A biological basis for musical tonality

12

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Contents

Abstract

Like other sensory qualities, the human ability to perceive tonal sound stimuli has presumably evolved because of its utility. Although a variety of tonal sounds are present in the human auditory environment, the vocalizations of other humans are the most biologically relevant and the most frequently experienced. It is thus reasonable to assume that our appreciation of tonal sounds has arisen primarily for the benefits that accrue from this conspecific information. It follows that the structure and function of the tonal sounds produced by the human vocal apparatus may provide the key to understanding how and why we perceive tonality in music the way that we do. Here we consider recent evidence that bears on this idea.

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1. Introduction

Tones are periodic sound stimuli perceived as having a pitch. In nature, such stimuli are produced by objects that resonate at frequencies humans can hear when acted on by a force, most commonly by animal species that generate such sounds for social communication (e. g., the sounds of stridulating insects, the vibrations produced by the songbird syrinx, and the vocalizations of many mammals). Although many such stimuli are present in the human auditory environment, the vocalizations of other humans are the most biologically relevant and frequently experienced (Ter-

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hardt 1984; Schwartz et al. 2003; Gill and Purves 2009). The prevalence and importance of vocal stimuli suggests that an appreciation of tonal sounds in music is linked to human vocalizations.

The merits of understanding musical tonality based on vocalization depend on explaining why we hear musical tones the way we do. To date, this framework has been successfully applied to a variety of phenomena including perception of the missing fundamental (Terhardt 1974; Schwartz and Purves 2004), the fundamental root of musical chords (Terhardt 1984), pitch shift of the residue, spectral dominance and pitch strength (Schwartz and Purves 2004), musical interval preferences (Schwartz et al. 2003; Ross et al. 2007), and scale preferences (Gill and Purves 2009). The work described here focuses on this framework as a way to explain the characteristic affective impact of major and minor music (Bowling et al. 2010).

2. The emotional effects of major and minor music

The affective impact of music depends on many factors including, but not limited to, intensity, tempo, rhythm and the tonal intervals used. For most of these factors the way emotion is conveyed seems intuitively clear. If, for instance, a composer wants to imbue a composition with excitement, the intensity tends to be forte, the tempo fast and the rhythm syncopated. Conversely, if a more subdued effect is desired, the intensity is typically piano, the tempo slower, and the rhythm more balanced (Cohen 1971; Bernstein 1976; Juslin and Laukka 2003). These effects on the listener presumably occur because in each case the characteristics of the music accord with the ways that the corresponding emotional state is expressed in human behavior. The reason for the different emotional impact of the tones used in music, however, is not clear.

Much music worldwide employs subsets of the chromatic scale, which divides each octave into 12 intervals defined by the frequency ratios shown in Fig.1A. In Western music over the last few centuries the most commonly used subsets are the diatonic scales in Fig.1B, the Ionian and the Aeolian scales in particular (Pierce 1962; Bernstein 1976; Randel 1986; Burns 1999; Burkholder et al. 2006). These two scales are usually referred to simply as the major and the minor scale, respectively (Fig.1C) (Aldwell and Schachter 2003). Other things being equal, music using the intervals of the major scale tends to be perceived as relatively excited, happy, bright or martial, whereas music using minor scale intervals tends to be perceived as more subdued, sad, dark or wistful (Zarlino 1558; Hevner 1935; Cooke 1959; Crowder 1984; Krumhansl 1990; Gregory et al. 1996; Peretz et al. 1998; Burkholder et al. 2006). There has been no agreement, however, about how and why these scales and the intervals that differentiate them elicit distinct emotional effects (Heinlein 1928; Hevner 1935; Crowder 1984).

