Contemporary Music Review
Vol. 30, No. 5, October 2011, pp. 329–344

Routledge
Taylor & Francis Group

The theories of Helmholtz in the work of Varèse

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In 1905 Varèse discovered the French edition of Die Lehre von den Tonempfindungen als physiologische Grundlage für die Theorie der Musik *[On the Sensations of Tone as a Physiological Basis for the Theory of Music] of Hermann von Helmholtz (1863), the explicit intention of which was to bring together the common frontiers of science and music. This discovery was a revelation for the 22-year-old composer that went on to condition his whole philosophy of sound. The experiences of the German scientist, achieved with the aid of sirens, resonators or tuning forks, caught the imagination of the young composer. This article investigates the importance of the theories of Helmholtz for the Varèsian aesthetic and tries to put into context the methods of composition inspired by these experiments concerning the spectral constitution of timbres, resultant sounds and beating. We also examine the ways in which a change in the understanding of consonance, initiated by Helmholtz, drove Varèse towards an original conception of atonality.*

Keywords: Atonality, Beating, Helmholtz, Consonance, Resultant Sounds, Varès

The idea of an art–science is at the heart of the Varèsian aesthetic. If the recourse to geometric representations (symmetry, projection, rotation, hyperbola and parabola) plays an essential role in his compositions, it is above all the scientific approach to sound which, for Varèse, constitutes the principal motivation towards the ideal of the artist–engineer. He considered, as an essential prerequisite for the craft of the composer, a profound understanding of acoustics (Charbonnier, 1970, p. 71):

> A composer, if he wants to obtain the results called for by his conception, must never forget that his raw material is sound. He must think in terms of sounds and not in terms of notes on paper, on a page. He must understand not only the mechanism and the possibilities of the different sonorous machines that bring his music alive, but must also be equally familiar with the laws of acoustics.

In 1905, Varèse discovered the French edition of *Die Lehre von den Tonempfindungen als physiologische Grundlage für die Theorie der Musik* of Helmholtz (1863), curiously

ISSN 0749-4467 (print)/ISSN 1477-2256 (online) © 2011 Taylor & Francis
http://dx.doi.org/10.1080/07494467.2011.665578

translated as *Théorie physiologique de la musique fondé sur l'etude des sensations auditives* [Physiological Theory of Music Based on a Study of Auditory Sensations] (1868, TPM).[1] This discovery by the 22-year-old composer constituted a complete revelation that conditioned his whole philosophy of sound, as he declared in a conversation with Alcopley in 1963 (Varèse, 1983, p. 180):

> Helmholtz was the first person to make me perceive music as being a mass of sounds evolving in space, rather than as an ordered series of notes (as I had been taught).

From that point, Varèse engaged himself on a path contrary to one focused on the evolution of musical grammar, by concentrating his attention on sounds themselves, and on the means whereby they could be made to live and come together. Taking his cue from the experimental method of Helmholtz, which employed several devices such as sirens, resonators and tuning forks, the composer–engineer experienced for himself sirens, percussion instruments or discs. He called for the creation of laboratories where composers and physicists could collaborate[2] in creating electronic musical instruments.

However, in the light of this adoption of a more scientific viewpoint on sound and composition, one could ask whether the TPM exerted a tangible influence on the language of Varèse. According to the composer Hugues Dufourt (Dufourt, 1991, p. 112), 'The imagined physics of Varèse draws new intuitive certainties from science, and borrows from it the foundations of its own representation.' Does what Helmholtz brings amount simply to a stimulus for the imagination? Does the use of the knowledge of acoustics amount only to a means of producing acoustic analogies? Has Varèse's reading of the treatise given him sufficient practical methods for composition? The purpose of this article is to probe the TPM in order to understand how Varèse could transfer some of the acoustic properties described by the German scientist into the domain of composition. Before examining this matter, we will briefly re-trace the reception of the TPM and its influence on French artistic life.

Reception of the *Théorie physiologique de la musique*

The collusion between music, science and aesthetics, as well as having its roots in antiquity, begins to find a second wind in the middle of the 19th century. In a preliminary notice for *Esthétique musicale. Technie ou lois générales du systéme harmonique* [Aesthetics of Music. Technique or General Laws of the Harmonic System] (Durutte, 1855), Camille Durutte foresaw that the object of music, considered as a science,

> consists essentially in the aesthetic modification of time, that is to say in the rhythm of the duration of the vibrations, the laws of music are necessarily the laws of mathematics.

Durutte sought a way out of empiricism by looking for a 'supreme law of harmony (or law of generation of chords)', which would permit 'reliance on a single group, not only of all the chords known, but of all the chords possible' (1885, p. xx). The theories of Durutte have had a certain influence, and it is probably through the *Technie* that Varèse discovered Wronski's definition of music as 'the embodiment of the intelligence of sounds' (1885, p. vi), a definition that he made his own.

Contrary to the *Technie*, the *Théorie physiologique de la musique* of Helmholtz had taken an approach to musical phenomena based on experimentation. In the introduction, Helmholtz affirms his ambition to bring together music and science (1954, p. 1):

> In the present work an attempt will be made to connect the boundaries of two sciences, which, although drawn towards each other by many natural affinities, have hitherto remained practically distinct—I mean the boundaries of *physical and physiological acoustics* on the one side, and of *musical science and aesthetics* on the other.

