Music *and* Hearing Aids

A CLINICAL APPROACH

Marshall Chasin, AuD, MSc

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Music (and Speech) for the Audiologist

Without explicitly recognizing it, audiologists have all of the tools needed for the understanding and analysis of music. In some cases, any limitation can be traced to lack of extrapolation of a concept and, in other cases, it is merely terminology. A discussion of the musical notes, versus the fundamental frequency (in Hz), is one such area. A full list of the various musical notes and the value of their fundamental frequencies is found in Appendix A of this book.

Beginning with this chapter (and continuing in Chapters 3 and 4) there will be icons delineating where more research needs to be performed and many of these can be addressed within the confines of a student research project, such as an AuD Capstone study. All 12 of these research studies in this book are replicated in Appendix B of this book.

LETTERS AND FREQUENCIES

Musicians use the letters, A, B*b*, C, whereas audiologists would say 440 Hz, 466 Hz, and 524 Hz. According to the situation, in both cases this may be correct but still lead to an oversimplification.

Figure 2–1[1] shows several musical notes along with their fundamental frequencies. Depending on the musical instrument being played, the note A may indeed have its fundamental energy at 440 Hz, but it also may have higher frequency harmonics whose exact amplitude may vary depending on the quality of the instrument and the instrument being played.

For example, a flute and a violin are both "half-wavelength resonators" (as are the human vocal cords) and, as such, would have energy at A [440 Hz], but also at integer multiples of 440 Hz (namely 880 Hz, 1320 Hz, 1760 Hz, and so on). The amplitudes of the higher frequency harmonics would define the timbre, but they also serve to help distinguish between various instruments, such as a flute and a violin. To say that "middle C" on a piano keyboard is exactly at 262 Hz is both true and false. Its fundamental frequency is at 262 Hz, but a piano is made up of higher frequency harmonics at integer multiples of 262 Hz. And, the amplitude of these harmonics assist a listener in distinguishing a piano from the flute or violin, or any other "half-wavelength" resonator instrument.

Other musical instruments, such as the clarinet, trumpet, and trombone are "quarter-wavelength" instruments and have odd numbered harmonics of the fundamental. An A [440 Hz] on a trumpet would have harmonics at 1320 Hz (440 × 3), 2200 Hz (440 × 5), and so on.

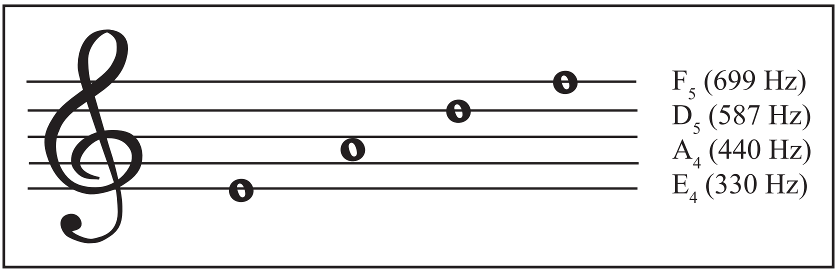


Figure 2–1. Some musical notes and their fundamental frequencies (in Hz) on a treble clef.

[1] I wish to thank and to acknowledge Composer Shaun Chasin (http://www.chasin.ca) for many of the spectra and all of the audio files used in this book.

Many adult males, including myself, have a speech fundamental frequency of around 125 Hz—an octave below middle C. And being a "half-wavelength resonator" there are harmonics at integer multiples of 125 Hz similar to the piano, flute, or violin (at 250 Hz, 375 Hz, 500 Hz, and so on). A listing of some examples of quarter- and half-wavelength resonator instruments can be found in Table 1–1 in Chapter 1.

A resulting feature of any wavelength associated musical instrument is that a half-wavelength resonator musical instrument (e.g., saxophone) has twice as many harmonics as a quarter-wavelength resonator musical instrument (e.g., clarinet) of the same length for any given frequency range. Despite the increased density of harmonics in a saxophone, does this translate into twice as many auditory cues? A hypothesis is that a half-wavelength resonator instrument may be better for a hard-of-hearing person (or child) to hear (Figure 2–2). This may depend on the severity, and even audiometric configuration of the hearing loss, and may have ramifications for the answer to the question "what musical instrument should my hard-of-hearing child learn to play?" If it turns out that an instrument with a denser, more tightly packed harmonic structure does provide a better sound or timbre for a hard-of-hearing person then a saxophone, being a half-wavelength resonator instrument, may be better than a clarinet. Of course, other factors do come into play acoustically, in that larger (or longer) musical instruments do have a lower set of resonant frequencies such that more of the music may be within a healthier region of hearing for that person. To my knowledge, this has never been formally studied and more research will be required (see Study 2–1).