3. Major vs. minor music compared to speech

Given the roots of the human tonal sense (see Introduction), an attractive hypothesis is that musical tones take on their affective qualities by mimicry of emotions expressed vocally. This general idea is supported by several observations. First, voiced speech sounds are harmonic, and has often been

A Chromatic Scale

Interval Name	Number of Semitones	Frequency Ratio
Unison (Uni)	0	1 : 1
Minor Second (m2)	1	16 : 15
Major Second (M2)	2	9 : 8
Minor Third (m3)	3	6 : 5
Major Third (M3)	4	5 : 4
Perfect Fourth (P4)	5	4 : 3
Tritone (tt)	6	7 : 5
Perfect Fifth (P5)	7	3 : 2
Minor Sixth (m6)	8	8 : 5
Major Sixth (M6)	9	5 : 3
Minor Seventh (m7)	10	9 : 5
Major Seventh (M7)	11	15 : 8
Octave (Oct)	12	2 : 1

B Diatonic Scales

Ionian	Dorian	Phrygian	Lydian	Mixolydian	Aeolian	Locrian
M2	M2	m2	M2	M2	M2	m2
M3	m3	m3	M3	M3	M3	m3
P4	P4	P4	tt	P4	P4	P4
P5	P5	P5	P5	P5	P5	tt
M6	M6	m6	M6	M6	M6	m6
M7	m7	m7	M7	m7	M7	m7
Oct	Oct	Oct	Oct	Oct	Oct	Oct
"MAJOR"					"MINOR"	

C Keyboard examples

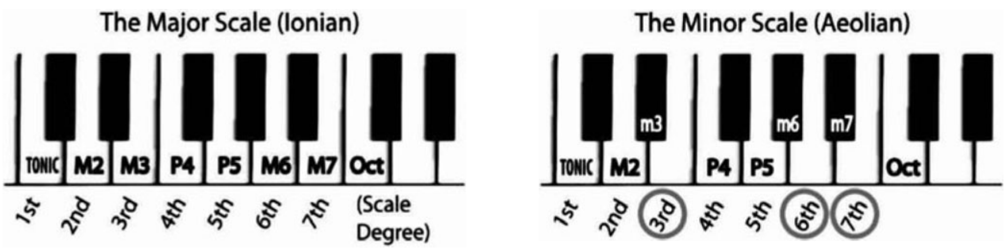

Fig. 1 Musical scales. **A** The 12 intervals of the chromatic scale showing the abbreviations used, the corresponding number of semitones, and the ratio of the fundamental frequency of the upper tone to the fundamental frequency of the lower tone in just intonation tuning. **B** The seven diatonic scales. As a result of their relative popularity, the Ionian and the Aeolian are referred to today as the major and minor scale, respectively. **C** Examples of a major and a minor scale on a piano keyboard; the circled intervals indicate the differences between the two

pointed out ratios between overtones in harmonic series correspond to the ratios that define musical intervals (Helmholtz 1885; Bernstein 1976; Rossing 1990; Crystal 1997; Schwartz et al. 2003; Ross et al. 2007; Gill and Purves 2009). Second, the physiological differences between affective states alter the spectral content of voiced speech (Spencer 1857; Juslin and Laukka 2003; Scherer 2003). Third, humans routinely extract important information about the emotional state of a speaker from vocal qualities (Johnstone and Scherer 2000; Scherer et al. 2001; Juslin and Laukka 2003). And fourth, as already mentioned, other aspects of music appear to convey emotion through mimicry of human behaviors that signify emotional state. It is therefore logical to ask whether spectral differences that specifically distinguish major and minor melodies parallel spectral differences that distinguish speech uttered in different affective states.

3.1 Empirical differences between major and minor music

In music theory, major and minor scales (see Fig.1C) differ at the third, sixth, and seventh scale degrees. In each case, the major scale is characterized by a major interval (a whole tone) whereas the minor scale is characterized a minor interval (a semitone). To determine the way these intervals actually distinguish major and minor music, we analyzed more than 4000 major melodies and 3000 minor melodies drawn from databases of monophonic Western classical and folk music (Barlow and Morgenstern 1974; Eerola and Tovianien 2004). The prevalence of intervals in the melodies was assessed with respect to the annotated tonic of the melody (tonic intervals), as well as with respect to immediately following melody notes (melodic intervals). The results of these analyses are shown in Table I.

