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# Spectral slope discrimination in infancy: Sensitivity to socially important timbres

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**Abstract**

Spectral slope, the linear component of the spectral envelope, affects sound quality or timbre, and is important for object identification, speech discrimination, voice recognition, and interpreting vocal expressions of emotion. Eight-month-old infants discriminated between tones with spectral slopes of −10 dB/octave and −4 dB/octave, but not between positive or highly negative spectral slopes. Thus, the infant auditory system is tuned to be most sensitive to spectral slope differences in the range of those commonly found in speech and music.



*Keywords:* Auditory; Infants; Timbre; Spectral slope; Discrimination

One important source of information about objects in the world is the sounds they emit. Sounds can be distinguished on the basis of pitch, duration, loudness, and sound quality or timbre. While pitch, loudness, and duration can be specified largely on the basis of a single physical dimension (i.e., frequency, sound pressure levels or intensity, and time, respectively), no single physical dimension fully characterizes timbre. In fact, timbre is defined negatively as "that aspect of auditory sensation by which a listener can judge two sounds that are equal in pitch, loudness and duration to be dissimilar".[1] For example, if the same note is played on a flute and a piano for the same length of time at the same loudness, timbre is what differs between them. From a social perspective, timbre is vitally important. Speech sounds or phonemes are distinguished largely on the basis of timbre, and we recognize different speakers by the quality of their voice. Furthermore, timbre plays a large role in the vocal expression of emotion,

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and adults can recognize emotions in speech across languages and cultures (Scherer, 1989; Frick, 1985; Murray & Arnott, 1993). In this paper, we ask whether the infant auditory system is tuned to process aspects of timbre that are important in speech and music perception.

Infants certainly process some aspects of timbre. They can recognize their mother's voice at 2 days of age (DeCasper & Fifer, 1980). They can distinguish speech sounds early in life (Kuhl, 1979). Speech directed to infants tends to be emotionally expressive (Fernald, 1991; Trainor, Austin, & Desjardins, 2000) and infants as young as 5 months of age respond differently to different emotional messages (Fernald, 1993; Rock, Trainor, & Addison, 1999; Walker-Andrews & Grolnick, 1983). It should be noted, of course, that in both voice and emotion recognition, changes in pitch and prosody may also serve as cues for discrimination. However, it is clear that at least as young as 7 months, infants can discriminate sounds differing only in timbre (Clarkson, Clifton, & Perris, 1988) and categorize speech-like sounds by timbre (Trehub, Endman, & Thorpe, 1990). Yet we understand little about the particular cues infants use for timbre discrimination.

Most sounds in the world are complex, that is, they are composed of several frequency components or harmonics. These components may differ in relative intensity or amplitude. The spectral envelope is defined as the curve that connects the points representing the amplitudes of the frequency components in a tonal complex (Moore, 1997). Studies using multidimensional scaling of adult perceptions of steady-state complex stimuli, based on pairwise timbre similarity judgements, show that perceived differences in the timbre of steady-state sounds depend largely on characteristics of the spectral envelope (Wedin & Goude, 1972; deBruijn, 1978).

By manipulating the relative intensities of the harmonics (frequency components) that make up a stimulus, the shape of the spectral envelope can be changed, while keeping the frequencies of the harmonics (and therefore to first approximation, the pitch) the same. In other words, the relative intensities at each of the frequency components in a complex tone can be changed, resulting in a change in timbre, but not in pitch. These changes to the spectral envelope are generally perceived by adult listeners to be a change in the sound quality or timbre. Adults are very good at discriminating small changes in the spectral envelope (e.g., Green, 1983). Infants have also been found to be able to detect changes in the spectral envelopes of complex steady-state tones. Seven-month-old infants discriminate between tonal complexes that have the same fundamental frequency, but differ in their harmonic components (Clarkson et al., 1988). Trehub et al. (1990) found that 7- to 8.5-month-old infants are able to differentiate between spectral structures of complex tones despite variation in fundamental frequency, intensity and duration. Furthermore, 7-month-old infants are also able to discriminate sounds with highly different spectral profiles (i.e., rising vs. falling spectrum) (Clarkson, 1996).