The originality of his thinking is in aiming for an explanation of the connections between a physical phenomenon (the sounding wave), physiology (hearing) and aesthetics (the tonal system). The part dedicated to the physiology of hearing distinguishes Helmholtz's treatise from the work of his predecessors that content themselves with a purely acoustic approach. He justifies this move by the fundamental difference that he sees between poetry and the plastic arts on the one hand, and music on the other. Indeed, the latter results, according to him (p. 2),

> . . . in a much closer connection with pure sensation than any other arts. The latter rather deal with what the senses apprehend, that is with the images of outward objects, collected by physical processes from immediate sensation.

The artistic experience produced by a musical work does not lie in the representation of an external object, but rather in the auditory sensation that forms the 'primary material' of the music. Helmholtz did not deny that there was a level of representation in music (such as a harmonic progression, or an instrumental timbre), but he considered that this level is less important for aesthetic understanding. In short, music is more directly affected by sensory perception than the other arts, which is why his study needs to base itself on auditory sensation. Helmholtz thus effects a tipping of acoustics towards psychoacoustics that leads him to uncover a new explanation for consonance.

The TPM was quickly recognised as a fundamental advance in the areas of science and philosophy, although it was received by musicians with more or less indifference, even a certain suspicion. Ernst Mach was one of the first to pay homage to Helmholtz in one of his *Cours scientifiques populaires* [Popular Courses in Science] (Mach, 1866), which undertook to present the principal points of the theory in a more accessible form. Mach underlined the fact that the principal intention of the TPM had been to found the theory of music on experimental evidence and not on all manner of speculation. From this point of view, Mach compared the thinking of Helmholtz with

> the introduction by Herbart of mathematical methods and the natural sciences into psychology, the scientific treatment of the political, statistical information and political economy by Mil, Quételet and the others … (Mach, 1866, p. 86).

Physicists were equally propagators of the theories of Helmholtz, for example Radeau in his *L'acoustique ou Les phénomènes du son* [Acoustics, or the Phenomena of Sound] (1867) or Blaserna in his *Le son et la musique* [Sound and Music] (1877), which includes a lecture by the German thinker entitled, 'The physiological causes of musical harmony'.

Charles Henry, in his *Introduction à une esthétique scientifique* [Introduction to a Scientific Aesthetic] (1885), seizes on the Helmholtzian theories of auditory sensation in order to justify his approach to art as a play of nervous energy. Consonance is a force that induces nervous energy, just as dissonance is a force that inhibits it, since it proceeds from discontinuity (beating). Music being the concrete representation of abstract directions (high/low, right/left), he affirms that sonorities are mentally projected, following these analogies with a universal physiological character. Henry conceived of a chromatic circle with 12 divisions, which represented in analogous fashion the scale of sensations of colour alongside that of auditory sensations. His theories had a recognised influence in France, notably on Claude Debussy and Paul Valéry. It is possible that the idea of sound projection, dear to Varèse, was related both to the theories of Henry and to the concept of the fourth dimension presented in public by Henri Poincaré in *La Science et l'Hypothèse* [Science and the Hypothesis] (1902).[3]

At the beginning of the 20th century, the mixing of art and science, and its corollary the artist–engineer, became a mark of modernity. The figure of Leonardo da Vinci, already symbolised by Charles Henry in *Introduction à une esthétique scientifique*, was set up as a model by Paul Valéry in his 'Introduction à la méthode de Léonard de Vinci' [Introduction to the method of Leonardo da Vinci] (1895). According to Blaise Cendrars (1987, p. 77), between 1907 and 1914, 'One was equally busy with many of the latest scientific theories of electro-chemistry, of biology, of experimental psychology and of applied physics …'. Almost 40 years after its first German publication, the resistance with which musicians and musicologists had opposed the work of Helmholtz was dying out. Hugo Riemann or Carl Stumpf no longer called into question the whole of his research, even while they contested particular points (notably the explanation of consonance). According to Marcus Rieger (2006, pp. 151–152),

> In musical practice, one can observe equally the manner in which the questioning of Tonempfindungen [the sensation of tone] transforms itself into a passion for knowledge that realigns science and nature.

However, it is necessary to put this optimistic vision in context. Even if Leos Janacek, and above all Varèse, drew on the musical consequences of the theories of Helmholtz, neither Schönberg, nor Hindemith, nor Stravinsky held onto these ideas. The TPM, whose reputation was secure by the start of the 20th century, in the end touched musicians only marginally. Varèse, who loved the *Notebooks of Leonardo da Vinci*, could not but adhere to the theories of the German scientist and, more generally, to all those attempts to bring together music and science. The one who claimed in 1917 'science alone can infuse it (music) with an adolescent vigour' (Varèse, 1983, p. 24) preferred to choose his models from among the sciences, rather than submit himself to the academic teaching proposed by the Schola Cantorum and the Conservatoire.