As expected, the most salient empirical distinction between major and minor music is

Table 1

(A) Tonic Intervals

Major Melodies			Minor Melodies		
Intervals	Classical (%)	Folk (%)	Intervals	Classical (%)	Folk (%)
Unison/Octave	19.9	20.4	Unison/Octave	19.4	19.1
Minor Second	0.4	0.1	Minor Second	0.6	0.2
Major Second	12.8	15.9	Major Second	13	19.6
Minor Third	0.8	0.0	Minor Third	15.8	15.6
Major Third	18.2	16.8	Major Third	0.7	0.2
Perfect Fourth	10.6	9.5	Perfect Fourth	10.5	10.1
Tritone	1.1	0.4	Tritone	1.7	0.2
Perfect Fifth	19.1	19.6	Perfect Fifth	20.3	19.9
Minor Sixth	0.4	0.0	Minor Sixth	7.9	1.6
Major Sixth	8.4	8.9	Major Sixth	1.3	2.9
Minor Seventh	0.6	0.2	Minor Seventh	3.4	7.5
Major Seventh	7.7	8.1	Major Seventh	5.4	3.1

(B) Melodic Intervals

Major Melodies			Minor Melodies		
Intervals	Classical (%)	Folk (%)	Intervals	Classical (%)	Folk (%)
Unison	10.7	24.9	Unison	11.4	24
Minor Second	20.8	13.3	Minor Second	28.2	19.1
Major Second	36.1	29.9	Major Second	27.6	27.6
Minor Third	9.4	11.6	Minor Third	10.4	12.1
Major Third	6.9	8.6	Major Third	5.4	6.2
Perfect Fourth	7.6	7.4	Perfect Fourth	7.2	7.1
Tritone	0.4	0.2	Tritone	1.1	0
Perfect Fifth	2.7	2	Perfect Fifth	3.2	2.5
Minor Sixth	1.1	0.6	Minor Sixth	1.8	0.8
Major Sixth	1.3	0.9	Major Sixth	1.2	0.1
Minor Seventh	0.4	0.3	Minor Seventh	0.4	0.1
Major Seventh	0.1	0	Major Seventh	0.2	0
Octave	1.3	0.3	Octave	1.2	0.2
Larger	1	0	Larger	0.9	0

Frequency of occurrence of chromatic intervals in major and minor Western classical and folk music. A Tonic intervals, defined as the number of semitones between a melody note and its tonic.
B Melodic intervals, defined as the number of semitones between adjacent melody notes. The intervals that strongly distinguish major and minor music are highlighted in grey

the third scale degree. In both the classical and folk music, major thirds made up 16–18% of the intervals in major melodies and less than 1% of the intervals in minor melodies; this pattern was reversed for minor thirds, which comprised less than 1% of the intervals in major melodies and about 15% of the intervals in minor melodies. Tonic intervals of the sixth and seventh scale degrees also distinguish major and minor music, but less robustly. These intervals are only about half as prevalent in music as thirds, and their distribution in major versus minor music is less differentiated. With respect to melodic intervals, the only salient distinction between major and minor melodies is the prevalence of major versus minor seconds, major music being characterized by an increased prevalence of major seconds and minor music by an increased prevalence of minor seconds.

In short, the prevalence of major vs. minor thirds is the primary empirical distinction between major and minor music.

3.2 Comparison of music and speech spectra

To address the question of whether these empirical differences between major and minor music parallel the characteristics of vocalizations in corresponding emotional states, we compared the spectra of major and minor thirds, sixths, and sevenths with the spectra of speech uttered in a subdued or excited manner. Spectral comparisons were based on fundamental frequency and frequency ratios, two critical acoustic features in the perception of both voiced speech sounds and musical intervals. In speech, fundamental frequency carries information about the sex, age, and emotional state of a speaker (Hollien 1960; Crystal 1997; Protopapas and Lieberman 1996; Banse and Scherer 1996; Harrington et al. 2007). Frequency ratios between the first and second formants (F1, F2) differentiate particular vowel sounds, allowing them to be understood across speakers with anatomically different vocal tracts (Delattre 1952; Pickett et al. 1957; Peterson and Barney 1962; Crystal 1997; Hillenbrand et al. 1995). In music, the fundamental frequencies of tones carry the melody. The frequency ratios between notes define the intervals and provide the context that determines whether the composition is in a major or minor key.

