The psychoacoustic secret of vibrato

When making a new violin, viola or cello, careful control over the construction process is necessary to achieve certain desired tonal characteristics in the new instrument. This article will discuss (by way of example) what we consider the critical “triad” in the construction of a violin. Each of the notes must be clearly heard. The notes of the triad are as follows:

- Construction parameters of the instrument
  here: The significance of violin varnish

- Acoustic influences of these parameters
  here: The influence of the varnish on the resonance damping

- Musical perception of these parameters
  here: The influence of the resonance damping on the vibrato and the modulability of the sound

The greater the resonance density of the instrument (i.e. more resonances per frequency band) and lower the resonance damping, the stronger and more narrowbanded the level differences we will find in the frequency response of the instrument. The stronger and more nar-rowbanded these level differences are, the greater the influence of the player’s vibrato in producing an amplitude modulation of the fundamental and overtones. In terms of the musical liveliness of the vibrato, it is critical for the periodic frequency shift of all of the harmonics of the played note to produce strong amplitude modulations of these harmonics.
It is true that the player produces a periodic frequency modulation by moving the left hand (i.e. through periodic lengthening and shortening of the vibrating string). However, the instrument’s resonance profile (which is “cleaved” by the resonance peaks) also trans-forms this frequency modulation into an amplitude modulation of the harmonics.

Accordingly, the sound level of each harmonic will have a periodically fluctuating value due to the vibrato. If the instrument’s resonance profile has a large number of closely spaced resonances with low damping, then even a small frequency shift in the vibrato will suffice to cause the harmonics of the played note to periodically move across the existing resonance peaks of the instrument (which are instrument-specific and cannot be varied by the musician) with large level differences.

This sort of amplitude modulation is critical to the vibrato sensitivity and the liveli-ness of the sound. Psychoacoustic experiments have shown that electronically manipulated vibrato that is solely frequency-modulated tends to be perceived as “synthetic” and “vulgar”, while pure amplitude modulation of the harmonics (with the frequency modulation artificially re-moved) is perceived as live and natural [Wei-nreich, G., personal message, Ann Arbor 2000].

It is my opinion that this psychoacoustic phenomenon is due to the fact that a pure frequency modulation causes only a periodic frequency shift of the excitation pattern (which is unchanged in terms of its shape) on the basilar membrane, while an amplitude modulation of the harmonics leads to a periodic change in the shape of the excitation pattern. It is a known fact that the excitation patterns on the basilar membrane of the inner ear are produced by the incoming sound. These excitation patterns cause the hair cells to vibrate in turn. This causes neuronal firing of the hair cells – the basis for our hearing.

The reason that the vibration of a note on a violin causes a periodic change in the shapes of the excitation patterns is due to the fact that the excitation patterns are highly dependent on the input amplitudes of the incoming sound. Of course, these input amplitudes are periodically modulated by the vibrato produced by the player’s left hand.

To what extent does the excitation pat-tern on the basilar membrane of the inner ear change if the input amplitude fluctuates periodically, i.e. if an amplitude-modulated sound is present? A periodic variation of the excitation pattern arises for two reasons:

a) The periodically fluctuating area of the excitation pattern: The greater the amplitude of a frequency component, the greater the widening of the excited region on the basilar membrane.

b) The nonlinear broadening of the upper flank of the excitation pattern: The greater the amplitude of a given frequency component, the flatter and more drawn out the widening of the excited region on the basilar membrane towards higher frequencies.

In other words, the change in the shape of the excitation pattern is highly dependent on how effective the instrument is in “conjuring” periodic amplitude modulations of the harmonics of the played note from the vibrato produced by the left hand. The musician cannot do anything: In the strictest sense, he or she produces only a frequency modulation of the note (see above). In terms of the sound, the effectiveness of this frequency modulation is dependent on the resonance properties of the instrument, as described above.
A change in the shape of the excitation pattern causes significantly larger neuronal excitation differences in the brain’s hearing process than a plain periodic frequency shift of a largely homogeneous excitation pattern.
What does this mean in terms of the acoustic properties of the violin’s resonance profile? The greater the resonance density of the instrument (number of resonances per frequency band) and the lower the resonance damping, the greater the extent to which even tiny variations by the player (such as vibrato and bowing changes) will produce a change in the neuronal excitation and thus an increase in the perceptibility of the note.
The “fiery tone” that likely results from this phenomenon is an essential characteristic of good violins. What we are dealing with here is a phenomenon which I like to call “perceptibility through quality” (or “projection through quality”) in contrast to plain “perceptibility through intensity”. It is this quality that allows the sound of a fantastic violin to project effortlessly all the way to the back row of a hall even when played pianissimo. The secret of “projection” is clearly related to the “vibrato sensitivity” of good instruments described here.

