The Perception of Microsound and its Musical Implications

CURTIS ROADS

Media Arts and Technology Program and Center for Research in
Electronic Art Technology (CREATE), University of California,
Santa Barbara, California 93106, USA

ABSTRACT: Sound particles or microsounds last only a few milliseconds, near the threshold of auditory perception. We can easily analyze the physical properties of sound particles either individually or in masses. However, correlating these properties with human perception remains complicated. One cannot speak of a single time frame, or a "time constant" for the auditory system. The hearing mechanism involves many different agents, each of which operates on its own timescale. The signals being sent by diverse hearing agents are integrated by the brain into a coherent auditory picture. The pioneer of "sound quanta," Dennis Gabor (1900–1979), suggested that at least two mechanisms are at work in microevent detection: one that isolates events, and another that ascertains their pitch. Human hearing imposes a certain minimum duration in order to establish a firm sense of pitch, amplitude, and timbre. This paper traces disparate strands of literature on the topic and summarizes their meaning. Specifically, we examine the perception of intensity and pitch of microsounds, the phenomena of tone fusion and fission, temporal auditory acuity, and preattentive perception. The final section examines the musical implications of microsonic analysis, synthesis, and transformation.

KEYWORDS: music perception; temporal acuity; microsound; music composition; sound particles; grains; pulsars; pointillism

THE TIMESCALE OF SOUND PARTICLES

Music transpires on many timescales. For a given musical composition, the topmost timescale is the macroform comprising the major sections of the work. Beneath this layer are the myriad phrases or mesostructures within each section. Each phrase can be partitioned into a collection of individual sound objects (or notes) that form the sonic surface of the work. In 1946, the Nobel prize–winning physicist and inventor, Dennis Gabor, postulated the existence of another multilayered stratum beneath the sonic surface: the microsonic hierarchy. In Gabor's view, all sonic phenomena can be decomposed into collections of sound particles on a timescale of 1 to 100 ms. He called these particles *sound quanta.* As Gabor observed, the timescale of sound quanta is of special significance to auditory perception because it delimits the thresh-

Address for correspondence: Curtis Roads, Media Arts and Technology Program and CREATE, 3431 South Hall, University of California, Santa Barbara, CA 93106. Fax: (805) 893-2930.

clang@create.ucsb.edu

Ann. N.Y. Acad. Sci. 999: 272–281 (2003). © 2003 New York Academy of Sciences.
doi: 10.1196/annals.1284.038

old of hearing for such properties as pitch, timbre, amplitude, spatial position, and microevent order.[1–3]

For events that last less than about 1 ms, many mechanisms of sound recognition break down, relegating these events to subsymbolic status. For example, the individual samples of a linear pulse-code–modulated audio signal, which last 22 μs or less (depending on the sampling rate), can hardly be distinguished from one another. It takes a series of hundreds of individual samples to form an acoustic particle that the ear can distinguish as being unique.

Computer-based tools let us view and manipulate the microsonic layers, from which all acoustic phenomena emerge. Electronic musicians can synthesize new tones made up of streams or clouds of sonic particles. This is the domain of *particle sound synthesis,* which takes different forms depending on the properties of the particles and the strategy for particle generation. *Granular synthesis* and *pulsar synthesis* are two of the best-known techniques.[4–6]

In the field of psychoacoustics, much study has gone into the perception of microevents. The source material for these studies consists primarily of individual particles (impulses, tone and noise bursts, tone pips). Understandably, these studies do not address the musical potential of direct composition with sound particles. Since particle synthesis techniques are now widespread in electronic music circles, it is time to reconsider these studies in this light.

With modern sound analysis software, it is easy to analyze the acoustical properties of sound particles from myriad angles. However, correlating them with human perception remains complicated. We cannot paint a complete portrait of the relations between microsound and perception. The perception of microsound in musical contexts is intertwined with cognitive functions, both rational and emotional, that resist understanding from a scientific point of view. The background and mood of the individual listener are like a narrow filter imposed on the sonic sensation. No two persons hear with the same brain. We could say that the communication between the composer and the listener is "imperfect." This is not a flaw; rather, it is part of the fascination of music.