Figure 2 shows the distributions of fundamental frequencies for ten speakers uttering speech in an excited (red) versus a subdued (blue) manner. As expected from previous studies on vocal emotion (Banse and Scherer 1996; Juslin and Laukka 2003; Scherer 2003; Hammerschmidt and Jurgens 2007), the fundamental frequencies of excited speech are significantly higher than those of subdued speech.

Musical intervals are defined by the fundamental frequency ratio between two notes. Thus a single fundamental cannot be identified in the same way as for a voiced speech sound; instead, the two notes must be considered together. The combined harmonics of any two notes comprise a subset of a single harmonic series with a fundamental given by their greatest common divisor (the implied fundamental). Figure 3 illustrates the distributions of these implied fundamental frequencies in major versus minor compositions. Comparison of Figs. 2 and 3 shows that the implied fundamentals of tonic thirds and sixths parallel the differences in the fundamental frequencies of excited and subdued speech.

The ratio of the peak harmonic frequencies in the first two formants (F1 and F2) in excited and subdued speech with the frequency ratios of the intervals that specifically distinguish major and minor music can also be compared. This analysis focused on F1 and F2 because they are the most powerful resonances of the vocal tract, and because they are necessary and sufficient for the dis-

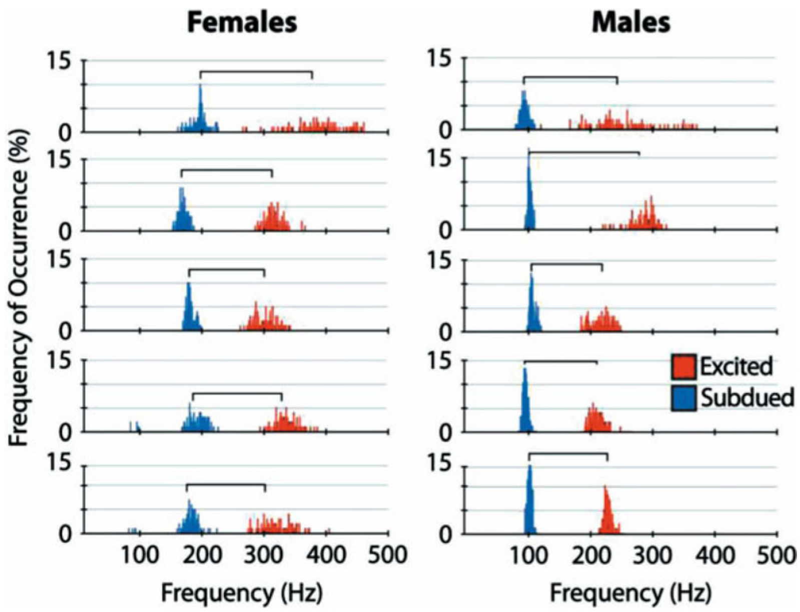

Fig. 2 The fundamental frequency distributions of excited (red) and subdued (blue) speech for 5 female and 5 male speakers derived from single word utterances; brackets indicate means. Participants were instructed to utter the words as if they were excited and happy, or conversely as if they were subdued and sad. The difference between the mean fundamentals of the excited and subdued distributions across speakers is highly significant ($p < 0.0001$ in dependent t-tests for paired samples)

crimination of vowel sounds (Delattre 1952; Pickett et al. 1957; Rosner and Pickering 1994). The distributions of F2/F1 ratios in excited and subdued speech spectra are shown in Fig. 4. In excited speech, ~36% of formant ratios correspond to major thirds, sixths and sevenths, whereas ratios corresponding to minor thirds, sixths and sevenths were entirely absent. In contrast, in subdued speech only ~20% of the formant ratios corresponded to major thirds, sixths and sevenths, whereas ~10% of the ratios corresponded to minor thirds, sixths and sevenths. These parallel differences between the occurrence of formant ratios in excited and subdued speech and the ratios of the musical intervals that distinguish major and minor melodies provide a further basis for associating the spectra of speech in different emotional states with the spectra of intervals that distinguish major and minor music.