Compositional Methods Inspired by the Physiological Theory of Music

Among the devices employed by Helmholtz are sirens. The siren, used as a sound generator by Seebeck and Ohm, was improved by Helmholtz by providing it with a regular rotation (Figure 1). The German scientist used it, for example, to show that the pitch of a sound wave depended uniquely on the number of vibrations, and not on their form or on their intensity. He was thus able to produce a table giving the frequencies of each pitch across seven octaves. Varèse was fascinated by the experiences with sirens described in the TPM to such an extent that he purchased two of them in a flea market, with which he made his first experiments with spatial music (using also the whistling of children). He discovered that he could, 'obtain wonderful parabolic and hyperbolic curves of sound' (Varèse, 1983, p. 180). But the siren, used as an instrument in *Amériques* (1921), *Hyperprism* (1923) and *Ionisation* (1931), was equally an opportunity to produce contrasts of sonority. Thus, as he affirmed in 1926 in writing about the sirens in *Amériques*:

> it is astonishing to see at what point pure sound, without harmonics, gives another dimension to the quality of the musical notes which surround it. Truly, the use of pure sounds in music has the same effect on the harmonics as a crystal prism has on pure light. This use irradiates them with thousands of unexpected and varied vibrations. (1983, p. 44)

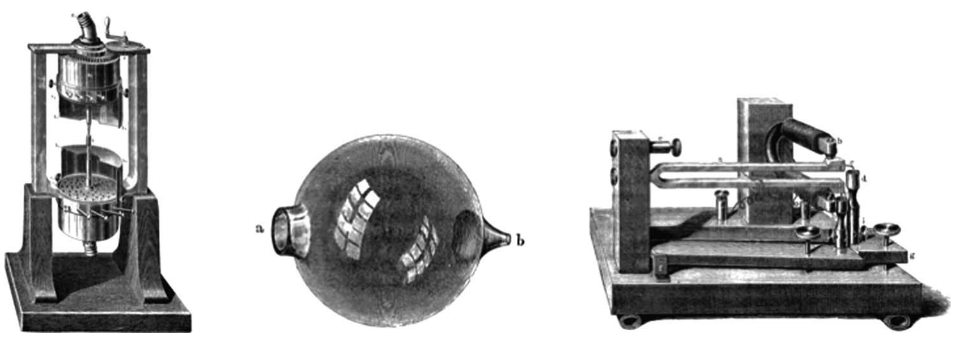

Figure 1 Experimental apparatus used by Helmholtz, from left to right: double siren, resonator, tuning fork-based frequency generator.

This metaphor of the prism refers to the decomposition of the white light of the sun into the colours of the rainbow. But the way in which Varèse explains it carries a confusion. In fact, on the one hand the siren used by Varèse, contrary to that of Helmholtz, could not be held at a fixed pitch, and on the other hand the expression 'pure light', which refers to white light (considered as pure and unpolluted) could not be compared with the timbre of the siren, which in reality is not pure (a non-sinusoidal wave). One sees the idea, however, that a sort of decomposition of a sound is achieved as the siren sweeps over the harmonics. One can observe this phenomenon in the sonograms (Figure 2) of a passage from *Hyperprism* (bars 26–29). The siren begins its intervention 'from nothing', its sound masked by the percussion. One can observe equally an attraction of the note held by the piccolo (A5) towards the 2nd harmonic of the E♭ clarinet (B♭5) as in the recorded versions (Boulez, 1995; Chailly, 1998). Do the glissandi of the siren tend to produce a deviation in the tuning of the instrumentalist? Is this an effect intended by Varèse in order to generate a variation of the interferences between the two frequencies or an effect of non-tempered tuning?

Thanks to his use of resonators, Helmholtz was able to demonstrate the existence of the harmonics described in the theory of Fourier. In parallel, he discovered the frequencies of inharmonic partials and the importance of attack transients. Above all, he could begin a systematic study of instrumental timbre in terms of its spectral content. He noticed for example that the greater the number of high partials, the greater the apparent brightness of the sound. In chapter 3 of the TPM, Helmholtz uses the expression 'sound mass' ('masse sonore') to designate a sound composed of elementary sounds (harmonics). This could be the origin of the idea of the sound mass dear to Varèse. The sound masses of Varèse are for example aggregates composed of structures of intervals and in groups of differentiated timbres, set in motion by the play of loudness envelopes and rhythmic profiles. In all his works, one can hear confrontations of sound masses giving rise to the phenomena of penetration, repulsion, fusion and fission. The work of Helmholtz seems thus to have given a theoretical basis for Varèse's idea of a music composed of sound material moving in space.

Another experimental device invented by Helmholtz, the frequency generator, consisted of tuning forks set in vibration by means of electromagnets.[4] The apparatus was designed to produce and control the spectral content of complex sounds. It could vary the timbre, as described theoretically, by modifying the number of harmonics. It was thus capable—and this made a great impression at the time—of reproducing artificially a certain number of known timbres (vowels and diphthongs, certain registers of the organ, clarinet and horn). It does not seem wholly improbable that these demonstrations of Helmholtz, showing that it is possible to reproduce timbres artificially, opened the way for the idea of inventing artificial sonorities. Concerning Varèse, one cannot speak of instrumental synthesis in the spectral sense of the word, for he did not take an instrumental spectrum as a model in order to reproduce it on the orchestra. For him it was a case of creating the conditions that allowed the possibility of a fusion of timbres among themselves.

