“Specific sensations of noise”

Wundt on noise and tone

Author: Denis Seron

Affilitation: University of Liège, FNRS

email: d.seron@uliege.be

Abstract

This chapter discusses some of Helmholtz’s views on noise and their critique by Wilhelm Wundt. The question raised is whether all noises are qualitatively complex and thus subject to psychological analysis, or whether some of them are simple and thus undefinable. This question boils down to asking whether the difference between noise and musical sound is primitive or not. Wundt views it as primitive, while Helmholtz does not. The issue has important implications for the study of sensory experience. Both authors share an analytic conception of psychology, for which the question of what are the ultimate elements of auditory experience is central and indispensable.

Keywords

Wundt, Helmholtz, sensation, noise

The difference between noise and musical sound has been a topic of increasing interest in the aesthetic literature of recent years. One reason for this is that it determines our view of what a musical work consists in. For example, it is often stressed that the difference plays a practical role in the process of music recording. Noises generated by the instruments (finger squeaks, key slaps, etc.) or the background audience (coughing, talking, etc.) are commonly removed from the recording — which requires some knowledge of what differentiates noise from musical sound. The problem, however, is that this knowledge in turn seems to presuppose some understanding of what the musical work is. For it does not seem that undesirable noises are removed in virtue of any specific intrinsic feature. For example, a cannon shot will be eliminated in most cases, but not in Tchaikovsky's *1812 Overture*. One and the same note is sometimes retained and sometimes undesirable. The choice of discarding an element as "noise" does not depend on intrinsic features, but on whether it is considered as part of the work being performed (Judkins 2011: 14). But how are we to identify what belongs in the work and what does not? Recorded works are obviously not limited to score notations, and a number of them — improvisations, for example — are not even scored. The question actually seems to involve us in some sort of circle. On the one hand, noise is not identifiable intrinsically, but extrinsically as what is not part of the musical work. This corresponds to what Kromhout (2021: 61) calls "the conceptual logic of noise reduction, which defines noise negatively and retroactively as everything that can be ignored, eliminated, or instrumentalized". On the other hand, the musical work is what remains when noise is expunged. From this it is tempting to conclude that it is simply a matter of convention whether a sound is taken to be "musical" or not. In this respect, the aesthetic approach to noise may seem somewhat unsatisfying, insofar as it fails to provide any intrinsic or *natural* (as opposed to merely conventional) criterion for what makes certain sounds "musical" and others not. This paper aims to explore an alternative view which was widely held in the 19th century.

The question of what differentiates musical sound from noise was hotly debated among philosophers, psychologists and natural scientists in the 19th century. Interestingly, however, their approach pointed in the exact opposite direction, the idea being that the difference must be a difference in nature, that is, a difference grounded in intrinsic or natural features of sounds. Hermann von Helmholtz's treatise *On the Sensations of Tone* of 1863 is commonly seen as the most representative and influential work in this direction. In what follows, I discuss some of Helmholtz's views on noise and their critique by Wilhelm Wundt. The question I am concerned with is whether all noises are qualitatively complex and thus subject to psychological analysis, or whether some of them are simple and thus undefinable. This question boils down to asking whether the difference between noise and musical sound is primitive or not. Wundt views it as primitive, while Helmholtz does not. The issue has important implications for the study of sensory experience. Both authors share an analytic conception of psychology, for which the question of what are the ultimate elements of auditory experience is central and indispensable.

In a nutshell, the problem for these authors is the following. First, they consider auditory experiences to be analyzable in terms of auditory sensations or sounds. Second, they define musical sounds or "tones" — as opposed to noises — as regularly periodic sounds. Third and finally, the question is whether noises are somehow reducible to tones, that is, always characterizable as a combination of tones. If noises are reducible to tones, then the ultimate elements of any auditory experience are tones. If they are not, it is necessary to postulate some noise/tone dualism at the level of immediate experience.