4. Discussion

The primary tonal distinction between excited and subdued speech is the fundamental frequency of a speaker's voice; when a speaker is excited the generally increased tension of the vocal folds raises the fundamental frequency; conversely when a speaker is subdued, decreased tension lowers the fundamental frequency (see Fig. 2). In music two factors determine the frequency of a musical interval's implied fundamental: 1) the ratio that defines the interval; and 2) the pitch height at which the interval is played. The defining ratios of minor thirds and sixths (6:5 and 8:5 respectively) yield smaller greatest common divisors than the defining ratios of major thirds and sixths (5:4 and 5:3); thus minor thirds and sixths played at

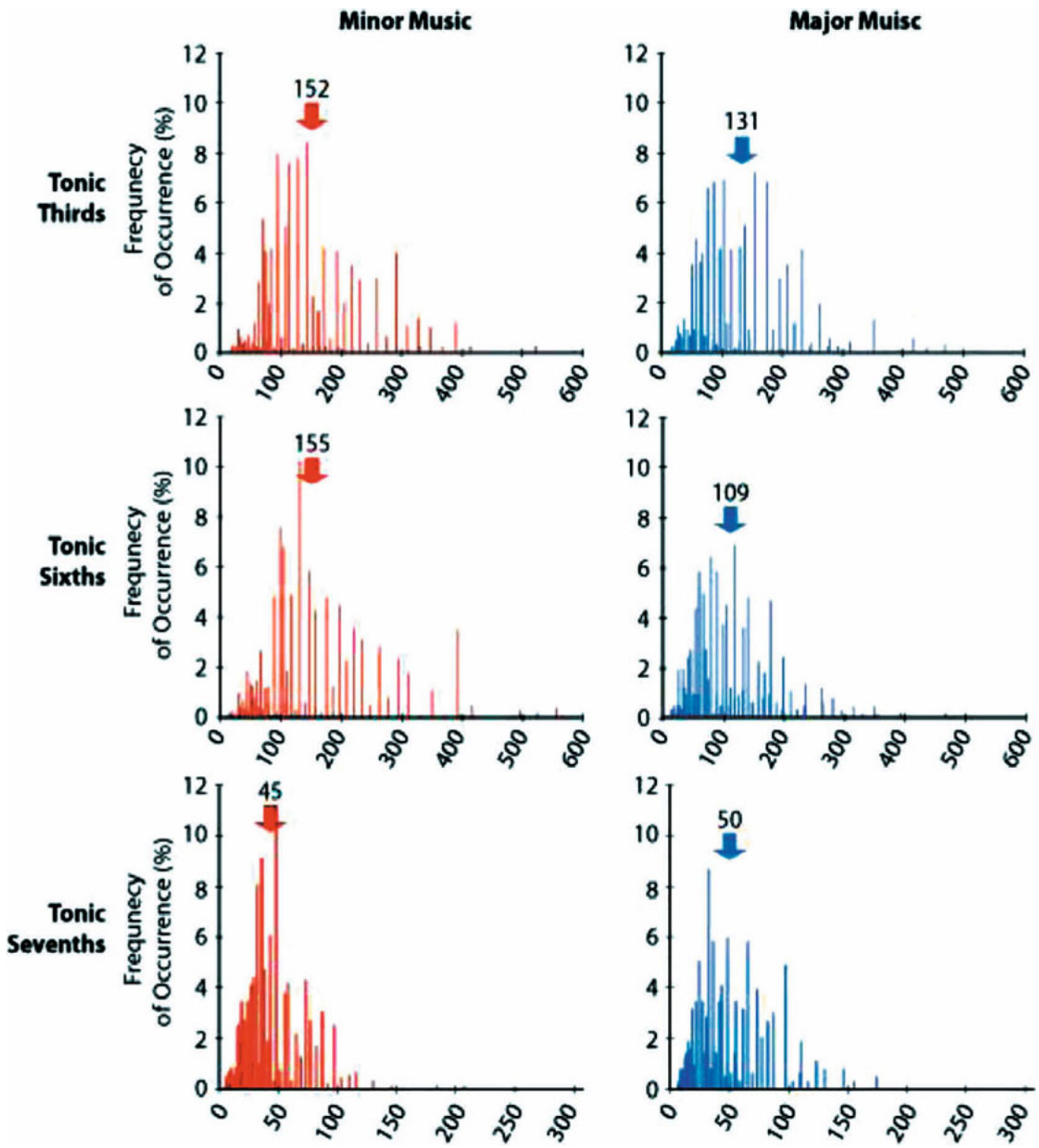

Fig. 3 The implied fundamental frequencies of tonic thirds, sixths, sevenths in major and minor melodies from Western classical music (folk music shows the same trends). Arrows indicate the mean implied fundamental frequency values for each distribution. Differences between the distributions of implied fundamental frequencies for major and minor themes are highly significant for thirds and sixths ($p<0.0075$ or less in independent two-sample t-tests)

the same pitch height as their major counterparts will always have lower implied fundamentals. Although the average pitch height of minor melodies is slightly higher than that of major melodies (see Fig. 2), the mean implied fundamentals of tonic thirds and sixths in major music are higher than those in minor music.