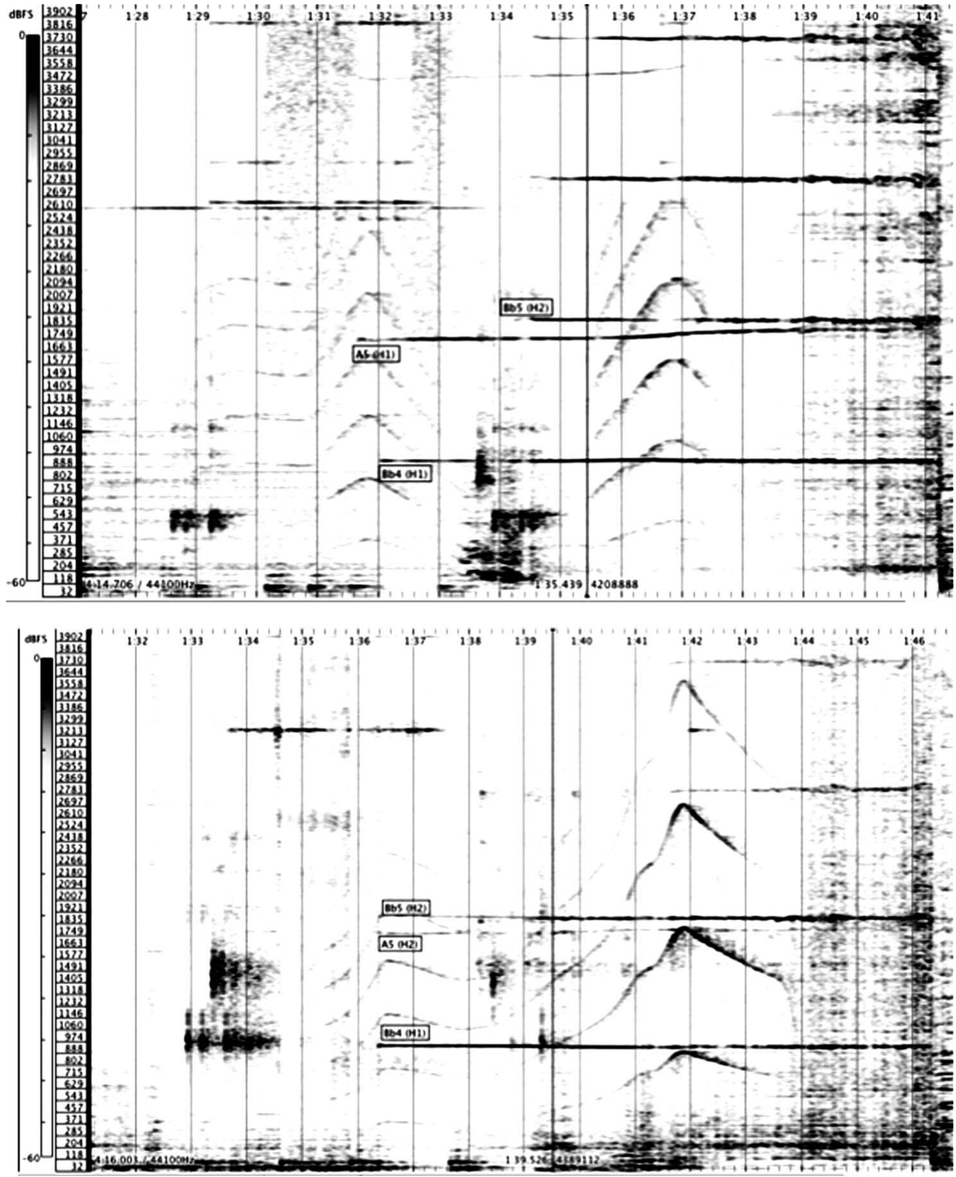

Figure 2 Sonograms (Sonic Visualiser, Cannam et al., 2010) showing the use of the siren in *Hyperprism* (bars 26–29), in the upper version: Boulez (1995), in the lower version: Chailly (1998).

One can find very numerous examples of aggregates of 9–12 sounds—in fact these are a constant feature of Varèse's style—which constitute sound masses of which the consistency and evolution are completely planned. Varèse planned the realisation of these aggregates,

> because they embrace a vast register between the low and the very high, organised as they are on the 'speculation of distances'; separated by a pianissimo, they attain, in the space of a second, volumes of sound unexpected and literally explosive. (Varèse, 1983, p. 63)

Most often, while the instruments enter in stages to create an increasing density of the sonic material, the first entry is in the middle register, the other sounds alternating between low and high registers.

The final aggregate of *Hyperprism* illustrates the formation of this kind of sound mass, which puts together by stages individual sounds around a central sound. Preceded by the entrance *fortissimo* of three horns in unison (bar 85), the aggregate is formed starting from the last note of the motif (C3, horn 2), which serves as the foundation for the network of sounds which are going to fuse together. Varèse shows his desire to enclose as vast space as possible by using a pedal tone on the bass trombone (B0, 61.74 Hz) and one of the highest notes of the piccolo (G6, 3139.96 Hz). The addition of the eight other sounds of the aggregate takes place within a very short time (around 3 seconds). After holding for a moment (around 4 seconds), the aggregate is transformed by means of a number of processes (Figure 3):

- filtering of the lowest register by suppression of the three lowest notes (B0, B♭2, C3).
- densification of the spectrum by the addition of metallic percussion.
- granular effect brought about by the piccolo trill (G/A♭, around 3200 Hz).