The minimum and maximum sound levels of the harmonics produced within a vibrato period cause a different excitation pattern on the basilar membrane and thus different specific loudnesses. Fig. 1 below shows the maximum difference in the specific loudness which is produced by the vibrato of a musical note:

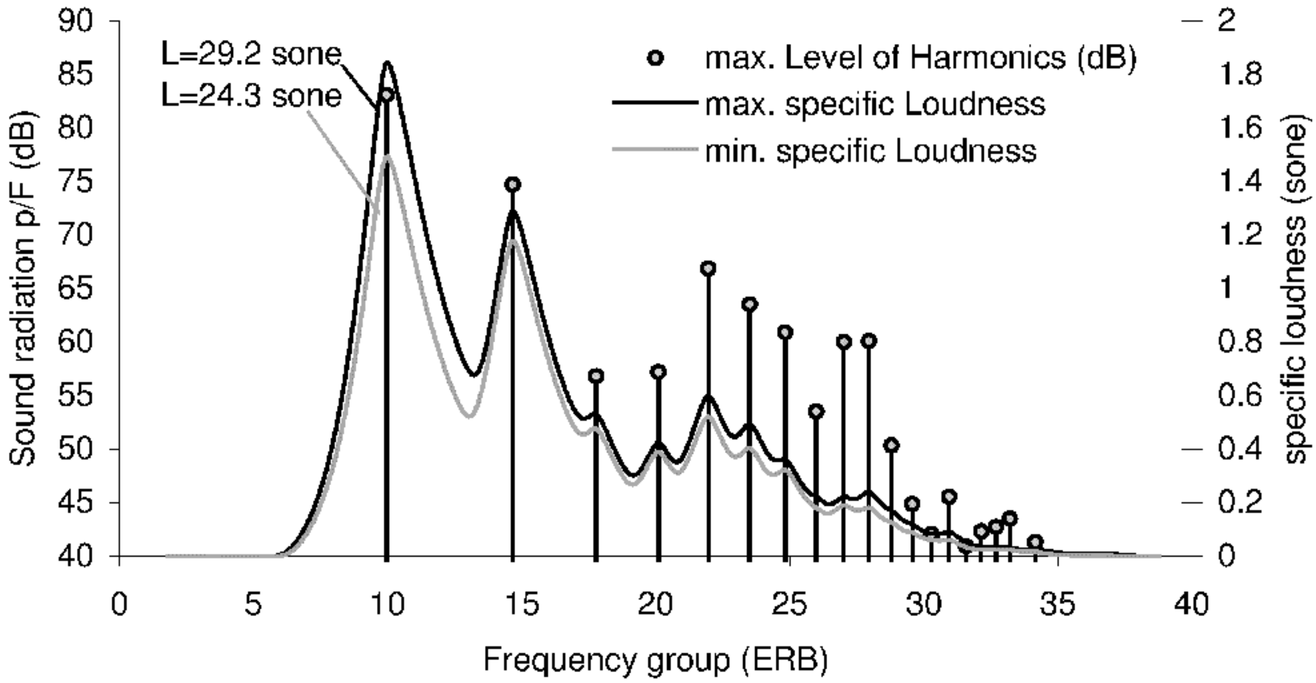


Fig. 1: Excitation pattern of the inner ear when listening to a bowed note played by a violin. Gray curve: Specific loudness due to the minimum harmonic levels within the vibrato shift. Black curve: Specific loudness due to the maximum harmonic levels.