The remainder of this paper harvests results from scientific studies in the perception of microsound. I compare scientific studies with my own experiments in the studio and analyze the musical implications from the perspective of the composer of electronic music. Some of this material appeared in my book entitled "Microsound,"[6] but this paper is a new formulation based on additional research.

THE LIMITS OF TEMPORAL PERCEPTION

Sound has a powerful effect on human beings. As it penetrates the human auditory system, acoustic energy is converted from variations in air pressure (outer ear) into mechanical vibrations (middle ear), liquid waves (inner ear), and ultimately patterns of electrical impulses transmitted to the brain via the auditory nerve. In turn, these electrical patterns trigger biochemical changes in the brain and the body. Since the auditory system processes different media (mechanical, liquid, electrical, chemical) and employs multiple agents operating on their own timescales, one cannot speak of a single time frame or a "time constant" for the auditory system.[7] The brain integrates signals being sent by diverse hearing agents into a coherent auditory picture.

The earliest research on the latency of the human auditory system can be traced to the great pioneer of nineteenth-century acoustics, H. Helmholtz. He was trained as a surgeon and professor of anatomy. One of his first discoveries was the speed at which nerves conduct electrical impulses.[8] This and later research have determined that the nerve fibers conduct impulses at rates between 1 and 100 meters per second, with faster rates corresponding to larger nerve bundles.[9] This was the first physical measurement of the "thickness of the present,"[10] corresponding to the accumulation of sources of inherent latency in the human auditory system.

Since that time, ascertaining the temporal limits of sound perception has intrigued scientists.[10–14] Measurement is made complicated by the fact that it is hard to separate temporal effects from spectral effects. As is well known in signal processing, to change the duration of a sound simultaneously changes its spectrum. In particular, the shorter a sound, the broader its spectrum. To cite one example, subjects can discriminate a single click from a pair of clicks separated by as little as a few dozen microseconds. The single click and the double click have spectral differences that appear in the highest octave of perception. When noise is added to mask frequencies in this octave, the threshold value of the gap between the particles increases dramatically, indicating that the initial result was not a direct measure of temporal resolution.

Gabor[1–3] suggested that at least two mechanisms are at work in the detection of microsonic events: one that isolates events in time and space, and another that ascertains their pitch. In line with this theory, Edward G. Jones pointed out a bifurcation of function in his description of two parallel auditory pathways, the tegmental and the direct.[15] Zatorre *et al.*[16] point to a similar bifurcation of auditory pathways for "temporal" versus "spectral" information.

In their important book "Audition," Buser and Imbert[12] summarize a number of experiments with transitory audio-phenomena. The general result of these experiments is that for stimuli lasting less than 200 ms, many aspects of auditory perception change character. Different modes of hearing come into play in the perception of intensity, fusion/fission, and pitch. The next sections address these issues.

MICROTEMPORAL INTENSITY PERCEPTION

In general, subjective loudness diminishes with shrinking duration below 200 ms. Specifically, at low amplitudes, short sounds must be much greater in intensity than longer sounds in order to be perceptible. The difference in the detectability threshold is on the order of +20 dB SPL (approximately 1000%) for tone pips of 1 ms as opposed to those of 100 ms in duration.[12]

MICROTEMPORAL FUSION AND FISSION

Machine circuits can easily track pulse patterns in range of gigahertz, as any computer demonstrates. By contrast, the human auditory system is constrained by severe limits in its temporal resolution. Human beings lose track of pulse rhythms at tempi greater than about 20 Hz. If one tone pip follows less than 200 ms after another, the onset of the second tone pip will tend to be masked by the former, a time-lag phe-

TABLE 1. Average pitch recognition time as a function of frequency

Frequency (Hz)	100	500	1000	5000
Minimum duration for pitch recognition (ms)	45	26	14	18

nomenon known as *forward masking,* which contributes to the illusion of continuous tone. When the onset time between pips is less than about 50 ms (corresponding to a particle emission rate of 20 Hz) human perception reaches "attentional limits" and groups the successive events into the illusion known as a continuous pitched tone.

Similarly, at fast tempi, a rapid sequence of tones at different pitches blends into a continuous "ripple." Here the auditory system is unable to successfully segment the incoming information into a temporal structure (i.e., to track its rhythm and melody) and simplifies the situation by interpreting it as a rapidly varying texture. Bregman describes these phenomena in his theory of *auditory streams.*[17–19] Conversely, a stream of particles that is already perceived as a fused tone can be made to segregate or disintegrate when the pitches, timbres, spatial positions, or amplitudes of the particles differ beyond certain thresholds, or more obviously when the onset time between events is sufficiently great.