In the present paper, we concentrate on the *spectral slope*, which is a global property of the spectral envelope representing the linear component of change in relative intensity level across spectral frequency. Most sounds in the natural world, including voices, have negative spectral slopes (i.e., intensity decreases with increasing harmonic number), and thus low frequency components have relatively more intensity than the high frequency components. Spectral slope is important in object identification, the perception of speech sounds and the vocal expression of emotion. Female voices have been found to have flatter spectral slopes than male voices, resulting in relatively greater intensities at the high frequencies than in male voices (Hattatori, Yamamoto, & Fujimura, 1958; Monsen & Engebretson, 1977; Huffman, 1990;

Klatt & Klatt, 1990; Nittrouer, McGowen, Milenkovic, & Beehler, 1990). The perception and identification of vowels can also be affected by spectral slope steepness (Lea & Summerfield, 1994). Flatter spectral slopes (i.e., less negative spectral slopes, and therefore relatively more intensity at high frequencies) have been found for voices expressing fear and rage, whereas steeper negative spectral slopes (i.e., relatively less intensity at high frequencies) have been found for vocal expression of happiness (Scherer, 1989).

Spectral slope is also implicated in our social impressions of others. Sounds that have more intensity at high frequency components (i.e., less negatively sloped or positively sloped) are perceived to sound nasal. Nasality influences social attitudes and perceptions, such that increased nasality is associated with negative characteristics, such as weakness (Bloom, Zajac, & Titus, 1999) and "whining" (Laver, 1980). Female voices are generally more nasal than men's voices (Seaver, Dalston, Leeper, & Adams, 1991). However, mothers' infant-directed singing is less nasal than their non-infant-directed singing in that the former contains relatively more intensity at the low-frequencies than the latter (Trainor, Clark, Huntley, & Adams, 1997). Nasality also affects adults' social perceptions of infant vocalizations. Vocalizing 3-month-old male infants are rated as more socially favorable than female infants, even when the sex of the infant is not revealed (Bloom, Moore-Schoenmakers, & Masataka, 1999). The only acoustic difference between male and female infant vocalizations appears to be higher nasality in the female vocalizations. This has important social implications because mothers have been observed to be less responsive to infants producing sounds of greater nasality (Masataka & Bloom, 1994).

In sum, spectral slope perception is important in object identification and speech perception as well as social and emotional interaction. We ask whether young infants are sensitive to spectral slope. The average spectral slope of the human voice has been measured to be between about −12 and −4 dB/octave (Sundberg, 1991, p. 118; Hall, 1980, p. 206). We analyzed the spectral slope of published spectra for different orchestral instruments (from Olson, 1967 and Fletcher & Rossing, 1991) and found that this same range applies to musical instruments as well. Previous research has established that 7-month-old infants are able to discriminate a single positive spectral slope (linear increase of 3 dB per 200 Hz) from a single negative spectral slope (linear decrease of 3 dB per 200 Hz) (Clarkson, 1996). Infants are particularly interested in speech and musical sounds. Since the majority of these meaningful sounds in the environment have spectral slopes in the moderately negative range, enhanced sensitivity for spectral slopes in this range would be expected if spectral slope is important for infants' discrimination of timbre. In the present experiment, 8-month-old infants' discrimination of a wide range of spectral slopes was measured to test whether the developing auditory system is differentially tuned to specific ranges of spectral slopes.

## 1. Method

### *1.1. Participants*

Forty-one (30 males, 11 females) normal, full-term 8-month-old infants ($M = 33.9$ weeks, range $= 32.0$–$36.1$ weeks) participated. All infants were born within 2 weeks of full term

Table 1
Spectral slope pairs tested, the number of infants tested on each pair, and the number reaching criterion in Phase 1

| | Slope 1 (dB/octave) | Slope 2 (dB/octave) | Number of infants tested | Number of infants reaching criterion | Proportion of infants reaching criterion |
|---|---|---|---|---|---|
| (i) | −16 | −10 | 11 | 5 | .45 |
| (ii) | −10 | −4 | 8 | 8 | 1.00 |
| (iii) | −3 | +3 | 11 | 2 | .18 |
| (iv) | +4 | +16 | 11 | 4 | .36 |

and were healthy at the time of testing, had no history of chronic ear infections or suspicion of hearing loss. Infants were randomly assigned to one of five discrimination conditions until eight infants in each condition passed from Phase 1 to Phase 2 of the testing procedure (see Section 1.4) or a maximum of 11 infants had been tested in each condition. Table 1 shows the total number of infants tested in each condition.