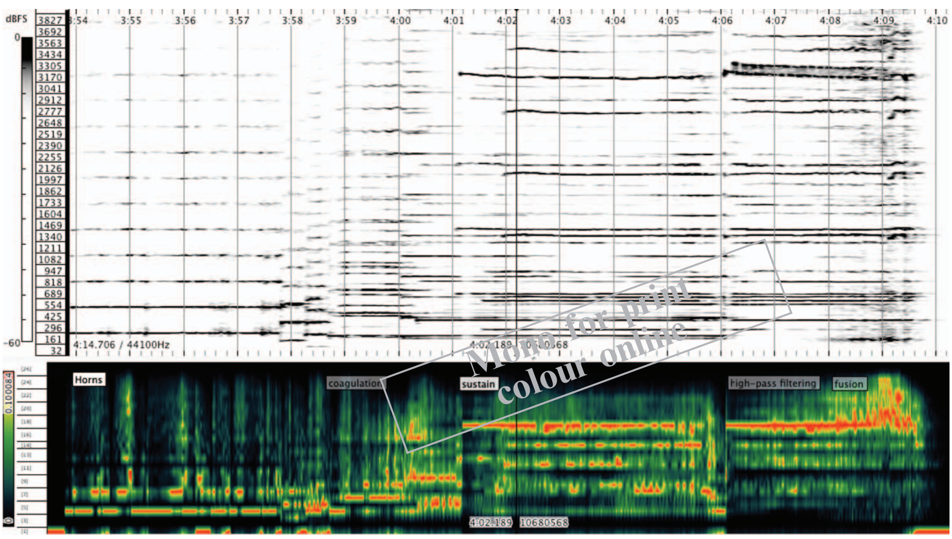

Figure 3 The final aggregate of *Hyperprism* (bars 86–90) in the version: Boulez (1995), upper panel—sonogram; lower panel—coefficient of energy in the critical bands (Sonic Visualiser, Cannam et al., 2010).

- fusing together of components by the play of the dynamics (piano subito/ crescendo).
- increase in brilliance of the composite sound by increasing the energy in the highest partials.

The second part of Helmholtz's work is devoted to the study of simultaneous sounds (resultant sounds and beating). Difference tones had been demonstrated in 1740 by the German organist Georg Andreas Sorge and had been the subject of a thorough investigation by the violinist Giuseppe Tartini. Helmholtz had a double siren[5] constructed in order to make a systematic study of difference tones, which led him to discover the existence of other tones, more difficult to perceive on account of their very low intensity. Combination tones[6] proved to be a phenomenon of sensory origin (an acoustic emission from the ear in response to a stimulus). Helmholtz invented a method whereby difference tones could be made more audible. It is necessary that the two sounds be produced with a strong intensity and in a sustained manner, and that they make an interval less than an octave. The lower sound must be produced first so that at the moment when the higher sound is produced one can hear the sought after difference tone. Resultant tones are not isolated phenomena; they occur in an uncontrolled fashion amongst the numerous superpositions of the harmonic partials. In 1930, on the occasion of a roundtable on 'the mechanisation of music', Varèse underlined the importance of this phenomenon for orchestration. In 1936, at a conference in Santa Fe, he envisaged the possibility of producing resultant sounds with electronic instruments: 'The never-before-thought-of use of the inferior resultants and of the differential and additional sounds may also be expected. An entirely new magic of sound!' (Varèse, 1998, p. 198). Did Varèse use resultant sounds in his instrumental compositions?

This question has been approached by a number of musicologists (Decroupet, 2001; Lalitte 2003, 2007, 2008). One can find several examples of their use, which, on investigation, serve to reinforce certain components of an aggregate, to produce interferences between components, to add virtual sounds or to detune the sound. If one applies Helmholtz's method to produce difference tones, one can discover in *Hyperprism* several passages that bring this phenomenon into play. Varèse chose tense intervals like the major 7th or the minor 9th, which produce a difference tone respectively of a tone (un-tempered) above or below the lower sound of the interval (the choice of octave is irrelevant since the differential applies to the lower sound of the interval). The appearance of the difference tones, producing interferences, has the effect of reinforcing the dissonance. Varèse uses difference tones calculated within thin textures, often reduced to two held sounds in order to increase the impact of the effect as at the beginning of the second movement of *Octandre*. Table 1 gives the differential sounds and the beating frequencies of intervals produced during three passages of *Hyperprism*.

In the case of the final aggregate of *Hyperprism*, the objective of the composer seems different. He has calculated the difference tones with the aim of obtaining a saturation of the chromatic space. The final aggregate comprises nine sounds (in the order of their appearance): C3, B1, A4, B♭2, [B0], E♭4/F#4, G6, E3, F4. Taking again the same criterion for the choice of interval (major 7th or minor 9th), the actual difference tones correspond to C#2, G#2, D3 and F#3. Three of these tones (C#2, G#2, D3), previously played by the horns in unison before the production of the aggregate, complete 'virtually' the total chromatic (Table 2).

These few examples show the point at which Varèse thought of composition as a writing of sound based on a transference of the laws of acoustics, which he had borrowed from the theory of the physiology of music (or from other acoustic treatises). Henri Barraud relates that, during an evening with the conductor Mitropoulos, Varèse described the score of *Amériques* in the manner of an acoustic engineer:

> Varèse explained his whole work as a succession of sound phenomena which he took apart for us by analysing the interferences provoked by a certain bringing together of timbres, certain agglomerations of sounds, calculating the raised frequencies added to the ensemble by the addition of such or such an instrument, by a cymbal and so on. (Barraud, 1968, pp. 153–154)

The theory of the physiology of music offered Varèse the opportunity to imagine compositional modalities totally unknown in his era and to work the material of sound in terms of coagulation, density, fusion, filtering, resonance, granularity … long before the appearance of electronic music.