Using sound analysis techniques such as the tracking phase vocoder[20] or matching pursuit analysis with wavelets,[21,22] we can make a sound such as continuous speech disintegrate (or coalesce) by deleting (or adding) individual particles on the Gabor matrix or time-frequency plane (Ref. 6, track 65 of the audio compact disc).

MICROTEMPORAL PITCH PERCEPTION

The acoustician Werner Meyer-Eppler was one of the most important figures in the early development of electronic music. (Karlheinz Stockhausen considers him to be his most important teacher.[24]) In the 1950s, Meyer-Eppler's experiments showed that the time needed to recognize the pitch of a tone is dependent on the tone's frequency, with the greatest pitch sensitivity in the middle frequency range between 1000 and 2000 Hz. TABLE 1, cited in Ref. 25, confirms this view.

As TABLE 1 shows, it takes only 14 ms to recognize a pitch of 1000 Hz, while tones both higher and lower than 1 kHz take longer to recognize. Doughty and Garner[11] divided the mechanism of pitch perception into two regions. They estimated that above about 1 kHz a tone must last at least 10 ms (ten cycles) to be heard as possessing the characteristic of pitch. Below 1 kHz, at least two to three cycles of the tone are needed. As Helmholtz[25] observed, the phenomenon of recognizable pitch evaporates below approximately 40 Hz.

MICROTEMPORAL AUDITORY ACUITY

Green[26] suggested that temporal auditory acuity (the ability of the ear to detect discrete events and discern their order) extends down to durations as short as 1 ms. Microevents that are less than about 2 ms in duration are heard as a click, but we can still change the waveform and frequency of the events to vary the timbre of the click.

Such spectral cues also help us detect whether a brief asymmetric particle is played forward or backward.

Detection of gaps in white noise extends down to the range of 2 ms.[27] For narrowband noise signals, the detection of gaps ranges from 22 ms for a band centered at 250 Hz to 3 ms for a gap centered at 8 kHz. Many studies show increased temporal acuity for sound events above 2 kHz. Detection of gaps in pure sinusoids goes down to 5 ms for "preserved phase" sines where the endpoint and beginpoint of an interrupted sine tone match.[27] Shorter events (in the range of microseconds) can be distinguished on the basis of amplitude, spectrum, and spatial position.

MICROTEMPORAL LOCALIZATION

Human beings sense delays in signal arrival times between the two ears with an accuracy of a few microseconds.[28] This interaural sensitivity is exploited by the auditory system in order to localize microsounds in space. The perception of the spatial position of a sound particle is distorted by a *localization blur* introduced by the human auditory system. Localization blur means that a point source sound produces an auditory image that spreads out in space. For brief Gaussian tonebursts, the horizontal localization blur is in the range of 0.8° to 3.3°, depending on the frequency of the signals.[29] The localization blur in the median plane (starting in front, then going up above the head and down to behind the head) is greater, on the order of 4° for white noise and becoming much greater (less accurate) for purer tones.

MICROTEMPORAL PREATTENTIVE AND SUBLIMINAL PERCEPTION

Certain sounds are too extreme in frequency or amplitude to be perceived; some transients are too short in duration. Yet the nervous system may react to these varieties of acoustic radiation, regardless of whether they penetrate the consciousness of the subject.

One of the most important measurements in engineering is the response of a system to a unit impulse.[30] Auditory neuroscientists have sought a similar type of measurement. The impulse response equivalent in the auditory system are the *auditory evoked potentials,* measured on the scalp, which follow stimulation by tone pips and clicks. The first response in the auditory nerve occurs about 1.5 ms after the initial stimulus of a click, in the realm of *preattentive perception.*[31] Preattentive perception performs a rapid analysis by an array of neurons, and combines this with past experience into a wave packet in its physical form, or percept in its behavioral form. The neural activities sustaining these acts of preattentive perception take place in the cerebral cortex. Sensory stimuli are preanalyzed in both the pulse and wave modes in intermediate stations of the brain. As Freeman[31] notes, in the visual system, complex operations in the retina and lower brain such as adaptation, range compression, contrast enhancement, and motion detection take place. Sensory stimuli activate *feature extractor* neurons that recognize specific characteristics. Comparable operations have been described for the auditory cortex. The last responses to a click occur some 300 ms afterward, in the medial geniculate body of the thalamus in the brain.[12] As Buser and Imbert indicate, the latent response is relevant to attention and expectation.

