonal hierarchies and intervallic rivalries in musical key-finding.* Paper presented at the Society for Music Perception and Cognition, Toronto, Ontario, Canada.
Shmulevich, I., & Yli-Harja, O. (2000). Localized key-finding: Algorithms and applications. *Music Perception, 17,* 531–544.
Simon, H. A., & Kotovsky, K. (1963). Human acquisition of concepts for sequential patterns. *Psychological Review, 70,* 534–546.
Simon, H. A., & Sumner, R. K. (1968). Pattern in music. In B. Kleinmuntz (Ed.), *Formal representation of human judgement* (pp. 219–250). New York: Wiley.
Smith, N. A., & Cuddy, L. L. (2003). Perceptions of musical dimensions in Beethoven's *Waldstein* sonata: An application of tonal pitch space theory. *Musicae Scientiae, 7,* 7–34.
Stevens, S. S., & Volkman, J. (1940). The relation of pitch to frequency: A revised scale. *American Journal of Psychology, 53,* 329–353.
Stevens, S. S., Volkman, J., & Newman, E. B. (1937). A scale for the measurement of the psychological magnitude of pitch. *Journal of the Acoustical Society of America, 8,* 185–190.
Sundberg, J., Askenfelt, A., & Frydén, L. (1983). Musical performance: A synthesis-by-rule approach. *Computer Music Journal, 7*(1), 37–43.
Sundberg, J., Frydén, L., & Askenfelt, A. (1983). What tells you the player is musical? An analysis-by-synthesis study of musical performance. In J. Sundberg (Ed.). *Studies of musical performance* (pp. 61–75). Stockholm: Royal Swedish Academy of Music.
Takeuchi, A. H. (1994). Maximum key-profile correlation (MKC) as a measure of tonal structure in music. *Perception & Psychophysics, 56,* 335–346.
Thompson, W. F., Sundberg, J., Friberg, A., & Frydén, L. (1989). The use of rules for expression in the performance of melodies. *Psychology of Music, 17,* 63–82.

Van Egmond, R., & Butler, D. (1997). Diatonic connotations of pitch-class sets. *Music Perception, 15,* 1–29.
Van Noorden, L. P. A. (1975). *Temporal coherence in the perception of tone sequences.* Unpublished doctoral dissertation, Technische Hogeschool Eindhoven, Eindhoven, the Netherlands.
Vitz, P. C., & Todd, T. C. (1969). A coded element model of the perceptual processing of sequential stimuli. *Psychological Review, 76,* 433–449.
Vos, P. G., & Van Geenen, E. W. (1996). A parallel-processing key-finding model. *Music Perception, 14,* 185–224.
Ward, W. D. (1954). Subjective musical pitch. *Journal of the Acoustical Society of America, 26,* 369–380.
West, R. J., & Fryer, R. (1990). Ratings of the suitability of probe tones as tonics after random orderings of the diatonic scale. *Music Perception, 7,* 253–258.
Winograd, T. (1968). Linguistics and the computer analysis of tonal harmony. *Journal of Music Theory, 12,* 2–49.

Appendix A

Tone Durations (in Milliseconds) for Each Pitch at Each Tonal Magnitude in the Hierarchical Condition of Experiment 1

	Tonal magnitude									
Pitch	0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5
C	417	571	760	979	1,224	1,486	1,757	2,027	2,291	2,542
C#/D♭	417	339	267	204	151	109	76	52	35	23
D	417	423	416	397	368	330	289	247	207	170
D#/E♭	417	346	279	218	165	121	87	61	42	28
E	417	474	524	561	582	587	577	553	519	478
F	417	458	489	506	508	495	469	435	394	351
F#/G♭	417	360	302	245	193	147	110	80	57	40
G	417	516	621	724	818	898	959	1,001	1,022	1,026
G#/A♭	417	350	286	226	173	129	94	66	46	31
A	417	434	438	429	407	375	336	295	253	213
A#/B♭	417	343	274	212	159	116	82	57	39	26
B	417	385	345	299	252	206	164	127	97	72

(*Appendixes continue*)

Appendix B

Frequencies of Occurrence and Individual Tone Durations (in Milliseconds) for Each Pitch at Each Tonal Magnitude in Experiment 2

	Tonal magnitude				
Pitch	0.5	1.0	1.5	2.0	2.5
			Frequency of occurrence		
C	11	15	20	24	30
C#/D♭	7	5	4	3	2
D	8	8	8	7	7
D#/E♭	7	6	4	3	2
E	9	10	11	12	12
F	9	10	10	10	10
F#/G♭	7	6	5	4	3
G	10	12	14	16	18
G#/A♭	7	6	5	3	3
A	9	9	9	8	7
A#/B♭	7	5	4	3	2
B	8	7	6	5	4
Total	99	99	100	98	100
			Duration (controlled)		
C	76	56	42	35	28
C#/D♭	119	167	208	278	417
D	104	104	104	119	119
D#/E♭	119	139	208	278	417
E	93	83	76	69	69
F	93	83	83	83	83
F#/G♭	119	139	167	208	278
G	83	69	60	52	46
G#/A♭	119	139	167	278	278
A	93	93	93	104	119
A#/B♭	119	167	208	278	417
B	104	119	139	167	208
			Duration (uncontrolled)		
C–B	100	100	100	100	100

Appendix C

Tone Durations (in Milliseconds) for the Tonic and Nontonic Pitch at Each Tonal Magnitude for the Binary Melodies in Experiment 3

	Tonal magnitude									
Pitch	0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5
Tonic	417	571	760	979	1,224	1,489	1,757	2,027	2,291	2,542
Nontonic	417	403	386	366	343	319	295	270	246	223

Received July 9, 2002
Revision received March 18, 2003
Accepted August 14, 2003 ■