Dissonance as Roughness: a Step Towards Atonality

The scientific description of the phenomenon of beating is at the heart of Helmholtz's theory of consonance. Helmholtz explains that if the beats are slow (around 4–6 beats/second), the impression that they create is rather pleasant and can give, 'a more lively, tremulous or agitating expression' (p. 167), but if they are fast (around 30 beats/second) 'the sensible impression is also unpleasant' (p. 168). In general, what makes the beating disagreeable is the intermittent excitation of the auditory nerve. Helmholtz deduced that consonance is a continuous sensation, and that dissonance is an intermittent one. Beats are also produced between the components of a complex sound: the more the harmonics of two sounds coincide, the less beating there will be. He obtained, by calculating the beats up to the 9th harmonic, a curve of roughness between two complex sounds. Helmholtz concluded that there is not a clear distinction between consonances and dissonances (as the ancients believed), but that there exists a continuous series of degrees, of assemblages of sound whose harshness increases progressively.

According to James Tenney (1988), the appearance of the Helmholtzian conception of consonance constitutes an important paradigm shift in music. Helmholtz had shown that his conception came not from mathematical or acoustic postulates, but from sensory ones. The notion of psychoacoustic roughness defended by Helmholtz did not depend solely on interval, but on register, on spectrum and on the level of intensity. The prediction of dissonance by the theory of beats thus depended on the function of absolute frequencies rather than on interval. This approach to consonance has been confirmed by the numerous works on psychoacoustics since those of Plomp and Levelt (1965) showing that the sensation of dissonance depends on the frequency difference relative to the width of the critical band.

The important point is that Helmholtz made a very clear distinction between sensory dissonance and cognitive dissonance—that is to say between nature and culture. According to him,

> Whether one combination is rougher or smoother than another, depends solely on the anatomical structure of the ear, and has nothing to do with psychological motives. But what degree of roughness an ear is inclined to endure as a means of musical expression depends on taste and habit; hence the boundary between consonances and dissonances has been frequently changed. (Helmholtz, 1954, p. 234)

Thus there exists an objective fact underlying dissonance, that of the roughness of the interval; however, it is the embedding in a given culture that inclines the listener to tolerate the roughness more or less. Finally, Helmholtz's message is that of a relative distancing between naturalist conceptions and the tonal system (cf. Rameau who sought a justification in natural resonance). Helmholtz concluded from his work that,

> the system of Scales, Modes, and Harmonic Tissues does not rest solely upon inalterable natural laws, but is also, at least partly, the result of aesthetical principles, which have already changed, and will still further change, with the progressive development of humanity. (1954, p. 235)

Such a conclusion no doubt contributed to drive Varèse towards the road of atonality. The first 30 years of the 20th century were crucial for the determination of new languages whose expression lies outside of the tonal system. Numerous composers such us Scriabin, Lourié, Roslavetz, Golïshev, Hauer, Schönberg, Berg, Webern, Eimert, Krenek, Bartók, Dallapiccola, Cowell, Ruggles, Crawford-Seeger ... were open to the discovery of systems that allowed the organisation of the chromatic world. Where did Varèse sit in this ferment of tendencies and ideas? While Varèse affirms, 'My language is naturally atonal' (1983, p. 64), the end is clearly to mark himself off from dodecaphonicism, and more widely to suggest his emancipation from all forms of system. We possess almost no explicit account from the composer of his compositional procedures. Paradoxically, the terminology, stamped on the scientific vocabulary used by the composer in his interviews and presentations (parabola, hyperbola, mass, projection, translation, gravitation, crystallisation ...), renders his intentions even more opaque. Believing in the virtue of the imagination, Varèse put up a certain resistance to analysis and repelled all reductive approaches to his work, as is related by Jean-Claude Risset (2004) who knew Varèse well at the end of his life.

The musicologist H. H. Stuckenschmidt (1956, p. 107) claims that, 'since 1910, he [Varèse] had introduced into his compositions constructions of sevenths and ninths which established a sort of counterbalance to the twelve tones.' A certain number of documents, available for consultation today at the Sacher Foundation (notably the 12-note series written out on manuscript paper, sometimes accompanied by their derived and transposed versions) show that the composer had a close interest in serialism. Among these documents, there exists a diagram traced by Varèse's hand, discovered quite recently by Chou Wen-Chung (Chou, 2006, p. 357). The inscription, 'Berlin 1910', indicates that it was drafted during one of Varèse's visits to Berlin between 1907 and 1913.