SPEECH VERSUS MUSIC

Frequency of Harmonics

A salient feature of speech is that all speech sounds can be divided into two linguistic categories: sonorants and obstruents. Sonorants have most of their energy in the lower frequency

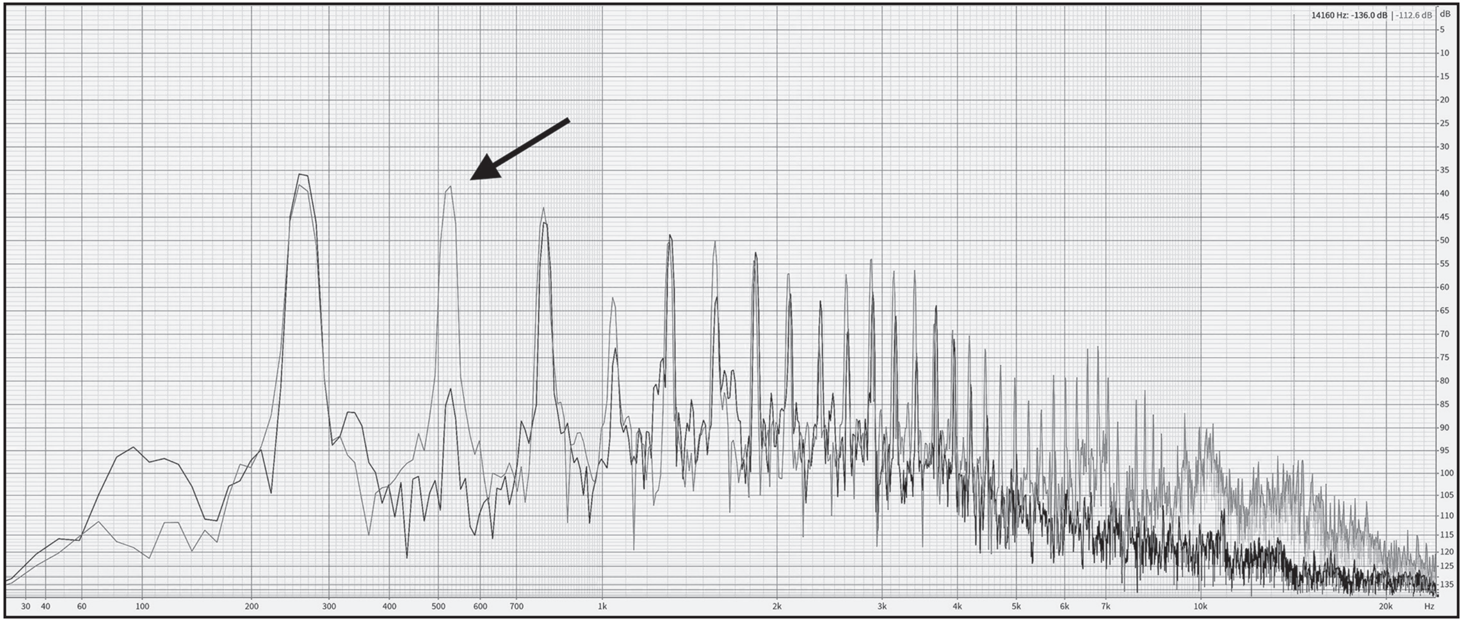


Figure 2–2. The B*b* clarinet and B*b* saxophone playing the same note. The clarinet is a one-quarter wavelength instrument with odd number harmonics of the fundamental, whereas the saxophone is a half-wavelength instrument with integer multiples of the harmonics of the fundamental. The more densely packed harmonic structure curve on the top is the saxophone. The arrow indicates a significant harmonic of the saxophone that would not be seen in the clarinet. There is significantly more harmonic energy in the saxophone than the clarinet.

region and are (typically) voiced sounds that are made up of continuous airflows and have characteristic resonant or formant frequencies. In English, this includes all vowels, nasals, and liquids ([l] and [r]). In contrast, the obstruents do not have resonant or formant frequencies but do have broad bands of energy, typically in the higher frequency regions. This includes stops, affricates, and fricatives. Obstruents can have a secondary effect on the formant pattern (or transition) of the adjacent vowel or nasal and this is certainly an important element to the perception of the speech sound. However, speech in general has low frequency sonorants with well-defined harmonics underlying a well-defined resonant pattern and also high frequency obstruents with no well-defined resonant pattern, and little, if any, high frequency harmonic information.