In contrast to the defining ratios thirds and sixths, the defining ratio of the minor seventh (9:5) yields a larger greatest common divisor than the defining ratio of the

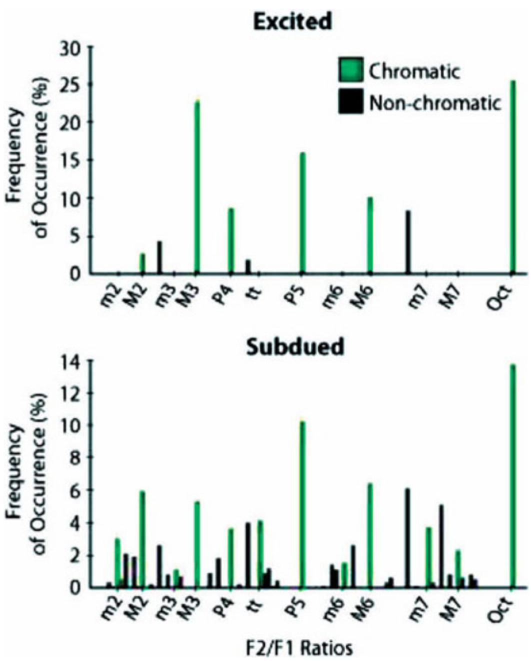

Fig. 4 Comparison of the ratios of the first two formants in excited and subdued speech derived from single word utterances. The F2/F1 ratios have been collapsed into a single octave such that they range from 1 to 2. The distribution of formant ratios in excited and subdued speech; green bars indicate ratios within 1% of chromatic interval ratios (see Table IA); gray bars indicate ratios that did not meet this criterion

major seventh (16:9), making its implied fundamental at a given pitch height higher than its major counterpart. This fact indicates why the pattern observed for tonic thirds and sixths is not apparent for tonic sevenths. Furthermore, nearly all of the implied fundamentals of tonic sevenths (~99%) fall below the range of the fundamentals in speech. These results accord with music theory. Unlike tonic thirds and sixths, tonic sevenths are not taken to play a significant role in distinguishing major and minor music (Aldwell and Schachter 2003). Rather these intervals are generally described as serving other purposes, such as creating a sense of tension that calls for resolution to the tonic (op cit.). As a result, major sevenths are commonplace in both major and minor music (see Table I).

