For a sine tone, it is easy to assess whether it ties in with the 1-Hz-criterion, or with the 2‰-critrerion: the limit is at 500 Hz, with a transition from one limit value to the other♣. For sounds comprising several partials, this decision is not so simple anymore. Given an E_2-string, the first 6 partials are below 500 Hz, all further partials are above that limit. In such cases the following holds: frequency changes become audible if for at least one (audible) partial the threshold or frequency discrimination is surpassed. For the E_2-string it thus is not the 1 Hz / 82,4 Hz ≙ 12‰ criterion that forms the basis for the decision but the 2‰-harmonics-criterion. This is a good match to the tolerance range we found in electronic tuners. With the conversion into the unit cent that is customary among musicians, the tolerance range is **3 – 5 cent** (with 1 cent = 1/100th semi-tone interval ≙ 0,58‰). The 1-cent-accurracy that is sometimes demanded is exaggerated: on the guitar, the temperature of the strings would have to be kept constant within 0,1°C (which may be difficult when playing your hot grooves, as cool as they may feel). If the guitar can be tuned with an accuracy of ±2‰, we are on the safe side. This does not mean, though, that every larger deviation will immediately sound out-of-tune. Our hearing system can be quite forgiving and ready to generously compromise in certain individual situations.

8.2.3 Pitch perception

It has already been noted above that pitch and frequency are different quantities. Our auditory system determines the pitch according to complex algorithms – an associated comprehensive discussion would go beyond the scope of this book (specialist literature exists for this). A first important processing step is the frequency/place transformation in the inner ear (cochlea): a travelling wave runs within the helical cochlea, with the wave-maximum depending on amplitude and frequency of the sound wave. Tiny sensory cells react to the movement of this travelling wave; they transmit nerve impulses among various nerve fibers to the brain. The latter performs further advanced processing. A regularly plucked guitar sound consists of a multitude of almost harmonic partials. Round about the first 6 – 8 of these partials result in distinguishable local travelling-wave maxima, the higher partials are processed grouped together.

Normally, we cannot hear the individual partials when a string is plucked. Rather, we hear a complex tone with *one single* pitch. With a little effort, however, these individual partials may be heard, after all. To do this, we first suppress a given partial using a notch-filter, and then switch off the filter-effect so that the original signal is reproduced. From the moment the filter is switched off, the partial in question will be audible for a few seconds, and then merge again with its colleagues to form the integral sound experience that was originally audible. A sufficient level of the partial is a requirement; the partial may not be masked to such an extent by its spectral neighbors that it does not contribute at all to the aural impression. How the single elements are grouped and combined together – that has long been a topic of research for the Gestalt-psychologists. This topic resulted first of all in the **Gestalt laws** for the visual system (see Chapter 8.2.4). In particular, it is the “principle of common fate” that also plays a role in the auditory system if the issue is to group the individual partials of a complex sound event, attributed them to sound sources, and to assign to the latter characteristics such as e.g. a pitch.

♣ Both “1 Hz” and “2‰” are to be taken as approximate values that are subject to individual variations.

As a rule, the pitch recognition works rather well for complex tones with *exactly harmonic* partials – especially if there are lots of partials. However, just like in the visual system with its optical illusions, we know in the auditory area of special sounds that lead to seemingly paradox perceptions. If the partials are not harmonic – as it is the case e.g. for bells – the pitch algorithm develops estimates based on probabilities. Results can be that a subject (test person) cannot decide between two pitches, or that two subjects allocate entirely different pitches to the one and the same sound. Sounds of strings are, however, only mildly in-harmonic, and merely octave confusions are conceivable in the worst case. As a rule, for the **pitch of a string tone** a value is determined that is close to the fundamental but not identical to it. In a first step, the auditory system allocates to all non-masked partials their **spectral pitch**, and on that basis calculates a **spectral rating curve** that has a flat maximum at **around 700 Hz** ♣ – this is the **virtual pitch**. Higher-frequency and lower-frequency partials therefore contribute less to the pitch than middle-frequency components. Experiments carried out by Plomp♥ show that it is – in particular – not the fundamental that defines the perceived pitch. In a piano tone, the frequency of the fundamental was decreased by 3%, while all other partials were increased by 3 %; the result being that the perceived pitch went up by 3%. While the fundamental can have a big influence on the **tone color**, it is rather insignificant for the pitch as long as there are sufficient higher harmonics available.

Now, in the **guitar**, the harmonics are progressively shifted towards higher frequencies (at 1 kHz easily by + 15 cents). If we calculate back the pitch from this, we arrive at a value that is higher than the reading on an **electronic tuner** (measuring merely the fundamental). We should still not retune to make the tuner display 15 cent more – things are more complex. The perceived pitch of the fundamental (or its frequency) is not simply the n-th fraction of the frequency of the n-th partial: Fastl/Zwicker [12] report of hearing experiments with harmonically complex tones with a perceived pitch *lower* that the objective fundamental frequency. The error of the mentioned electronic tuner would thus tend in the same direction as processing in the hearing system. Moreover, it needs to be considered that the pitch (despite constant frequencies of the partials) is dependent on the **sound level**: as the level increases, the pitch decreases by as much as 5 cents per 10 dB. Even larger effects can be created by **additional sounds** that are superimposed on the guitar sound: literature [12] knows of pitch shifts that can be as large as a semi-tone in extreme cases! Such shifts may not be part of everyday guitar playing, but all in all there is a wide field leaving much space for fundamental research. What also transpires: **cent-exact tuning is not actually possible**. Even though frequencies of individual partials may be measured and adjusted with high precision – it's the hearing system that decides whether the tuning is "correct" … and it will use complicated, situation dependent and even individual criteria. That laboratory experiments indicate that pitch differences of **3 – 5 cent** are recognized does not imply that this accuracy needs to be always observed. It is impossible to specify a mandatory limit for tones hat would be audibly out-of-tune, because too many parameters determine the individual case – but in practice the following rule-of-thumb has proven itself: **a tuning error of no more than 5 cent is desirable**, with 10 cents often being acceptable. Those listeners who have privilege to experience sound through "golden ears" may happily halve these numbers.

♣ Terhardt E.: Pitch, Consonance, and Harmony. JASA 55 (1974), 1061–1069.
♥ Plomp R.: Pitch of complex tones. JASA 41 (1967), 1526–1533.