Figure 4 shows the 12 tones of the total chromatic graded on 6 levels. In the 1st hexachord, the pitches follow one another by minor 9ths (from C to F), in the 2nd hexachord by major 7ths (from F# to B). At the bottom left, an 'all-interval' chord is constructed following the lines traced by Varèse: from the 1st sound (C), to the 12th (B), then the 2nd (C#), the 11th (B♭), etc. But the most interesting thing is shown by the horizontal lines that link the intervals according to their degree of

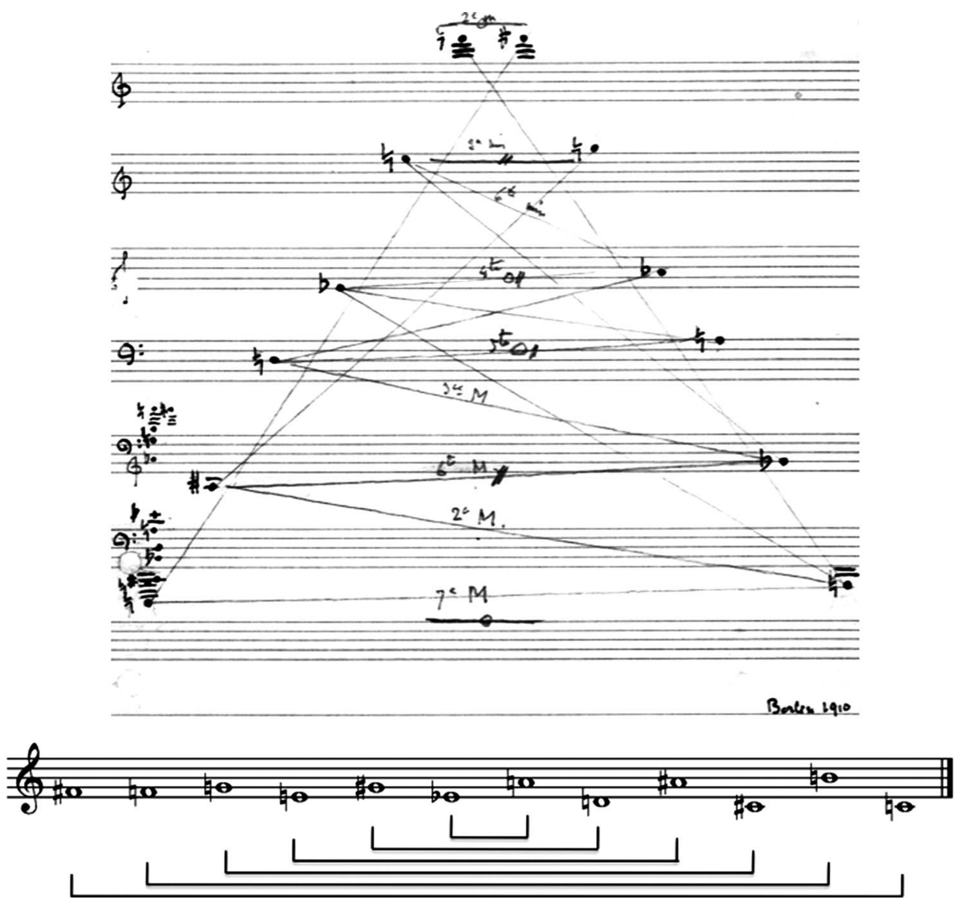

Figure 4 Diagram drawn by Varèse in Berlin in 1910, and a horizontal reproduction reduced to within the range of an octave.

consonance or dissonance, indicated by the circles or the oblique strokes. The major 7th and the minor 2nd are dissonant, the minor 3rd and the minor 7th are 'imperfect' consonances, and the 4th and the 5th are consonances. This classification of the intervals corresponds to that proposed by Helmholtz: absolute consonances (octave, 12th, double octave), perfect consonances (5th and 4th), medium consonances (major 6th and major 3rd), imperfect consonances (minor 3rd, minor 7th, minor 6th), dissonances (major 2nd, minor 2nd, major 7th). This diagram can be represented, in a more synthetic manner,[7] in the form of a chromatic series containing all the intervals (Figure 4). This series contains a certain number of properties that are beyond the scope of this article to discuss. We will mention only the organisation of the intervals on either side of two tritones: one external (the two extreme sounds), the other internal dividing the scale into two symmetrical hexachords (the intervals of one being the inversion of the other). Consistent with Helmholtz's curve of consonance, the intervals follow one another from the most dissonant to the least dissonant (1st hexachord) and conversely in the 2nd hexachord.

Did Varèse use this diagram for compositional purposes? And, in that case, how did he use it? Some indications permit us to respond to the 1st question in the affirmative. Thus, the chromatic loop of the 1st three pitches of the scale (F#, F, G), is met with very often in the melodic formulas of Varèse. A typical example is that of *Density 21.5* (cf. Lalitte, 2008). There are numerous musicologists who have pointed out the successions of major sevenths or of minor ninths, and or again the basic configurations of intervals of the 4th, tritone and minor 7th or of the 5th, tritone and minor 9th (Bernard, 1987; Motte-Haber, 1993). One can equally observe in Varèse the tendency to use aggregates spread out in stages. Varèse's melodies tend to unfold the total chromatic (more often 11 notes rather than 12) but without any respect as to their order. This is the case at the beginning of the 1st movement of *Octandre* or in the trombone melody in *Hyperprism* (bars 62–68). The main thing, for Varèse, is not the presentation of a series of 12 tones, but rather their organisation around an axial sound, a pivot note. The composer draws from the scale groups of two, three or four sounds, which he disposes in different registers in order to produce the combinations of intervals that he wishes to obtain (chromatic, leaps of 7ths, tritones, etc.).