1. Noises are made up of tones (Helmholtz)

Helmholtz's aim in his *On the Sensations of Tone*, as indicated in the full title, is to provide "a physiological basis for the theory of music". In order to achieve this aim, he first needs a definition of musical sound, which is provided in the first chapter of the book. Significantly, noise interests Helmholtz only insofar as he seeks to define musical sounds, that is, sounds conceived (along with silences) as constituents of tonal music (see Wittje 2016: 10). "The first and principal difference between various sounds experienced by our ear, Helmholtz says, is that between noises and musical tones [*musikalischen Klängen*]" (Helmholtz 1870: 14; trans. 7). Sounds are either musical or not musical; the former he calls "tones" (*Klänge*), the latter "noises" (*Geräusche*).[1] Accordingly, what is wanted is some feature that is a necessary condition for a given sound being musical, or whose absence is a sufficient condition for its being noise. Needless to say, this issue is different from (although not unrelated to) the issue of harmony and consonance, since the required criterion should be broad enough to cover simple tones such as those produced by a tuning fork.[2]

In phenomenological or qualitative terms, sound theorists of the time commonly characterized this distinctive feature as "a certain smoothness and continuity about the musical note" (Rayleigh 1877: 4). "Metaphorically, one could say that there is something innerly clear and quiet about tones […], while noises have something innerly unclear, rough and unquiet" (Ebbinghaus 1902: 276). While a musical sound is "a perfectly undisturbed, uniform sound which remains unaltered as long as it exists" (Helmholtz 1870: 14, trans. 7–8), noise, John Tyndall says, is produced by pulses "of irregular strength and recurrence", which "dash confusedly into the ear, and reproduce their own unpleasant confusion in our sensations". "Music resembles poetry of smooth and perfect rhythm, noise resembles harsh and rumbling prose" (Tyndall 1867: 50).

---

[1] Helmholtz uses "*Klang*" as an umbrella term for any sound produced by a periodic vibration. If the vibration is simple, he sometimes uses instead the word "*Ton*". See (Helmholtz 1913: 38, trans. 22–23 modif.): "Though we have hitherto used the expressions '*Ton*' and '*Klang*' indifferently, we shall from now on restrict our use of '*Ton*' to mean the *Klang* of simple vibrations. It is absolutely necessary to distinguish in acoustics first, a *Klang*, that is, the impression made by any periodic movement of the air; secondly a *Ton*, that is, the impression produced by a simple vibration." For simplicity, I translate the German "*Klang*" as "tone" (rather than "musical tone"), and "*Ton*" as "tone" or (depending on the context) "simple tone". J. Tyndall in his lectures on sound translates "*Ton*" as "tone" and uses "clang" to denote a sound produced by a compound vibration (Tyndall 1867: 117–118; 1869: 138). Some translators — for example C.M. Williams and S. Waterlow in their translation of (Mach 1922) and C.H. Judd in his author-approved translation of (Wundt 1896) — always translate "*Klang*" as "clang". Alexander J. Ellis, the English translator of (Helmholtz 1870), translates "*Ton*" as "tone" and "*Klang*" as "note" or "tone" or "musical tone", "leaving the context or a prefixed qualification to determine whether it is simple or compound". See his (heavily altered) translation and footnote in (Helmholtz 1895: 22–24). Rayleigh, in his *Theory of Sound*, calls musical sounds "notes" and unmusical sounds "noises" (Rayleigh 1877: 4; Wittje 2016: 12). Our use of "noise" corresponds to the German *Geräusch*. On other terms usually translated by "noise" (*Lärm*, *Störschalle*), see (Wittje 2016). Needless to say, this paper is no way concerned with non-auditory (for example visual) meanings of "noise".

[2] I confine myself to noise and tone sensations and leave aside the issue of harmony and consonance — which, on Wundt's view, is about representations rather than sensations (Wundt 1880, Vol. 1: 406). Wundt also criticized Helmholtz's account of harmony and consonance. See (Wundt 1880, Vol. 2: 59).