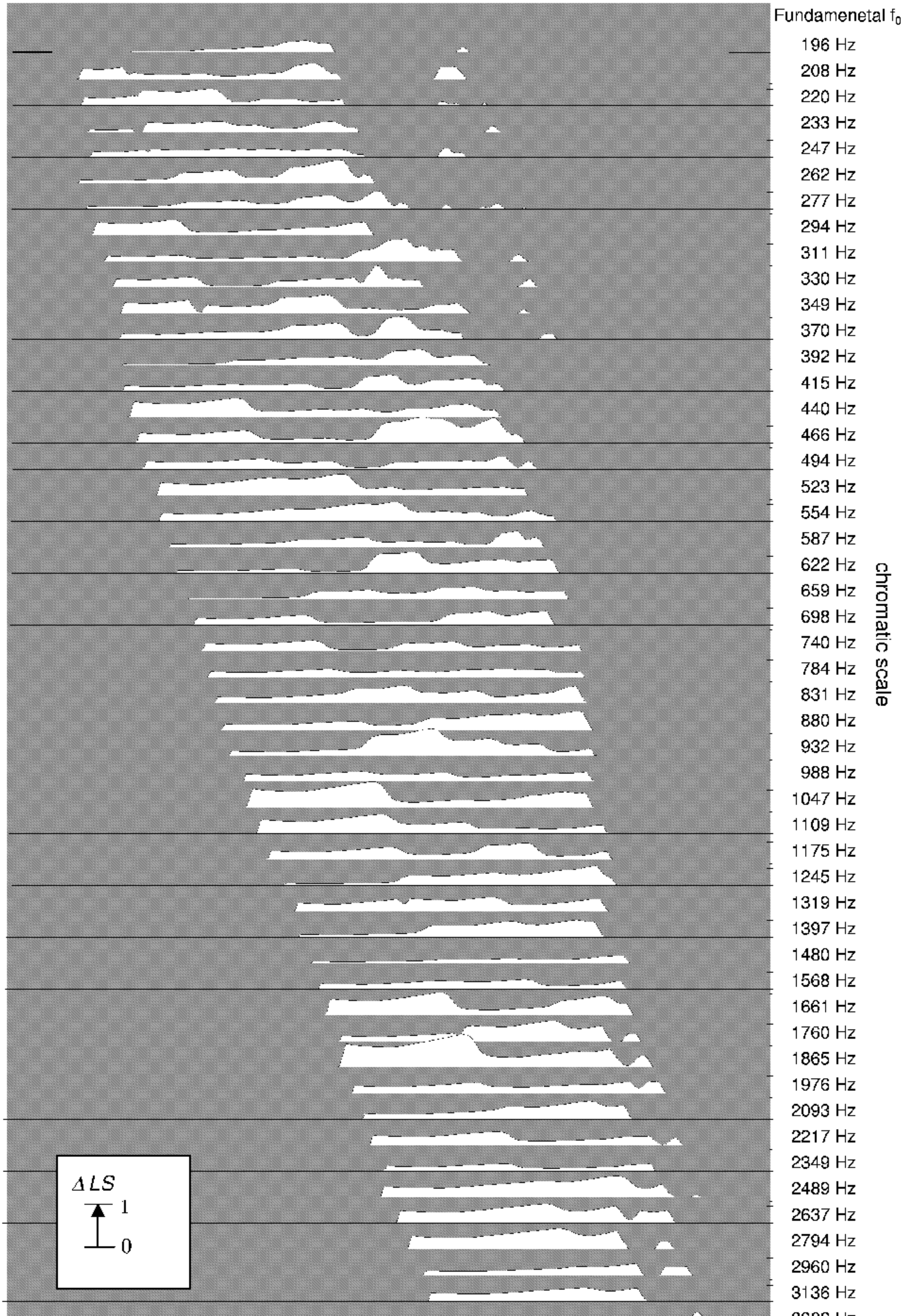
Note: During a single vibrato period (back and forth motion of the left hand), the minimum and maximum levels shown in the figure will be produced once. (Here: pitch=a1; vibrato shift=25 cents; computed from the resonance profile of a violin by Guarneri del Gesu from the year 1733).
For more information about this method, click on the following link:
www.schleske.de/index.php?http://www.schleske.de/06geigenbauer/akustik3schall3messmeth.shtml (as well as the other sections listed there on the topic of “Sound analysis”)