The unfolding of the chromatic scale allows us to understand the disposition of pitches in the final aggregate of *Hyperprism*. One can observe in Figure 5 that the sequential order and the register of the sounds suggest a division into two chromatic groups (C, B, B♭—G, F#, F) at each of the extremes, and two groups based on the minor 9th and tritone placed in the middle register. The division of the sounds in the aggregate obeys an intervallic symmetry between the two extremes of sound (B0–G6) each one separated by 34 semitones from the sound at the centre axis (A3). Inside this frame, the other sounds are divided in a more or less symmetrical fashion. However, it is less useful to interpret Varèse's intervallic structures as a fascination for symmetry than as a means of organising the total chromatic and of controlling the

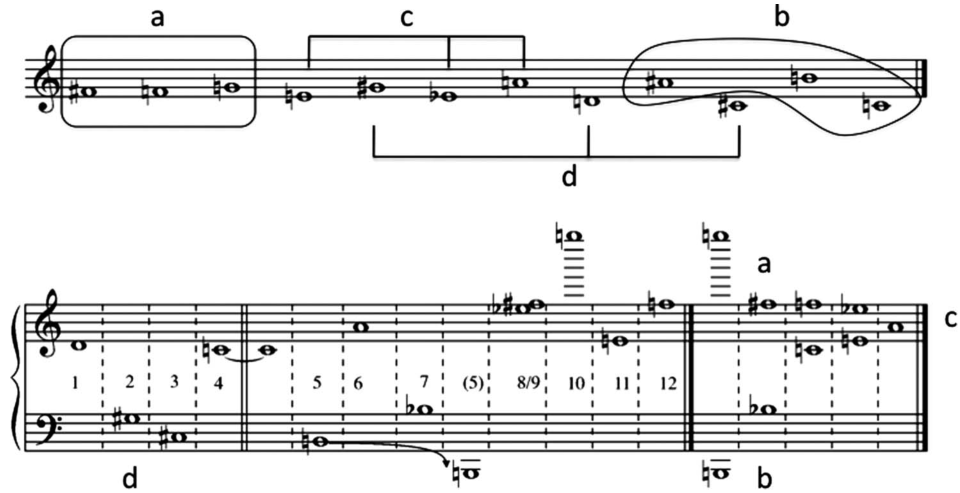

Figure 5 Intervallic structure of the final aggregate of *Hyperprism*.

sonic phenomena that arise from it. Thus, one can see clearly that Varèse tried to 'oxygenate' the extreme registers (with large intervals), while the middle of the aggregate contains more condensed sounds. Among them, the group of three sounds (F#4, F4, E♭4) constitute a sort of 'formant' (Figure 3) carrying a strong degree of roughness on account of the beats produced by the proximity of the sounds. To revisit the metaphor of language, it is never the case for Varèse, allergic to all systems, of inventing a grammar, but rather of working with the vocabulary of sound. Between the neo-tonal naturalism of Hindemith and the serial culturalism of Schönberg, Varèse chose a middle path by adopting an atonal way of writing without in any way renouncing hierarchies.

The TPM constitutes, for Varèse, the point of departure for a constantly renewed interest in sound and acoustic science. But, above all it appears a formidable reservoir of ideas from out of which Varèse developed his own musical conceptions and his methods of composition. He did not seek to apply set precepts to the letter, but more importantly to transpose the theories of Helmholtz into a musical universe, whatever their other scientific value, even if it meant overstepping them. The role of the physiological theory of music in the aesthetic of Varèse is not limited to the use of sirens. It is in fact at the foundation of his conception of music as 'organised sound' and it led him to conceive of composition as working with sound masses that operate in space. Helmholtz's concept of roughness served to guide him towards a conception of dissonance centred more on sonic phenomena than on the interval.

AQ5 **Table 1** Differential sounds in three passages of *Hyperprism*
Table 2 Difference tones in the final aggregate of *Hyperprism*

Translated from French by Peter Nelson

Notes

[1] The French translation of the title is misleading since it was not Helmholtz's intention to propose a theory of music, but rather a theory of the auditory sensations as applied to music. A better translation would be: *La théorie des sensations auditives comme fondement physiologique de la théorie de la musique* (A Theory of the Auditory Sensations as a Physiological Foundation for a Theory of Music). We will use the abbreviation TPM to refer to Helmholtz's treatise, since it is this edition that was read by Varèse. The citations from the TPM are from the English edition, published by Dover (1954).

[2] In 1927, with this in mind, Varèse made contact with Harvey Fletcher, director of acoustic research at the Bell Telephone Laboratories.

[3] The work of Poincaré had an immense impact on the collective imagination. Apollinaire, Delaunay, Gleizes, Matisse, Metzinger, Tablada and Valéry were fascinated by the fourth dimension. On this subject, cf. Lalitte (2009).

[4] The sound obtained was continuous, since it persisted for as long as the experimenter left the electro-magnet active, but less intense. It was necessary to place next to the tuning fork a resonator, which had the same frequency.

[5] The double siren consists of two Dove sirens having several series of holes on each disc. Both of them turn with the same speed, but it is possible to turn by hand one of the two air nozzles, injecting air across one of them in a way that marginally varies the frequency.

[6] Two tones of frequency f_1 and f_2 sound simultaneously, producing a difference tone corresponding to $f_2 - f_1$ and summation tone corresponding to $f_1 + f_2$ (Rossing, Moore & Wheeler, 2002, 157–159).

[7] Chou (2006, p. 356) claims to have seen another version of the diagram reduced to two levels.

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