At Helmholtz's time, music physicists had long discovered that this feature corresponded to certain quantitative, measurable properties of the sonorous bodies. Since Antiquity (Dostrovsky 1975: 180–181) and especially since Galileo, tones had been compared with periodic waves — an idea which is obviously presupposed by the view, dominant since the 17th century, that pitch is equivalent to frequency. Based on this, by linking the two aspects we can arrive to a definition that combines physics, physiology and psychology: some uniform motion of a body causes an equally uniform vibration of the air, which in turn excites the ear, producing a smooth and continuous sensation which corresponds to a musical sound or tone.[3]

Helmholtz thus defines tone as "the whole sensation excited in the ear by a periodic vibration of the air" (Helmholtz 1870: 37, trans. 22–23). By contrast, noises are generated by non-periodic vibrations:

> The irregularly alternating sensation of the ear in the case of noises leads us to conclude that for these the vibration of the air must also change irregularly. For musical tones on the other hand we anticipate a regular motion of the air, continuing uniformly, and in its turn excited by an equally regular motion of the sonorous body, whose impulses were conducted to the ear by the air (Helmholtz 1870: 15, trans. 8).

However, this characterization needs to be refined. Some noises, for example some thunder-claps, are generated by one single air wave. Thus it may be desirable to distinguish two cases: one in which the noise is produced by a single wave, and one in which it corresponds to an irregular sequence of waves. Noises of the former kind are clearly aperiodic. But what about the noises of the latter kind, for example coughing or sneezing noises? Following Wundt (1880: 386), we can broaden our notion of periodicity and call noises of the latter kind "irregularly periodic".[4] This leads us to revise Helmholtz's characterization of noise as "a sensation due to non-periodic motions of the sonorous body" (Helmholtz 1870: 16, trans. 8) and to say this: noise is a sensation produced by either a non-periodic or an irregularly periodic air wave. The latter case corresponds to Wundt's definition of noise as "a sensation produced by an irregularly periodic [*unregelmässig periodische*] motion of the air" (Wundt 1880, Vol. 1: 387).

It has been often observed that irregularly periodic noises can be obtained by combining regularly periodic waves, that is, tones. When on a piano you simultaneously strike all the keys comprised in one or two octaves, you obtain noise (Rayleigh 1877: 4; Helmholtz 1870: 14, trans. 8). The reverse is not true. "No combination of noises", says Rayleigh (1877: 4), "could ever blend into a musical note". Helmholtz generalizes this idea to all noises, concluding that all noises due to irregularly periodic motions are compound of (*i.e.*, analyzable in) sensations due to regularly periodic motions. In short, all such noises are made up of tones. Noise occurs when "many various sensations of tone are irregularly mixed up and as it were tumbled about in confusion" (Helmholtz 1870: 14, trans. 8, modif.). For this reason, Helmholtz regards noise as of secondary importance for the study of

[3] On this threefold approach, see (Helmholtz 1870 : 4–6, trans. 3–4) and (Vogel 1993 : 285).

[4] Helmholtz uses "periodic" and "regularly periodic" as synonyms, defining a periodic motion as "one which constantly returns to the same condition after exactly equal intervals of time" (Helmholtz 1870: 15, trans. 8).

auditory sensations. The only natural way to proceed must be from the simple to the complex; it is to start with the elements of all sounds, namely tones:

> We can easily compound noises out of musical tones […]. This shows us that musical tones are the simpler and more regular elements of auditory sensations, and that we have consequently first to study the laws and peculiarities of this class of sensations (Helmholtz 1870: 14–15, trans. 8, modif.).

This view is clearly supported by Ohm's acoustical law, according to which the human ear analyzes complex sounds in simple tones (Ohm: 1843). It is not only that all periodic sound waves can be mathematically decomposed — using Fourier analysis — in their sinusoidal components, nor is it only that they are so structured physically, but it is also that the human ear must be capable of performing such analysis upon any auditory stimuli.[5] Helmholtz regards the existence of this ability as a fact confirmed by our everyday experience. When several people are talking at the same time, we are perfectly able to pick out and understand individual voices (Helmholtz 1870: 40, trans. 25). For Helmholtz, the analysis of a sound in its constituent parts requires attention and thus, in a number of cases, learning and training. We focus on one individual voice rather than another or the whole sound.