The difference between the fundamental frequencies of excited and subdued speech also affects the prevalence of specific formant ratios. Given the same voiced speech sound, the positions of the first and second formants are relatively similar in excited and subdued speech, as they must be to allow vowel phonemes to be heard correctly. The higher fundamental frequencies of excited speech, however, increase the frequency distance between harmonics, causing lower harmonics to underlie the first and second formants. As a result the F2/F1 ratios in excited speech tend to comprise smaller numbers and thus more often represent musical intervals defined by smaller number ratios. Conversely, the lower fundamental frequencies in subdued speech decrease the distance between harmonics, causing higher harmonics to underlie the formants. Thus the F2/F1 ratios in subdued speech tend to comprise larger numbers, which more often represent musical intervals defined by larger number ratios. Intervals whose defining ratios contain only the numbers one through five (octaves, perfect fifths, perfect fourths, major thirds, and major sixths) are more prevalent in the F2/F1 ratios of excited speech, whereas intervals with defining ratios containing larger numbers (all other chromatic intervals) are more prevalent in the F2/F1 ratios of subdued speech (see Table IA and Fig. 4). In sum, the differences in the spectra of excited and subdued speech parallel differences in the spectra of major and minor music.

A final question is why the musical and emotional distinction between major and minor melodies depends primarily on tonic thirds, and how this fact aligns with the hypothesis that associations made between the spectral characteristics of music and speech are the basis for the affective impact of major versus minor music. One possibility is that among the intervals that differentiate major and minor tone collections thirds entail the lowest frequency and thus the most powerful harmonics. Accordingly, thirds are the most salient distinguishing intervals in the spectra of both voiced speech sounds and musical tones.

Conclusion

The results summarized here suggest that routine associations made between the spectra of speech uttered in different emotional states and the spectra of thirds and sixths in major and minor music are the basis for the different emotional effects of these different tone collections in music. These results support to the more general idea that tonality can be understood in terms of human vocalization. The implication of this and related work (see Introduction) is that musical aesthetics has a biological basis.

Glossary

Musical tone. A periodically repeating sound perceived as having a pitch.

Musical scale. A collection of tones that divide octaves (a doubling of frequency) into specific frequency intervals used to create music.

Scale degree. The number that specifies the position of a tone within a scale; the lowest note is the first scale degree, the second lowest tone is the second scale degree, etc.

Musical interval. The frequency relationship between two tones; specific musical intervals are defined by the ratios of their fundamental frequencies (see Fig.1A).

Major/Minor intervals. Musical intervals that differentiate major and minor scales, (see Fig.1). Major intervals are a semitone greater than the corresponding minor intervals.

Melody. An organized sequence of musical tones that expresses a musical theme or phrase.

Fundamental frequency. The lowest frequency of vibration in a harmonic series (e. g., the vibration of the full length of a plucked string).

Implied fundamental frequency. The frequency equal to the greatest common divisor of the fundamental frequencies of two or more musical tones.

References

Aldwell E, Schachter C (2003) Harmony & voice leading, 3rd edn. Wadsworth Group/Thomson Learning, Belmont, CA

Banse R, Scherer KR (1996) Acoustic profiles in vocal emotion expression. J Pers Soc Psychol 70: 614–636

Barlow H, Morgenstern S (1974) A dictionary of musical themes. Crown, New York, NY

Bernstein L (1976) The unanswered question: six talks at Harvard. Harvard University Press, Cambridge, MA

Bowling DL, Gill K, Choi JD, Prinz J, Purves D (2010) Major and minor music compared to excited and subdued speech. J Acoust Soc Am 127: in press

Burkholder JP, Grout D, Palisca C (2006) A history of Western music, 7th edn. Norton, New York, NY

Burns EM (1999) Intervals, scales and tuning. In: Deutsch D (ed) The psychology of music, 2nd edn. Academic Press, New York, NY

Cohen D (1971) Palestrina counterpoint: A musical expression of unexcited speech. J Music Theory 15: 85–111

Cooke D (1959) The language of music. Oxford University Press, Oxford, UK

Crowder RG (1984) Perception of the major/minor distinction: hedonic, musical, and affective discriminations. B Psychonomic Soc 23: 314–316

Crystal D (1997) The Cambridge encyclopedia of language, 2nd edn. Cambridge University Press, New York, NY

Delattre P, Liberman AM, Cooper FS, Gerstman LJ (1952) An experimental study of the acoustic determinants of vowel color: observation of one- and two-formant vowels synthesized from spectrographic patterns. Word 8: 195–210

Eerola T, Tovianien P (2004) Suomen Kasan eSävelmät (Finnish folk song database). Available from http://www. jyu.fi/musica/sks/ in November, 2008