A further 14 infants (3 males, 11 females, $M = 33.5$ weeks, range $= 32.0$–$36.1$ weeks) were tested in one condition in order to equate the number of infants reaching criterion (see Section 2).

### 1.2. Stimuli

Complex tones were generated on a Macintosh IIci computer using Synthesize software. All tones had a fundamental frequency of 200 Hz (this is in the range of female voices) and were 1,000 ms in duration, including linear 20-ms rise and fall times. Each tone consisted of the first five harmonics in cosine phase. Seven different spectral slopes were used: −16, −10, −4, −3, +3, +4, and +16 dB/octave. Each slope was presented at five different intensity levels (65, 67, 69, 71 and 73 dB(A) over a noise floor of 24 dB(A)) in order to minimize infants' use of local intensity cues. Discrimination of four pairs of spectral slopes were tested (see Table 1). As can be seen in Table 1, larger spectral slope differences were tested for positive than for negative spectral slopes, as discrimination was expected to be poorer for the positive than for the negative slopes.

### 1.3. Apparatus

Testing was conducted in a sound-attenuating chamber (Industrial Acoustics Co.). A Macintosh IIci computer with an audiomedia card generated the 16-bit sounds and ran the experiment. The sound stimuli were passed through a Denon amplifier (PMA-480) to a single loudspeaker (GSI) located inside the booth. The parent holding the infant sat in a chair arranged so that the loudspeaker was located on the infants' left. Under the loudspeaker were four compartments, each containing lights and a mechanical toy. It was not possible to see into the compartments except during reinforcement (see Section 1.4). The experimenter was seated facing the infant.

### 1.4. Procedure

Infants were tested individually in a go/no-go conditioned head-turn response procedure (e.g., Trainor & Trehub, 1992). The experimenter and parent listened to masking music through headphones so as to be unaware of what the infant was hearing. During the experiment, one of the spectral slopes in a pair (see Table 1), the standard spectral slope, repeated continuously from a loudspeaker on the infant's left. The interval between the tones was 1,000 ms. When the infant was attentive and facing the experimenter, a trial was initiated by the experimenter. There were two types of trials: control trials, in which a tone with the standard spectral slope was presented, and change trials, in which a tone with a different spectral slope was presented. If the infant made a 45° or greater head turn (as judged by the experimenter after training) toward the loudspeaker within 3,000 ms of the beginning of a change trial, a toy in one of the compartments under the loudspeaker lit up for 3,000 ms as a reinforcer. Head turns at other times and those that were less than 45° were not reinforced. Once the lights were extinguished, the experimenter attracted the infant's attention forward again. The computer kept track of any head turns that occurred within a 3,000 ms window on change trials (hits) as well as on control trials (false alarms) to provide an index of the rate of random turning. Trials were presented in a quasi-random order for each subject, with the constraint that no more than two control trials occurred sequentially.

Each infant was tested with one of the pairs of slopes shown in Table 1. For half of the infants, a tone with slope of *Slope 1* (see Table 1) was presented as the standard and a tone with *Slope 2* (see Table 1) was presented during change trials. For the other half of the infants, this was reversed. There were two experimental stages, *Phase 1* and *Phase 2*. During Phase 1, only change trials were presented and intensity was held constant at 71 dB(A) to make the task easier. Demonstration trials, in which the change slope was presented paired with the activation of a toy, were presented if the infant failed to turn on several trials in a row, in order to show that head-turning to a change tone would be rewarded. A criterion was set at 4 correct trials in a row within 20 trials. If the infant failed to reach criterion, the session was terminated. If the infant reached criterion, Phase 2 began. During this phase, both the standard and change tones were presented with the full range of intensity levels (65–73 dB(A)), with the intensity on a particular trial chosen randomly. There were no demonstration trials during Phase 2. Each infant completed 24 trials in Phase 2: 12 change trials and 12 control trials. The same procedure was followed for all slope pairs.