2. Simple noises (Wundt)

Helmholtz's theory of sound has been widely discussed and debated among scientists and philosophers. In the ensuing discussion I restrict myself to some broad considerations to do with noise.

A first difficulty of Helmholtz's view, raised by Sigmund Exner (1876: 230), concerns the analysis of noise sensations. As we have seen, some noises — for example, the crackling of an electric spark — are generated by one single sound wave and thus should be categorized as non-periodic. But if they are non-periodic, Exner argues, then such noises "have nothing to do with tones physically" and can hardly be said to be analyzable in tones defined as (regularly) periodic sounds. Periodic noises raise similar concerns. Supposing that Helmholtz is right, the ear analyzes them in regularly periodic sounds. For example, it decomposes the cacophony of a tuning orchestra in individual

---

[5] Ohm formulated his acoustic law as follows: "I had always taken it as an established fact that the components of a tone whose frequency is said to be f must retain the form $a.\sin 2\pi ft$ or $a.\cos 2\pi ft$, in which t denotes the time and a the vibration amplitude for the successive tone elements — and conversely, that a succession of impressions on our ear that continuously retain the form put forth here must also necessarily cause the sensation of a tone" (Ohm 1843: 513). Here is Helmholtz's version: "The rule by which the ear proceeds in its analysis was first laid down as generally true by G.S. Ohm. […] Every motion of the air, then, which corresponds to a composite mass of musical tones, is, according to Ohm's law, capable of being analyzed into a sum of simple pendular vibrations, and to each such single simple vibration corresponds a simple tone, sensible to the ear, and having a pitch determined by the periodic time of the corresponding motion of the air" (Helmholtz 1870: 54, trans. 33). See (Vogel 1993: 264 ff.), (Cheveigné 2005: 180–183) and, for a more historical account, (Kromhout 2020).

tones. But suppose that, by an extraordinary fluke of chance, all the instruments of the orchestra suddenly harmonize so as to provide a recognizable chord. What is the difference between the two sounds? There must be a psychological difference: the former, and not the latter, is experienced as noise. But is this difference explainable in physical terms? Aren't they both analyzable in simple tones? Exner's suggestion is that the former is not really or objectively a noise. Unlike the crackling of the electric spark, it is, in Exner's words, just a "subjective noise" (*subjektives Geräusch*), that is, a sound that "physically consists of tones that we cannot isolate due to deficient perceptual abilities".

This suggests that there are noises, for example orchestra cacophonies, whose quality of noise is, to some extent, independent of how the auditory stimulus is physically structured. In other words, the inference from the physical to the psychological here is not justified, and thus the definition of noise as a sensation produced by an non-periodic or irregularly periodic air vibration requires further qualification. This objection lies at the heart of Wilhelm Wundt's critique of the Helmholtzian approach to noise. The general idea is that this approach implies some *metabasis eis allo genos*. Wundt accepts that noises are composed of tones, but he denies that they "can be completely decomposed in simple tones" (Wundt 1880, Vol. 1: 390–391). His view is that they must contain some specific qualitative element — a "specific sensation of noise" (*eine spezifische Geräuschempfindung*) that is irreducible to any combination of tones. Therefore, the noise/tone difference is ultimately a matter of psychological rather than physical analysis. This is summarized in the following quote from Wundt's *Principles of Physiological Psychology* (second edition):

> Most physiologists in recent times, like Helmholtz, view noise as a sum of tone sensations that interfere irregularly. However, this view is based on an unjustified transfer of the physical analysis of noises to sensation. While such a transfer is permissible with tones — because a sensation of tone can really be decomposed into a sum of tone sensations —, this is by no means the case with noises. Instead, besides the accompanying tone components, there always remains a specific sensation of noise, which is inaccessible to such decomposition (Wundt 1880, Vol. 1: 391).[6]

This view is diametrically opposed to Helmholtz's view. Consider a noise *N* produced by an orchestra. You may be fully able to isolate *N*'s constituent parts such as violin or trumpet tones. Helmholtz, as we have seen, holds that this process of isolating sound elements requires attention. For him, this clearly proves that the structure of *N* is not intrinsic to the auditory sensation or nerve process. In other words, the constituent parts are *discovered* in the physical phenomenon rather than produced by experience. The "fusion and unification" of the partial sounds, he argues, "since it is to be broken down [*lösen*] through attention, cannot be accomplished by the activity of the nerve, but only by physical activity" (Helmholtz 1856: 527). Therefore, the noise/tone difference must be