I should also mention *subliminal perception* or perception without awareness. It has been shown that the brain takes notice of very high frequency sounds above 22 kHz, whether or not the mind is consciously aware of them.[32,33] Another example of perception without awareness occurs when rhythmic sounds are modulated in ranges below the threshold of perception. Recent studies have shown that these modulations nonetheless enter in unconscious synchronized motor responses.[34–37]

A class of psychological studies has tested the influence of brief auditory stimuli on various cognitive tasks. In most studies, these stimuli are verbal hints to some task asked of the listener. Some types of influences have apparently been shown, but the results are not clear-cut. Part of the problem is theoretical: how does subliminal perception work? According to a cognitive theory of Reder and Gordon,[38] for a concept to be in conscious awareness, its activation must be above a certain perceptual threshold. Magnitude of activation is partly a function of the exposure duration of the stimulus. A subliminal microevent raises the activation of the corresponding element, but not enough to reach threshold. The brain's "production rules" governing awareness cannot fire without the elements passing threshold, but a subliminal microevent can raise the current activation level of an element enough to make it easier to fire a production rule later.

This is potentially significant for music. If the subliminal hints are brief musical cues (to pitch, timbre, spatial position, or intensity), then we can embed such events at pivotal instants, knowing that they will contribute to a percept without the listener necessarily being aware of their presence. Subtlety of effect is an important aspect of the aesthetic of composition with microsound. Barely perceptible variations in the properties of individual microevents—their onset time, duration, frequency, waveform, envelope, spatial position, and amplitude—lead to different aesthetic percepts on a higher timescale. For example, a shift of phase in one sound particle is imperceptible, but successive shifts in a series of particles produce a strong impression.

My colleague Stephen Pope has suggested that the domain of subliminal perception is really much broader than it is often assumed to be. For example, how many listeners in a concert hall are truly aware of the unfolding mechanisms at work in Beethoven's late string quartets, much less those of Bartok? They may hear every note, but they are not fully aware of the structural connections that the notes form. Only a detailed analysis reveals these structures. In this sense, the effect of art is largely subliminal.

CONCLUSION: THE MUSICAL IMPLICATIONS OF MICROSOUND

> Music differs radically from language and speech.... [In music] we are dealing with a system of communication in which each piece of music consists of a few nonreferential items that are combined according to the prevailing stylistic "syntactic" rules of harmony, melody, timbres, rhythm, or musical form. Music is thus a game of combinatory acoustical constructs that the brain of the composer can conceive and that the listener should be able to learn or discover.... Contemporary music, by making use of new combinatory rules and the great novelty of its acoustic units and clusters, obliges the listener to expend greater effort in perceptual preparation and learning.
>
> —O.S.M. Marin[39]

Musical culture is constantly evolving. In considering the application of neuroscience to music, we must be careful to define music in the broadest possible sense. Otherwise the discourse may be distorted by outmoded models. To cite an example, at a past conference "The Brain and Music," the composer Michael Tippett[40] portrayed microtonality (the use of non-equal-tempered melodic scales) as "a deviation from an unconscious or innate notation of tempered whole tones and semitones." Yet equal temperament is an artifact of European music history, not an "innate" characteristic of the human brain. The invention of equal temperament is well documented.[41] Microtonal scales are in widespread use in nonwestern cultures and by avant-garde musicians.