With the exception of most percussion instruments, similar to the sonorants in speech, music is composed of well-defined harmonics and resonant patterns. For music, this is true of the lower frequency sounds *as well as* the higher frequency sounds. Even the top note on the piano keyboard (C [4086 Hz]) has its first harmonic just above 8000 Hz and its second harmonic at 12,258 Hz (3 × 4086 Hz). Changing the frequency location of a harmonic by only one-half of one semitone can be problematic and would significantly degrade the quality (and acceptability) of music (see Chapters 3 and 4 for more information, and Audio Files 3–4 and 3–5). Having said this, the main reason why the various forms of hearing aid frequency lowering work so well with speech is that only the higher frequency obstruents are affected, which has little or no effect on the harmonic structure. (Chasin, 2016, 2020). This limits the usage of (nonlinear) frequency lowering for most forms of music.

Sound Levels of Harmonics

All musical instruments (and even the human vocal tract) have a mechanical shape and volume that creates its own regions of greater harmonic energy. These are called formants and can create a series of resonances where the underlying harmonics can be "amplified" or enhanced in certain frequency regions. Despite having identical frequency components (i.e., harmonic frequency locations) for a given musical note between a violin and a flute, the amplitudes of the harmonics differ because of the different shapes of the flute and the violin. (And, of course the human vocal tract can change its shape generating different speech sounds, and consequently different resonances or formants.)

Musicians sometimes refer to this localized increase in harmonic amplitude as the "fat" part of an instrument. For example, a flute has its "fat" part at 880 Hz with higher amplitude harmonics in this region. It is simply impossible to play a flute at A [880 Hz] softly. This relatively higher level of harmonic energy defines the sound quality of the flute and helps to distinguish it from the violin whose "fat" part may be in a different frequency region.

This can become problematic when a multi-channel compression hearing aid system is used and is programmed improperly. Multi-channel compression inherently treats the lower frequency fundamental energy differently from higher frequency harmonic information, thereby altering the *amplitude balance* between the fundamental and its harmonics—a flute may begin to sound more like a violin, or an oboe. (See Chapters 3 and Audio File 3–10). Of course, even though the exact frequencies of the harmonics and their associated amplitudes are quite important in the identification of a musical instrument, other dynamic factors, such as attack and decay parameters of the note, as well as vibrato, are also important factors. A further examination of the exact specifics of how poor the settings of multi-channel compression needs to be before instrument identification becomes difficult, or the change in timbre becomes problematic, would provide important clinical (and hearing aid design) knowledge (see Study 2–2).

LOUD SPEECH AND LOUD MUSIC

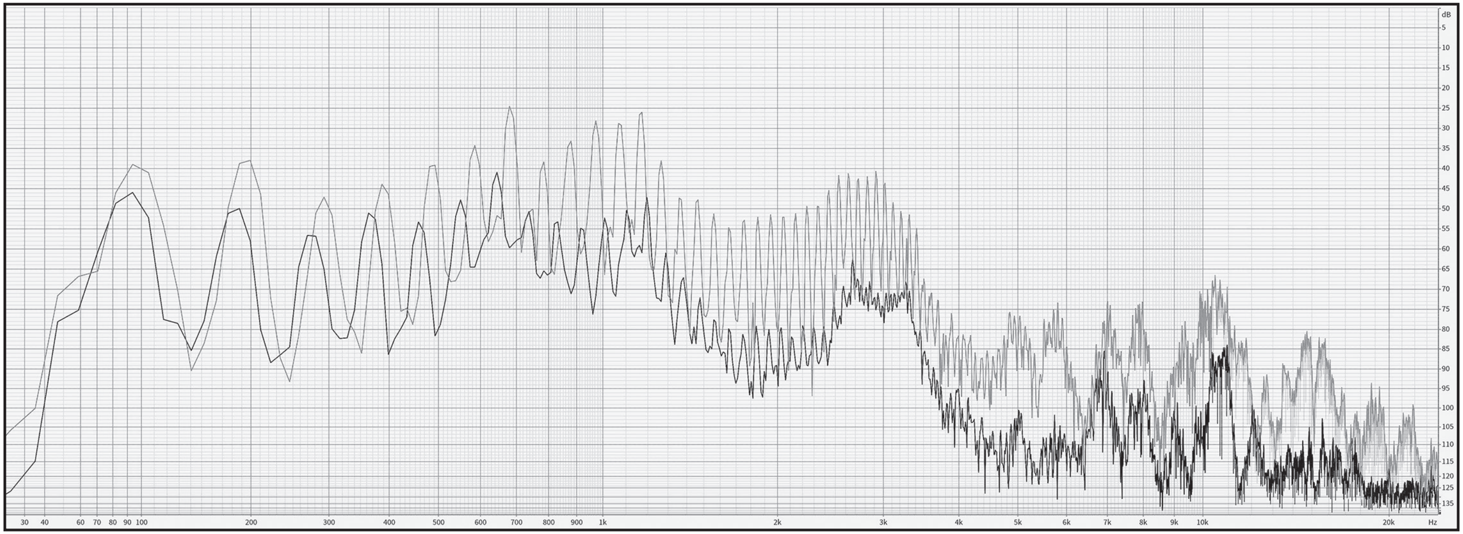
Modern hearing aid technology has the capability to be responsive to varying levels of inputs, namely, level dependent compression. A hearing aid will generate significant gain for soft level inputs, less gain for medium level inputs, and sometimes no (or even negative) gain for louder level inputs. Many people simply do not need a lot of hearing aid gain for the higher-level components of speech (and music). Understandably, there has been a significant amount of research in this area for speech, but relatively little for music. What exactly is loud music and is this the same thing for low frequency sounds and higher frequency sounds?