## 2. Results

There were no significant differences in performance in any condition depending on whether Slope 1 or Slope 2 was the background, so the data were collapsed across this variable.

All of the eight infants tested in the −4/−10 discrimination condition successfully reached criterion, but at most only 5 out of 11 infants tested in each of the other conditions did so (Table 1). A 2 (pass or fail) × 4 (condition) chi-square analysis was conducted on the number of infants passing or failing in Phase 1 of each condition, $\chi^2(3) = 16.955$, $p < .001$. Thus, the null hypothesis that there were equal proportions of infants passing and failing in each condition was rejected. A further set of chi-square analyses were conducted using pair-wise comparisons between each of the conditions, to determine which conditions differed significantly. Comparisons between the −4/−10 condition and each of the other conditions yielded significant results ($\chi^2(1) = 10.588$, $p < .001$ for −4/−10 and −10/−16; $\chi^2(1) = 10.588$, $p < .001$

for −4/−10 and −3/+3; $\chi^2(1) = 15.856$, $p = .000$ for −4/−10 and +4/+16). Comparisons between all other pairs of conditions were not significant. Thus, when there was no intensity variation, the −4/−10 condition was relatively easy compared to the other conditions.

In Phase 2, infants in the −4/−10 condition responded correctly (hits) on .47 proportion of trials and responded incorrectly (false alarms) on .35 proportion of trials, which differ significantly from each other according to a paired sample *t*-test, $t(7) = 3.52$, $p < .005$. The results are the same when $d'$ is used. A single-sample *t*-test showed that discrimination between the tones was significantly above chance levels, $d' = .32$, SD = .26, $t(7) = 3.52$, $p < .005$, indicating that infants were able to discriminate spectral slopes in this moderately negative range.[2] Because so few subjects were able to reach criterion in the other conditions, it was not possible to conduct statistical tests. However, the mean $d'$s and percents correct (based on change and control trials) in each case were very low for the few infants tested in Phase 2 ($d' = .20$, proportion of hits = .5, proportion of false alarms = .42 for −16/−10; $d' = -.09$, proportion of hits = .50, proportion of false alarms = .54 for −3/+3; $d' = .15$, proportion of hits = .52, proportion of false alarms = .46 for +4/+16). Thus, infants were only able to discriminate spectral slope in the −4/−10 case. Even when there was no intensity rove (Phase 1), infants found spectral slope discrimination difficult outside the −4/−10 dB/octave range.

Because few infants met the criterion in Phase 1 on the −16/−10, −3/+3, and +4/+16 conditions, few infants were tested in Phase 2 (with the intensity rove) in these conditions. While it is unlikely that infants would perform well in the more difficult Phase 2 task if they had difficulty in Phase 1, we decided to test this in one of the conditions. Thus, a further 14 infants were tested in the +4/+16 condition in an effort to match the number of infants reaching criterion to that of the −4/−10 condition. A total of 9 out of the 25 infants were able to reach criterion in Phase 1 and completed Phase 2. A single-sample *t*-test on the $d'$ values from Phase 2 found no significant difference from chance levels, mean $d' = .04$, SD = .39; $t(24) = .33$, $p = .37$. A paired *t*-test on the proportion of hits (.52) and false alarms (.50) in Phase 2 also found no significant differences, $t(8) = .34$, $p = .7$. Thus, even the top-performing 36% of infants in the +4/+16 condition did not show discrimination between the pair of tones, suggesting that this condition is much more difficult for infants than the −4/−10 condition, in which infants showed discrimination, even though 100% of infants were included.