Gill K, Purves D (2009) A biological rationale for musical scales. PLoS ONE 4, e8144.doi:101371/journal.pone.0008144

Gregory AH, Varney N (1996) Cross-cultural comparisons in the affective response to music. Psychol Music 24: 47–52

Hammerschmidt K, Jürgens U (2007) Acoustical correlates of affective prosody. J Voice 21: 531–540

Harrington J, Palethorpe S, Watson CI (2007) Age-related changes in fundamental frequency and formants: a longitudinal study of four speakers. In: Proceedings of Interspeech 2007, Antwerp

Heinlein CP (1928) The affective characters of the major and minor modes in music. J Comp Psychol 8: 101–142

Helmholtz H (1885) Lehre von den Tonempfindungen, 4th Edn., translated by Ellis AJ (1954) as: On the sensations of tone, 2nd edn. Dover, New York, NY

Hevner K (1935) The affective character of the major and minor modes in music. Am J Psychol 47: 103–118

Hillenbrand J, Getty LA, Clark MJ, Wheeler K (1995) Acoustic characteristics of American English vowels. J Acoust Soc Am 97: 3099–3111

Hollien H (1960) Some laryngeal correlates of vocal pitch. J Speech Hear Res 3: 52–58

Johnstone T, Scherer KR (2000) Vocal communication of emotion. In: Lewis M, and Haviland-Jones J M (eds) Handbook of Emotions, 2nd edn. Guilford, New York, NY

Juslin PN, Laukka P (2003) Communication of emotions in vocal expression and music performance: Different channels, same code? Psychol Bull 129: 770–814

Krumhansl CL (1979) The psychological representation of musical pitch in tonal context. Cognitive Psychol 11: 346–374

Krumhansl CL (1990) Cognitive foundations for musical pitch. Oxford University Press, New York, NY

Patel AD (2008) Music, language, and the brain. Oxford University Press, New York, NY

Peretz I, Gagnon L, Bouchard B (1998) Music and emotion: perceptual determinants, immediacy, and isolation after brain damage. Cognition 68: 111–141

Petersen GE, Barney HL (1962) Control methods used in a study of the vowels. J Acoust Soc Am 24: 175–184

Pickett JM (1957) Perception of vowels heard in noises of various spectra. J Acoust Soc Am 29: 613–620

Pierce JR (1962) The science of musical sound, revised edn. Freeman, New York, NY

Protopapas A, Lieberman P (1996) Fundamental frequency of phonation and perceived emotional stress. J Acoust Soc Am 101: 2267–2277

Randel DM (ed) (1986) The new Harvard dictionary of music, revised 2nd edn. Belknap Press, Cambridge, MA

Rosner BS, Pickering JB (1994) Vowel perception and production. Oxford University Press, New York, NY

Ross D, Choi J, Purves D (2007) Musical intervals in speech. Proc Natl Acad Sci 104(23): 9852–9857

Rossing TD (1990) The science of sound, 2nd edn. Addison-Wesley, New York, NY

Scherer KR (2003) Vocal communication of emotion: A review of research paradigms. Speech Commun 40: 227–256

Scherer KR, Banse R, Wallbott HG (2001) Emotional inferences from vocal expression correlate across languages and cultures. J Cross Cult Psychol 32: 76–92

Schwartz DA, Purves D (2004) Pitch is determined by naturally occurring periodic sounds. Hearing Res 194: 31–46

Schwartz DA, Howe CQ, Purves D (2003) The statistical structure of human speech sounds predicts musical universals. J Neurosci 23: 7160–7168

Spencer H (1857) The origin and function of music. Fraser's Magazine 56: 396–408

Terhardt E (1974) Pitch, consonance, and harmony. J Acoust Soc Am 55: 1061–1069

Terhardt E (1984) The concept of musical consonance: A link between music and psychoacoustics. Music Percept 1: 276–295

Zarlino G (1558) Bk. 3 of Le institutioni harmoniche, translated by Marco G, Palisca C (1968) as The Art of Counterpoint. Yale University Press, New Haven, CT