---

[6] See also (Wundt 1880, Vol. 1: 390–391): "The same analysis applies to a certain extent to noises. In most noises we can clearly distinguish individual tones. However, a noise can never be completely decomposed into simple tones, but besides the distinguishable tones of a certain pitch, there always remains a peculiar sensation that varies depending on the nature of the noise, which is different from the tone qualities and which accordingly we will have to consider as the specific sensation of noise [*die spezifische Geräuschempfindung*]."

defined in physical terms. By contrast, Wundt's claim is that the process of recognizing a sound as noise involves something different than its physical analysis. Noise sensations exhibit a certain distinctive feature that is an object of physiological psychology. It is this psychological feature that makes some elements of N noises rather than tones.

More precisely, the basic picture is as follows (Wundt 1896: 58 ff., trans. 48 ff.). Consider again the noise *N*. This noise is a complex experience, namely a "representation" (*Vorstellung*) in Wundt's terminology. It is composed of complex partial tones, for example violin or trumpet tones, each of which is analyzable in simple tone sensations. Simple tone sensations (*i.e.*, *Töne*) correspond to sine waves, that is, to waves that are defined by the following formula: $p = a.\sin(2\pi ft)$ — where p is the acoustic pressure, a the amplitude, f the frequency, and t the time. Their quality is called *pitch*. Of course, simple tone sensations are mere *abstracta* — of which the sounds generated by resonators and tuning forks are just approximations. As Helmholtz has shown, musical sounds are generally compound of a fundamental tone with its harmonics. The musician's tonal scale demands an even higher level of abstraction, insofar as it selects a small number of notes from a continuous series (Wundt 1896: 61, trans. 51).

The auditory sense is undoubtedly an "analyzing sense" (Wundt 1880, Vol. 1: 301). We have the ability of decomposing *N* in simple tones. "To a certain extent, namely insofar as accompanying tone sensations exist, we decompose irregularly periodic movements — noises — in regularly periodic oscillations, that is, tones" (Wundt 1880, Vol. 1: 391). Helmholtz is right on that point: in this respect, the processes of sensation and physical stimulation are parallel (Wundt 1880, Vol. 1: 391). Wundt's view, however, is that *N* must be something more than an irregularly periodic combination of tones. To appear as noise, it must contain some "specific sensation of noise". To put it otherwise, its full psychological analysis reveals, besides tone sensations, simple noise sensations that are qualitatively different from tone sensations. "The noises commonly so called are representational wholes [*Vorstellungsverbindungen*] that are composed of such simple noise sensations and of great many irregular tonal sensations" (Wundt 1896: 58, trans. 49, modif.).

Noises and tones, Wundt claims, form "two independent […] systems of auditory sensations" (Wundt 1896: 58, trans. 48). A major difference between the two is that noise sensations offer nothing comparable to tone pitches (nor thus with timbres). The system of simple noise sensations is "homogeneous" (*gleichförmig*) in the sense that noises are qualitatively uniform, with their only differences being differences in intensity and duration.

Wundt provides a phylogenetic explanation of the coexistence of two independent auditory systems in humans and higher animals (Wundt 1880, Vol. 1: 301–304; Wundt 1896: 58–59, trans. 49). At that time, the seat of tone sensations was unanimously localized in the cochlea. Wundt appropriated Victor Hensen's then-recent hypothesis that tones were produced by the hair cells of the basilar membrane rather than by the "Corti arches".[7] This led him to explain pitch differences, following Hensen, by the cochlea's shape rather than by the length of the hair cells within the Corti organ. Pitch differences correspond to differences in diameter between parts of the cochlea: wider parts react to lower tones and narrower parts to higher tones — just as violin strings sound differently depending on their length. Now, what about noises? As the physiologist Preyer says, "after removing the *cochleae nervus* alone, you would still be able to hear a lot, but no more tones [*Töne*]"

[7] See (Hensen 1863). A central argument was that the Corti organ is missing in birds, which have a keen auditory sense. For an overview of this and related controversies, see (Titchener 1912: 111–112) and (Bentley and Titchener 1904).