Fig. 1 makes it easy to see how the specific loudness varies as a result of the vibrato (or more precisely, as a result of the amplitude modulation of the vibrating harmonics). For the musical pitch that is shown here, the differences are particularly strong in the range of the fundamental. The reason is that in the case of the Guarneri violin, the frequency of the very strong T1 corpus mode lies in the immediate vicinity of the fundamental pitch a1 (frequency = 440 Hz). This means that over a full vibrato period of the a1 note, the specific loudness (and thus the excitation of the inner ear) changes periodically between the two curve shapes that are shown. The individual harmonics generally cause the specific values of the loudness at different points in time (and not simultaneously). This is due to the fact that the harmonics (which are vibrating back and forth across the resonance profile) sweep across the maximum and minimum values of the resonance profile within their vibrato interval at different times. (In the example shown above, the vibrato-related modulation of the overall loudness thus fluctuates (assuming the dynamic range stays the same) between L=29.2 sone and L=24.3 sone only if all of the harmonics simul-taneously

brush over the local maxima of the violin's resonance profile.)
The characteristics of the instrument's resonance profile in the range of the harmonics associated with the note in question are critical in determining to what extent the specific loudness (and the overall loudness) of a note changes during a vibrato period (i.e. to what extent the note can be musically modulated). In order to depict the nature of this resonance in more detail, Fig. 2 shows the vibrato-related differences in specific loudness for all of the playable notes (once again using the measured resonance profile of the Guarneri del Gesu 1733).

We developed this "musical modulation diagram" to show that the vibrato-related fluctuations of the specific loudness are considerable across the entire playing range of the instrument. It is clear that the fluctuations vary in their extent in the different frequency groups (ERB scale). This diagram shows to what extent it is possible using vibrato to modulate the overall loudness and also the "tonal color" of the instrument in question over its entire playing range! As is also clear from the diagram, this musical quality is not present to the same extent for all of the pitches. The differences in the shapes of the white areas show that each note does not possess the same "sensitivity" and does not respond in the same region of the basilar membrane to the player's vibrato. This means that each note is a separate world of its own in terms of its tonal color.
All of the relationships described here between the invariable resonance profile and the frequency-variable "vibrating" harmonics demand extremely sophisticated processing on the part of our hearing. Our neuronal network gets an incredible workout in the process. This is why these "live" notes tend to be so captivating.

The construction parameters which in-fluence the need (as described here) for narrowband resonances and regions of high resonance density are related above all to the violin varnish. The reason is that the instrument's varnish has a significant influence on the damping of the individual resonances. We also suggest you read the separate article entitled "Towards a more musical violin varnish":
www.schleske.de/index.php?http://www.schleske.de/09extras/extras3handbuch.shtml



Fundamenetal f_0
196 Hz
208 Hz
220 Hz
233 Hz
247 Hz
262 Hz
277 Hz
294 Hz
311 Hz
330 Hz
349 Hz
370 Hz
392 Hz
415 Hz
440 Hz
466 Hz
494 Hz
523 Hz
554 Hz
587 Hz
622 Hz
659 Hz
698 Hz
740 Hz
784 Hz
831 Hz
880 Hz
932 Hz
988 Hz
1047 Hz
1109 Hz
1175 Hz
1245 Hz
1319 Hz
1397 Hz
1480 Hz
1568 Hz
1661 Hz
1760 Hz
1865 Hz
1976 Hz
2093 Hz
2217 Hz
2349 Hz
2489 Hz
2637 Hz
2794 Hz
2960 Hz
3136 Hz
chromatic scale
ΔLS
1
0

Fig. 2: Depiction of the vibrato sensitivity (and thus the modulability and flexibility of sound) of a violin by Guarneri del Gesu. Vertical axis: Chromatic scale (frequencies of the fundamental pitches). Horizontal axis: “Frequency axis of the inner ear”