Figure 2–3A shows the spectrum of the low-back vowel [ɑ] at a quieter level and at a higher sound level. Figure 2–3B shows the same thing for the voiceless alveolar consonant [s]. As can be seen, as a person speaks at a higher level, it is primarily the lower frequency vowels and nasals (i.e., the sonorants, Figure 2–3A) that increase in level, whereas the higher frequency obstruent consonants (Figure 2–3B) are only at a slightly higher level. In conversational speech, one simply cannot utter a loud [s] as one can utter a loud vowel [ɑ]. For speech, as the speaking level increases, there is a relative low frequency boost as compared with the higher frequency region. This is all verifiable in any clinical setting using real ear measurement tools, with the modifications described in Chapter 1 to disable the reference microphone and disable the loudspeaker.

These are comments about the *relative* sound levels of these sounds. The absolute level will depend on speaking level, the syntactic category, as well as location of the speech sound within a word and also within the sentence. Nouns and sentence initial words tend to be of a higher speaking level than "helper words" such as adjectives and prepositions in conversational speech, especially if they occur nearer to the end of a sentence or phrase.

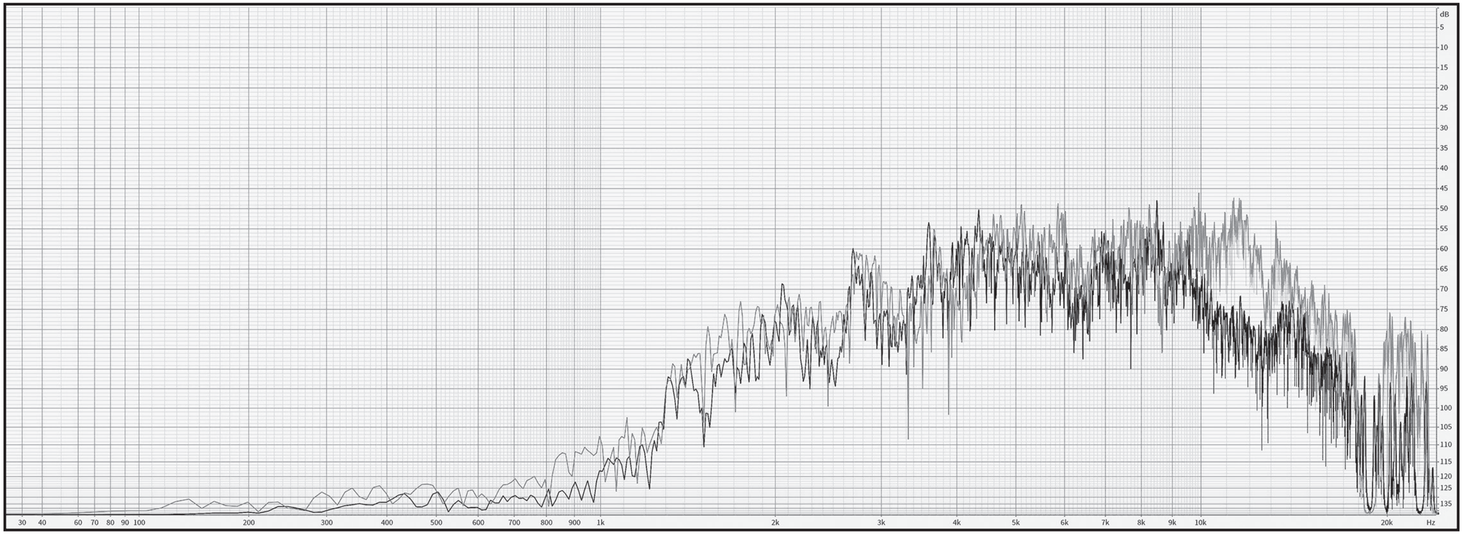
Music is a different type of input for hearing aids than is speech. Where speech can be soft (55 dB SPL), medium (65 dB SPL), or loud (80 dB SPL), especially for the lower frequency region, music can be soft (65 dB SPL), medium (80 dB SPL), or loud (95 dB SPL); music, especially live music, tends to be shifted up one "loudness" category as compared with speech. There are other "statistical" differences between speech and music, such as the crest factor, as well as spectral and temporal (attack/release) features; however, a major difference is that music is played, and frequently listened to, at a higher sound level than speech.