(Preyer 1879: 30). Thus, noise sensations must be located in some other part of the inner ear. The observation of lower animals and embryos of higher animals, Wundt argues, suggests that the cochlea evolved from a differentiation of some part of the vestibule which may have primitively functioned as an auditory organ. Hence Wundt's hypothesis is that the homogenous system of noise sensations developed first and then evolved into a heterogenous system due to the formation of the cochlea. The more primitive system —supported by many other parts of the inner ear (otoliths, vestibule, ampullae, auditory nerve, etc.) — remained along with the more developed one, so that humans have two distinct auditory systems instead of one.

3. Conclusions

The quality of an experience — what it is like to have it — is either simple or complex. The quality of feeling bitter, for example, may be clarified in terms of sadness and anger, but it is presumably impossible to explain what it is like to feel sad to someone who has never felt sad. Helmholtz holds that the noise quality of a given sound is wholly analyzable in tone qualities or pitches. For Wundt, on the contrary, psychological analysis reveals the existence of a noise quality that is irreducible to tone qualities and sensed by a special auditory organ.

Wundt's noise/tone dualism is fraught with difficulties. A first difficulty is the apparent existence of continuous transitions between tones and noises. Ernst Mach notably claimed to have experimentally demonstrated such continuities (Mach 1922: 218–219, trans. 266–268), concluding (without referring to Wundt) that the difference in question was not a difference in nature. The sensation produced by an explosion, he declares, "is *qualitatively* the same as that produced by striking at once a large number of adjacent piano-keys either high or low in the scale" (Mach 1922: 219, trans. 268, modif.). Therefore, there is no need to search for a specific organ for noise sensations. However, the objection may not be as strong as it seems. Actually, nothing rules out the possibility that the crossing of an intensive threshold sometimes involves a qualitative change.

Second, one might be tempted to object, like Mach and others (Titchener 1912: 96), that gunshots sound obviously higher than cannon shots and thus that noises present differences in pitch. Therefore, their quality is reducible to tone quality and it is superfluous to search for a specific noise organ. At first glance, this objection seems easy to answer. On Wundt's view, as we have seen, noises generally contain partial tones. Thus, pitch differences between noises can always be ascribed to tones that are mixed with them. But then the difficulty is that it seems hardly possible to determine the number of elementary noise qualities (Titchener 1912: 97) or even, as Ebbinghaus (1902: 281) pointed out, to figure out how a simple noise — that is, a noise without pitch — could sound.

A third and final difficulty concerns how Helmholtz and Wundt conceive of the method of analyzing a sensation in its parts. At first sight, it may seem that the question is merely whether a noise sensation can be (qualitatively) simple or not. But some of Helmholtz's phrasings suggest that his approach is somewhat different. In his view, as we have seen, it is attention that makes one experience the sound's constituent parts, which thus should be viewed as physical. "A composite tone", he says, "appears to us as a simple sensory sensation [*als eine einfache Sinnesempfindung*], but by appropriately directing our attention we are able to discover various sensory sensations in it"

(Helmholtz 1856: 527). In clear, this means that auditory sensations are initially simple and become complex only in a *distinct* experience that involves attention. This view is different from Wundt's, who regards the unanalyzed experience of a complex sound as a representation, that is, a complex of sensations.[8] But paradoxically it may be interpreted as in line with Wundt's view that there exist simple noises.

References

Bentley, I.M., and Titchener, E.B. (1904). Ebbinghaus' explanation of beats. *The American Journal of Psychology*, 15(1), pp. 62–71.

Cheveigné, A. (2005). Pitch Perception Models. In: *Pitch* (C.J. Plack, R.R. Fay, A.J. Oxenham, A.N. Popper, Eds.). New York: Springer.

