Between music and molecular studies: the third tone according to Hermann von Helmholtz.

Mion Marta

Otolaryngology Unit, Santa Maria della Misericordia Hospital, Rovigo, Italy

Abstract
In 1713, the famous violinist Giuseppe Tartini found that, while playing two different notes at the same time, another sound could be heard. He called it "the third tone". This phenomenon was extensively studied by several scientists, one for all Hermann von Helmholtz, who built specific resonators to demonstrate his theories. Only with the modern research, we were able to give the physiological and molecular explanation of the third tone.

Introduction

"Quite strange, very seriuos and rather shy… a very intelligent and poised man…", that's how Hermann von Helmholtz (1821-1894) looked in his times (Meulders 2005). Born in Postdam, he devoted his life to studying medicine and physics, but also aesthetic and subjective perception: he believed in "psychophysical laws" such as "psychoacoustic" (Mion 2021). In his masterpiece Die Lehre von den Tonempfindungen als physiologische Grundlage für die Theorie der Musik (von Helmholtz 1885), he proposed a revolutionary scientific explanation for the so-call "Tartini's third tone". Giuseppe Tartini (1692-1770), violinist, researcher of musical theory and "psychomathematical harmonist" (Barbieri 1990) said in his Trattato di musica secondo la vera scienza dell'armonia that: "It is physically certain that given two simultaneous loud and prolonged tones one can hear a third tone, different from the played sounds" (Tartini 1754), weaker than the main tones and corresponds to a lower note than the two notes played, and it has a precise arithmetical relationship to them. The concept of frequency did not belong to the cultural environment of Tartini, furthermore in those times the knowledge of acoustic was very poor, so the physical bases of the third tone were unknown. The violinist simply assumed that the third tone was created by the collision of air masses shifted by two instruments (for instance, two violins).

In the following century, after systematic and extensive studies conducted by several scientists as Thomas Young, Joseph Luis Lagrange and Rudolph Koenig, the third tone was more properly called "combination tone".

On the sensations of tone

Helmholtz disagreed with the previous theories and so he proposed, in his "On the sensation of tone" (von Helmholtz 1885), a new and innovative thought about the combination tones, which later became famous as the "distortion theory". Helmholtz was convinced that for not infinitesimal deformation of elastic bodies, as in case of the air compressed or expanded by the acoustic waves (especially for high intensities), the response of the system is non-linear. Given two simultaneous sinusoidal tones at frequency f1 and f2, the non-linearity generates a distortion of the original sounds with the creation of new distinctive frequencies: the combination tones that, according to Helmholtz, are formed within the auditory system, in the vibrant components of the middle ear. In this sense, the structure of the tympanic membrane and the ossicular chain could produce an asymmetric response to the positive or negative movement that would lead to the described distortion (Caselli 2018). Even if combination tones are explained by the phenomenon of distortion, they do not necessarily create annoying sounds, indeed the dissonance depends on the absolute frequencies of the notes and the relation between them and the third tone, as stated in the chapter "Interruptions in Harmony" of "On the sensation of tone" (von Helmholtz 1885).

Helmholtz Resonators

For his studies, Helmholtz introduced in 1863 his homonymous resonator (Fig.1 a,b: Helmholtz's resonators – by the courtesy of Dr. Sofia Talas, Institute of Physics, University of Padua), an oscillating hollow sphere that sways at its own resonance frequency. The device has got two openings: a funnel which had to be insert into the ear and another aperture open to the environment. Helmholtz managed to distinguish the harmonics of various sounds inventing multiple resonators, each with a specific resonant frequency (Mion 2021). They were primarily used to demonstrate the theory of tone quality, or the idea that complex sounds with different harmonics could be decomposed into elemental tones. Helmholtz established that "....musical tones are the simpler and more regular elements of the sensations of hearing, and that we have consequently first to study the laws and peculiarities of this class of sensations" (von Helmholtz 1885).

Fig.1 a,b: Helmholtz's resonators – by the courtesy of Dr. Sofia Talas, Institute of Physics, University of Padua

Molecular evidence

According to modern experiments, combination tones derive from a distortion of primitive sounds, as seen above, but not generated in the middle ear (as supposed by Helmholtz), but in the cochlea, an organ which is characterized by a non-linear behavior. The source of non-linearity and cochlear distortion responsible for the combination tones is an active positive feedback cycle of amplification: in response of a perceived sound, the hair of the cochlear external cells are deflected by the relative sliding movement of the tectorial and basilar membrane. The hair deflection opens some mechanoelectrical channels letting the potassium (K+) ions enter the cell; the entrance of positive charges generates a depolarization that causes a force which elongates the cell, promoting a further hair deflection that reinforce the initial deflection. The main contribution to the distortion is probably due to the non-linear behavior of the mechanoelectrical channels and to the non-linear relationship between the hair deflection and the entrance of the K+ ions. Thus, the physical explanations of Tartini's third tone analyzed by Helmholtz has got molecular origins and it is based on mechanoelectrical cellular channels (Caselli 2018).

Conclusions

Helmholtz thought of music as the art form that had “withdrawn itself from scientific treatment” (von Helmholtz 1857). Following his famous treatise on sound, Helmholtz inspired numerous researchers to deepen their studies about the laws underlying music, as Rudolph Koenig who made a career out of “building Helmholtz's ideas into apparatus” (Boring 1942).

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