Theoretically, discrimination between two tones of differing spectral slope could be based on listening for "local" changes that occur in a single harmonic within the complex, rather than attending to the whole complex. Specifically, a listener could "hear out" a single harmonic in the complex, and use intensity changes that occur in this single harmonic to make the discrimination between a pair of spectral slopes. A set of calculations (see Appendix A) was carried out to determine whether the intensity variation of 8 dB was sufficient to control for the use of local intensity differences. Each pair of spectral slopes contained the same five harmonics, but at different intensities. For example, tones with highly negative spectral slopes have more relative intensity at low frequency components than slopes with less negative or positive spectral slopes. In order to determine how large the difference was between the equivalent harmonics of any given pair of spectral slopes tested, local intensity cues between each pair of spectral slopes were calculated. In other words, the difference in intensity between each of the corresponding harmonics of the two complexes was determined. The maximum difference in

Table 2
Intensity rove needed to eliminate use of local intensity cues for each pair of spectral slopes

| Slope 1 | Slope 2 | Intensity rove needed (dB) |
|---|---|---|
| −16 | −10 | 13.48 |
| −10 | −4 | 11.70 |
| −3 | +3 | 8.15 |
| +4 | +16 | 25.00 |

intensity (the value of the largest local cue) across corresponding harmonics for each pair was considered to be the intensity variation required to mask local intensity cues (see the figure in Appendix A). Although the local intensity differences (i.e., differences at individual harmonics) between spectral slope pairs exceeded the intensity variation used during the test phase (Table 2), the greatest local intensity cues were in the +4/+16 condition, where performance was very poor. This suggests that infants were not attending to local intensity cues, but were attending to the global spectral envelope.

The data were also examined by intensity to determine if performance in the −10/−4 condition could have been due to infants responding only on the most intense trials (i.e., 73 dB(A)). A one-way repeated measures ANOVA on the proportion of head-turns in Phase 2 within each intensity condition showed that there was no significant effect of intensity on performance, indicating that infants were not responding to differences in loudness, but rather to differences in tone quality.

## 3. Discussion

Eight-month-old infants appear to be most sensitive to differences in spectral slope in a limited range around −10 and −4 dB/octave. Infants did not show discrimination between the highly negative spectral slope pair or between the positive spectral slope pair, even though the latter difference was large (+4/+16 condition). While infants were shown previously to discriminate a single highly negative spectral slope from a single highly positive spectral slope (Clarkson, 1996), the results of the present study extend Clarkson's (1996) findings by suggesting that infants are maximally sensitive to spectral slope differences in the moderately negative region that are contained in speech (Sundberg, 1991, p. 118; Hall, 1980, p. 206) and music (Olson, 1967; Fletcher & Rossing, 1991).

The results are particularly important because they suggest that 8-month-old infants are able to use the global component of spectral envelope to process and organize auditory input that is relevant to the real world tasks of object recognition, vocal expression of emotion, and social interaction. Spectral slope differs between male and female voices (e.g., Klatt & Klatt, 1990), and may be the basis by which infants are able to discriminate male from female voices matched in pitch (Miller, 1983). Infants' sensitivity to spectral slope differences in the range of human voices also suggests that infants are likely to be sensitive to socially relevant differences in vocal nasality, which depend crucially on spectral slope discrimination.

Differences in spectral slope may also contribute to infants' ability to discriminate their mother's voice from that of a stranger's at 2 days of age (DeCasper & Fifer, 1980), although other cues such as pitch and prosody must also play a large role in these types of discriminations. It should be noted that timbre is a highly complex dimension of sound, and it is likely that spectral slope and other steady-state characteristics of the spectral envelope are not the only relevant acoustic components in timbre discriminations. Indeed, dynamic aspects of the spectral envelope play a crucial role in the identification and recognition of consonants in speech for adult listeners (Liberman, Harris, Kinney, & Lane, 1961; Cutting & Rosner, 1974) as well as infants (Jusczyk, Rosner, Cutting, Foard, & Smith, 1977). Temporal characteristics of sound are also an important distinguishing feature in musical instrument timbres (Grey, 1977; McAdams, Winsberg, Donnadieu, De Soete, & Krimpoff, 1995; Cutting and Rosner, 1974). Nonetheless, it is clear from the results presented here that infants are at least sensitive to the global spectral envelope.