Dostrovsky, S. (1975). Early vibration theory: Physics and music in the seventeenth century. *Archive for History of Exact Sciences*, 14(3), pp. 169–218.

Ebbinghaus, H. (1902). *Grundzüge der Psychologie*, Vol. 1. Leipzig: Veit.

Exner, S. (1876). Zur Lehre von den Gehörsempfindungen. *Archiv für die gesamte Physiologie des Menschen und der Thiere*, 13(1), pp. 228–253.

Helmholtz, H. von (1856). Ueber Combinationstöne. *Annalen der Physik und Chemie*, 99(12), pp. 497–540.

— (1870). *Die Lehre von den Tonempfindungen als physiologische Grundlage für die Theorie der Musik*, 3rd ed. Braunschweig: Vieweg. Engl. trans. (1895): *Sensations of Tone as a Physiological Basis for the Theory of Music*. London New York: Longmans and Green. Reprint (1954) with a new Introduction by H. Margenau. New York: Dover.

Hensen, V. (1863). Zur Morphologie der Schnecke des Menschen und der Säugethiere. *Zeitschrift für wissenschaftliche Zoologie*, 13, pp. 481–512.

Judkins, J. (2011). Silence, sound, noise, and music. In: *The Routledge Companion to Philosophy and Music* (Th. Gracyk and A. Kania, Eds.). London New York: Routledge.

Kromhout, M.J. (2020). The unmusical ear: Georg Simon Ohm and the mathematical analysis of sound. *Isis*: *A Journal of the History of Science Society*, 111(3), pp. 471–492.

— (2021). *The Logic of Filtering: How Noise Shapes the Sound of Recorded Music*. Oxford: Oxford University Press.

Mach, E. (1922). *Die Analyse der Empfindungen und das Verhältnis des Physischen zum Psychischen*, 9th edition. Jena: Fischer. Engl. trans. (1959): *The Analysis of Sensations and the Relation of the Physical to the Psychical*. New York: Dover.

[8] Interestingly, it may also allow to avoid some difficulties of Helmholtz's characterization of the human ear as a Fourier analyzer. On these difficulties, see (Ward 1970: 438 ff.).

Ohm, G.S. (1843). Ueber die Definition des Tones, nebst daran geknüpfter Theorie der Sirene und ähnlicher tonbildender Vorrichtungen. *Annalen der Physik und Chemie*, 59(8), pp. 513–565.

Preyer, W.T. (1879). *Akustische Untersuchungen*. Jena: Gustav Fischer.

Rayleigh, J.W.S. (1877). *The Theory of Sound*, Vol. 1. London: Macmillan.

Titchener, E.B. (1912). *A Text-Book of Psychology*. New York: Macmillan.

Tyndall, J. (1867). *Sound. A Course of Eight Lectures delivered at the Royal Institution of Great Britain*, 3rd ed. London: Longmans Green. German trans. by H. von Helmholtz and G. Wiedemann (1869): *Der Schall. Acht Vorlesungen gehalten in der Royal Institution von Grossbritannien*. Wiesbaden: Springer.

Vogel, S. (1993). Sensation of tone, perception of sound, and empiricism: Helmholtz's physiological acoustics. In: *Hermann von Helmholtz and the Foundations of Nineteenth-Century Science* (D. Cahan, Ed.). Berkeley Los Angeles London: University of California Press, pp. 259–287.

Ward, D. (1970). Musical perception. In: *Foundations of Modern Auditory Theory* (J.V. Tobias, Ed.), Vol. 1, pp. 407–447. New York San Francisco London: Academic Press.

Wittje, R. (2016). Concepts and significance of noise in acoustics: Before and after the Great War. *Perspectives on Science*, 24(1), pp. 7–28.

Wundt, W. (1880). *Grundzüge der physiologischen Psychologie*, 2nd ed., 2 Vol. Leipzig: Engelmann. Partial Engl. trans. (1904): *Principles of Physiological Psychology*. London: Swan Sonnenschein; New York: Macmillan.

— (1896). *Grundriss der Psychologie*. Leipzig: Engelmann. Engl. trans. (1897): *Outlines of Psychology*. Leipzig London New York: Engelmann.