Table 2–1 shows examples of the sound levels of some instruments as measured from 3 meters away at a mezzo forte (mf) or average playing level. This does vary significantly from musician to musician and also depends on some of the acoustic characteristics of the musical instrument (based on Chasin, 2006).



A

Figure 2–3. A. Spectrum of the low-back vowel [ɑ] spoken quietly and then at a louder level (*top gray*) showing the increase in harmonic energy. Note that the fundamental frequency also increases slightly for the louder-spoken case because the laryngeal muscles are more contracted, thereby increasing their tension. *continues*



B

Figure 2–3. B. Spectrum of the high frequency obstruent [s] spoken quietly and then at a louder level (*top gray*) showing a relatively slight increase (as compared with the vowel [ɑ] in Figure 2–3A.)

Table 2–1. Average Sound Levels of a Number of Musical Instruments (From Over 300 Musicians) Measured From 3 Meters on The Horizontal Plane

Musical Instrument	dB(A) Ranges Measured From 3 Meters
Cello	80 to 104
Clarinet	68 to 82
Flute	92 to 105
Trombone	90 to 106
Violin	80 to 90
Violin (near left ear)*	85 to 105
Trumpet	88 to 108

Note. *Also given is the sound level for the violin measured near the left ear of the player. (Chasin, 2006).

So far, these adjustments seem rather straightforward: for a music program, adjust "quiet" music to be similar to medium speech; adjust "medium" music to be similar to loud speech; and adjust "loud" music to be similar to very loud speech. Thus, overall, perhaps subtract 5 to 10 dB from the amplification for a music program for loud music than what would be programmed for loud speech. And in some cases, depending on the fitting formula, if the sensorineural hearing loss does not exceed a moderate level, then 0 dB of amplification may be required for loud inputs (of 90 to 95 dB SPL). Simply removing the hearing aid may optimize the listening to the music, especially live music (Chasin, 2012).

Can we definitively say that music has well-defined features for soft, medium, and loud levels? Figure 2–4 is a spectrum for a French horn being played at a quiet level (pp, pianissimo) and at a higher level (ff, fortissimo). The file, Audio 2–1, demonstrates this difference. This relatively high frequency bias, as the playing level is increased, is the case for all brass instruments and also the case for reeded woodwind instruments, such as the clarinet and saxophone (Figure 2–5). Audio File 2–2 also demonstrates this high frequency cue for reeded woodwinds. That is, unlike louder speech, the increased playing level of brass and woodwind instruments is a high frequency increase cue.