It remains for future research to test whether infants younger than 8 months show sensitivity to spectral slope differences relevant to speech and music, as well as whether this sensitivity generalizes to sounds with more complex spectral envelopes, such as voices. More generally, this study did not directly address the role of experience in spectral slope discrimination. Thus, it is not known whether the enhanced discrimination for real world spectral slopes is due to exposure to real-world sounds, or whether this sensitivity has been specified by genetics. If experience is the main cause, it might be predicted that increased exposure to sounds with positive spectral slopes would increase the discriminability of positive spectral slopes. On the other hand, if discriminability of spectral slopes is genetically specified, further artificial exposure to environmentally rare spectral slopes would not be expected to modify spectral slope discriminability substantially.

Whatever the cause, from an infant's perspective, it would certainly be advantageous to be able to discriminate timbres that signal important social messages. By the measure of spectral slope discrimination, infants are tuned to be sensitive to timbre differences important for object recognition, speech discrimination and the vocal expression of emotion.

## Notes

1. 1973 American National Standards Institutes (ANSI), Psychoacoustic Terminology, s3.20.
2. The $d'$ values are generally quite low, even in the $-4/-10$ condition. The variation in intensity from trial to trial likely makes this task very difficult. It must be noted that the performance of prelinguistic infants in psychophysical tasks rarely reaches adult levels. This is likely due to motivational and attentional factors, in conjunction with the lack of verbal instructions. The important result is that performance in the $-4/-10$ condition was well above chance levels.

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## Appendix A

Here we determine the intensity rove needed to mask local intensity cues that could potentially be used to discriminate spectral slope.

The general equation used to generate the tones was

$$\mathrm{dB}_i = b \log_2 i$$

where $i$ is the harmonic number (from 1 to 5), $b$ the spectral slope value in dB/octave (from $-16$ to $+16$ dB/octave) and $\mathrm{dB}_i$ is the relative amplitude of harmonic $i$ in dB. This equation was applied to each component in the complex to give the relationship in dB/octave between each successive harmonic in the complex. The tones were also equated for intensity, such that the total intensity of the complex, $I_\mathrm{T}$ across the five harmonics, was kept constant at $I_\mathrm{T} = 1.0$. This ensured that there would be no clipping of any of the waveforms and that the total energy for the complex was the same for each tone. To determine the overall intensity in dB for the complex, the intensity for each component in the complex needed to be calculated and then summed across the five harmonics. An intercept value, $a$, was added to the general equation, such that for any slope value, the total intensity could be kept constant.

$$I_\mathrm{T} = \sum 10^{\mathrm{dB}_i/10}, \quad \text{where } \mathrm{dB}_i = a + b \log_2 i.$$

The equation now becomes:

$$I_\mathrm{T} = \sum 10^{(a + b \log_2 i)/10}.$$

Solving for $a$, the equation becomes:

$$a = 10 \left( \log_{10} I_\mathrm{T} - \log_{10} \sum 10^{(b \log_2 i)/10} \right).$$

Setting $I_\mathrm{T} = 1.0$, the equation becomes:

$$a = -10 \log_{10} \sum 10^{(b \log_2 i)/10}.$$

Due to the nature of the stimuli, local intensity cues could potentially be used as a basis for discrimination. The changes in spectral slope will change the absolute intensity of each of the components in the complex, and therefore local intensity cues, rather than the overall spectral envelope, could theoretically be used to detect the changes in complexes with differing spectral slopes. To minimize the use of local intensity cues, a roving intensity level needs to be introduced. To determine how much of an intensity variation was necessary, the intensity differences between the corresponding harmonics in the standard and comparison stimuli were calculated for every pair of tones that would be tested, and the maximum difference determined for each pair of tones. This difference was added to the overall intensity of the complex with the lesser slope (see Fig. 1). The overall intensities of the two tones were then calculated to determine the intensity rove needed to mask the local intensity cues at each harmonic. For stimuli with negative spectral slopes, the harmonics that change the most in absolute intensity are the highest harmonics, and for positive spectral slopes, lowest harmonics change the most. The complexes with positive slopes differ the most at the first harmonic, while those with