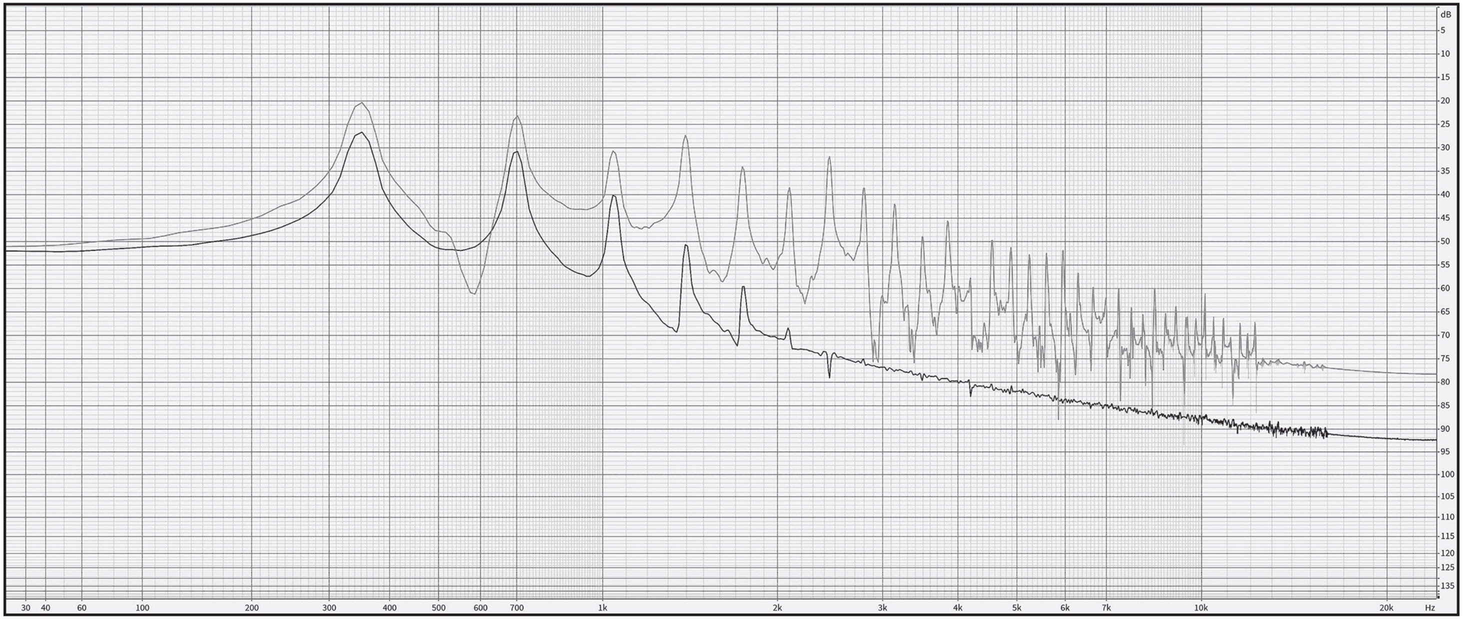


Figure 2–4. Spectrum of a French horn played quietly (pp) and again at a louder level (ff) (*top gray*) showing the relative increase in the higher frequency region where the fundamental only exhibits a slight increase in sound level.

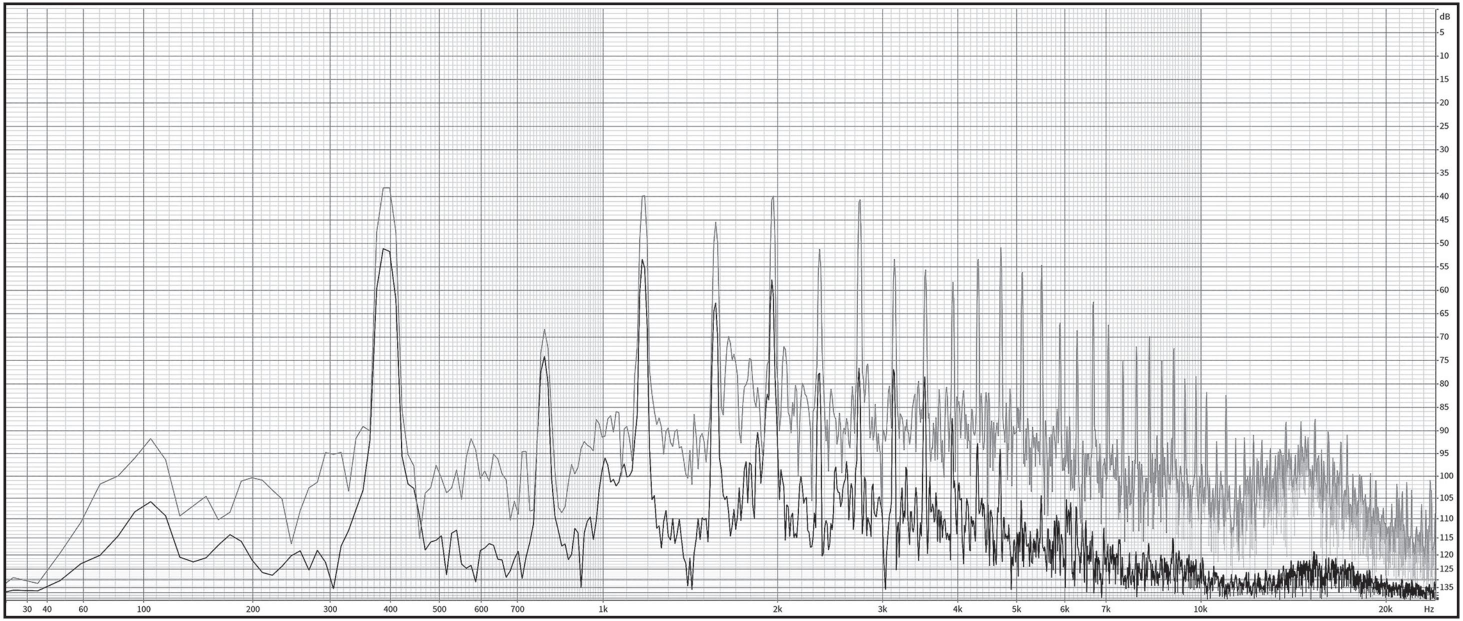


Figure 2–5. Spectrum of a clarinet played quietly (pp) and again at a louder level (ff) (*top gray*) showing the relative increase in the higher frequency region where the fundamental only exhibits a slight increase in sound level.

Figure 2–6 is a spectrum for stringed instruments such as the violin, and cello, where there is minimal bias and as the playing level increases, the relative balance of low frequency and high frequency sound energy is maintained. Audio File 2–3 demonstrates this relative balance for stringed instruments as the playing level is increased. With stringed instruments, one can simply reduce the playing level and the balance between the low and high frequency regions will be maintained.

The interested reader will be able to perform their own spectral analyses of these files to verify the relative high frequency increase in output for loud playing, as compared with the low frequency output.

As can be seen, different instruments have different properties as the playing level becomes louder and these can be grouped into "stringed instruments and the rest." Stringed instruments, such as the violin, appear to have similar increases in sound level for both the low frequency and higher frequency regions as the instruments are played at a higher level.

With reeded instruments, as one blows harder to create a louder sound, the reed distorts and its vibration pattern becomes nonlinear. This creates additional high frequency harmonic energy with almost no increase in the lower frequency fundamental energy—a high frequency combinatorial distortion artifact related to the mechanical properties of all reeds (see Figure 2–5). As discussed above, the same is true of brass instruments but the acoustics are different. Nonlinear behavior is created by an interplay between the mouthpiece and the impedance of the air column "downwind" (see Figure 2–4). In contrast, for stringed instruments, when playing louder, it's rather straightforward—the sound levels for all frequencies are increased similarly with a maintenance of the spectral shape (see Figure 2–6). The resonant pattern (and the dynamical characteristics) can be affected by the quality of the instrument and even the bow that is being used.

Questions such as "What is the spectral shape of a trumpet or any other instrument?" are misleading and ignore the playing level–dependent spectral shapes of many of the contributors to music. A summary of the general effects is shown in Table 2–2 as the singing or playing level is increased from an average (or mezze forte) level to a louder (fortissimo) level.