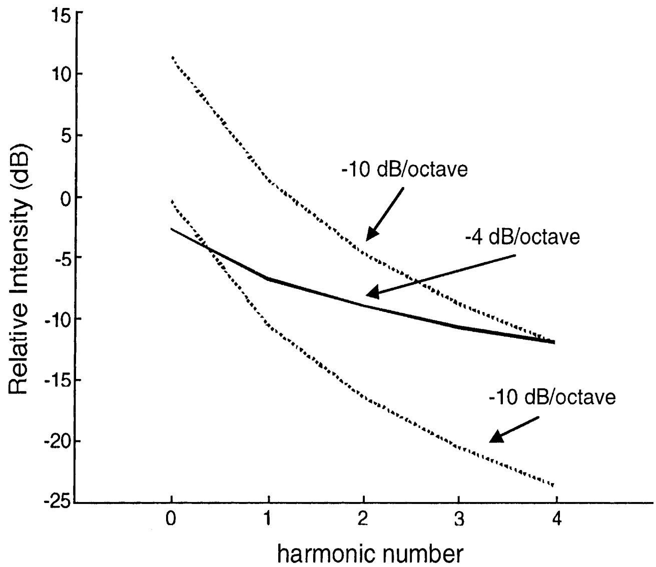


Fig. 1. Intensity differences between the −10 dB/octave (dashed lines) and −4 dB/octave (solid line) spectral slope pair. It can be seen that for negative spectral slopes, the greatest intensity change occurs at the last (fifth) harmonic. The two −10 dB/octave slopes are 11.70 dB apart.

negative slopes are most different at the fifth harmonic. Thus, the following calculations use the first harmonic intensity values for the positive slopes and the fifth (last) harmonic intensity values for the negative slopes.

Using the general equation $\mathrm{dB}_i = a + b\log_2 i$, the relative amplitude of the fifth (negative slopes) or first (positive slopes) harmonic, in decibels, was calculated for the standard complex with slope $b'$. The analogous harmonic of the comparison complex with slope $b''$ was set to be equal to the intensity of the standard

$$\mathrm{dB}_{ib'} = \mathrm{dB}_{ib''},$$

where $b'$ is the standard slope and $b''$ the comparison slope and $i$ is either harmonic number 1 or 5. Substituting the new value for $\mathrm{dB}_{ib''}$ into the general equation, with slope $b''$ gives

$$\mathrm{dB}_i = a + b''\log_2 i.$$

Solving for $a$, the equation becomes:

$$a = \mathrm{dB}_i - b''\log_2 i.$$

This equation can now be used to solve for the new value of the harmonics with slope $b''$.

$$\mathrm{dB}_i = (\mathrm{dB}_i - b''\log_2 i) + b''\log_2 i_{b''},$$

where $i_{b''}$ is harmonic 1–5 in the comparison complex. This equation gives the relative amplitudes of each of the harmonics in the comparison complex. To determine the new total intensity of the complex, the component intensities must be summed.

$$I_{\mathrm{T}b''} = \sum 10^{(\mathrm{dB}_{ib''}/10)},$$

where $I_{\mathrm{T}b''}$ is the total intensity of the comparison complex. To determine the change in relative amplitude between the two complexes, which represents the intensity rove needed, the following equation was applied:

$$\mathrm{dB}_{\mathrm{change}} = 10\log_{10}\left(\frac{I_{\mathrm{T}b''}}{I_{\mathrm{T}b'}}\right),$$

where $I_{\mathrm{T}b'}$ is the total intensity of the standard complex, and $\mathrm{dB}_{\mathrm{change}}$ is the change in relative amplitude of the between the standard and the comparison stimuli. Since the standard complex has total intensity equal to 1.0, setting

$$I_{\mathrm{T}b'} = 1.0,$$

the equation becomes:

$$\mathrm{dB}_{\mathrm{change}} = 10\log_{10}(I_{\mathrm{T}b''}).$$

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