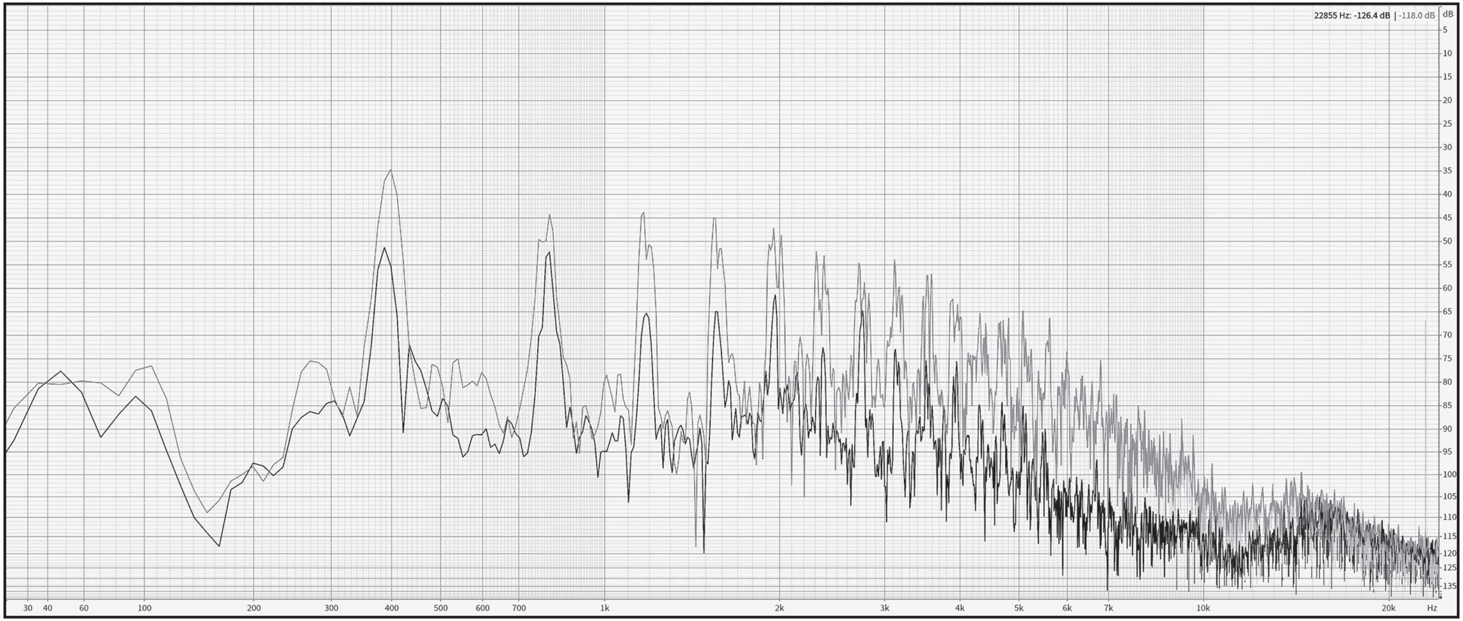


Figure 2–6. Spectrum of a violin played quietly (pp) and again at a louder level (ff) (*top gray*) showing a balanced increase between the lower frequency fundamental energy and the higher frequency harmonic energy.

Table 2–2. Summary Chart for The Differences Between Singing or Playing Level Between Average (Mezzo Forte or mf) and Loud (Fortissimo or f).

	Low Frequency Region	**High Frequency Region**
Vocal	11 to 15 dB	0 to 10 dB
Stringed instruments	11 to 15 dB	11 to 15 dB
Brass instruments	<10 dB	>30 dB
Reeded woodwinds	<10 dB	>30 dB

Note. The spectral level increases are shown for both the low frequency region and the high frequency region as the voice increases its sound level or the instrument is played louder. For vocals, the low frequency region increases slightly more than the higher frequency region. For stringed instruments, both frequency regions increase by roughly the same amount. And for brass and reeded woodwind instruments, there is a large high frequency region increase despite having minimal, if any, increase near the lower frequency fundamental frequency region. All numbers are increases from mf to f, in relative decibels.

More information about the nonlinear acoustical behavior of many musical instruments can be found in two chapters in *Springer Handbook of Systematic Musicology*, edited by Dr. Rolf Bader (2018). Specifically useful are the chapters by Nicholas Giordano, "Some Observations on the Physics of Stringed Instruments," and Benoit Fabre and colleagues, "Modelling of Wind Instruments." Another resource is Moore (2016) who discusses the acoustics of brass instruments. Finally, many local acoustical associations such as the Acoustical Society of America and the Canadian Acoustical Association have ongoing committees that study and develop standards in the realm of musical acoustics.

As is found in many proprietary hearing aid fitting software programs, for speech for louder inputs, one can prescribe less gain for low and mid-frequency sound than for softer speech. The high frequency gain should be left pretty much the same for all speaking levels.

However, for reeded woodwind and brass music, for loud playing levels, the higher frequency gain can be reduced relative to softer playing levels. And for the string instruments, there can be a gain reduction for all frequency regions as the playing level increases. This provides a fitting strategy for the hard-of-hearing client. This can (and should) be verified with real ear measures performed in the clinic.

Clinically, when using a real ear measurement system, in order to perform verification using music (or speech) stimuli, the following procedure needs to be performed:

- Calibrate the real ear measurement device in the normal fashion with an appropriate "unaided" (e.g., REUR) response being performed.
- The reference microphone and the equipment speaker need to be disabled, and this is usually accomplished by setting the stimulus level to "0 dB" or turning the stimulus to "Off." This step creates an "in situ" sound level meter.
- An "aided" (e.g., REAR) response should be performed with music (or speech) as the input stimulus.

For listening to music that is primarily of one type (e.g., strings, whether amplified or not) the above fitting strategies may point you in the correct direction, but for more varied instrumental (and perhaps mixed vocal) music such as orchestral or operatic music, it would be more of a trial-and-error approach. One could conceivably work out a fitting formula (such as a "weighted average" or dot product) for orchestral or jazz music based on the various energy contributions of each of the musical sections. To my knowledge, such a calculation has never been performed but the results would provide important clinical input regarding how a "music program" can function and how this may be different from a "speech" program. Until more research becomes available, at this point with our clinical knowledge, these should just be thought of as guiding principles rather than hard and fast rules (see Study 2–3).