An individual listener can appreciate radically diverse forms of musical expression. This alone indicates that the foundations of music cognition extend far deeper than any traditional music theory dogma. Ultimately, music is rooted in the sensomotoric dynamics of the human nervous system. From the rhythms of the brain, to the nervous system and the gestures of the muscles that it controls: "Music is primarily a matter of biology."[42] This being so, many issues in music perception can be analyzed without reference to musical stimuli, per se, such as the perception of temporal intervals on multiple timescales.[43]

Human auditory perception is exquisitely attuned to the musical properties of microevents. Since the development of computer-based techniques in the early 1970s, it has been possible to compose music on this scale.[4] Graphical audio tools make it easy to zoom in and operate on microsounds.[44] As FIGURE 1 shows, a new generation of sophisticated sound analysis tools is emerging, based on classifying sounds according to dictionaries of particles.[21,22,45] In certain ways, these non-Fourier tech-

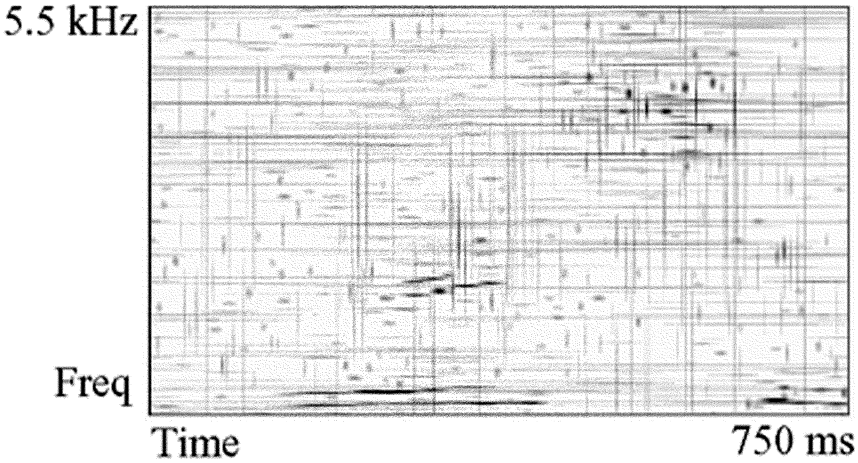

FIGURE 1. Time-frequency energy of a 750-ms speech signal (the word "wavelets") with white noise added, as viewed with the technique of matching pursuit wavelet analysis. This type of analysis is excellent at visualizing the highly localized particulate nature of sound energy. Both speech (*dark spots*) and white noise (*grey spots*) are seen as agglomerations of particles scattered on the time-frequency plane. From Davis *et al.*[22]

niques can mitigate the "acoustic uncertainty principle" that has vexed acoustic analysis in the past.[16] Moreover, the ability to go beyond mere visualization, to transform sounds in this domain, is fostering new and evocative forms of musical expression.

Techniques for the synthesis of microsonic sound particles are now in widespread use by composers of electronic music. My compositions *Clang-tint, Half-life, Tenth vortex, Eleventh vortex, Sculptor,* and *Volt air* are examples of multiscale compositions, where the organization of sound extends from the architecture of the macroform down to the tiniest of perceptible microevents. An important aspect of this work involves adjusting the silent spaces around sounds in order to obtain a precise microrhythm. In this fine editing mode, the ear is quite sensitive to adjustments on the timescale of a few hundred microseconds.

Just as it has become possible to sculpt habitats from fiberglass foam, the flowing structures that we create with microsound do not necessarily resemble the usual angular forms of musical architecture. To the contrary, they tend toward liquid-like or cloud-like structures. In the context of particle physics, Einstein[46] stated, "Atomism compels us to give up the idea of sharply and statically defining bounding surfaces of solid bodies." Likewise, particles of sound dissolve the solid notes into more supple materials that cannot always be measured in terms of definite intervals. As a result, sound objects may have "fuzzy edges," that is, ambiguous pitch and indefinite duration (due to particle evaporation, coalescence, mutation, and interaction with other layers of musical structure). We see close links to pointillist art theories involving thousands of brush strokes.[47]

Microvariations melt the frozen abstractions of traditional music theory such as continuous tone, pitch, instrument timbre, dynamic marking, and even event duration, reducing them to a constantly evolving stream of particle morphologies. Intervals may emerge, but they are not an indispensable grid. There is rather an interplay between intervallic and nonintervallic material.

Within these flowing structures, the quality of particle density—which determines the transparency of the material—takes on prime importance. An increase in particle density induces tone fusion. It lifts a cloud into the foreground, while a decrease in density causes evaporation, dissolving a continuous sound band into a pulsating rhythm or vaporous background texture. At a constant density, a change in the characteristics of the particles themselves induces mutation, an open-ended transformation. Such processes—coalescence, disintegration, evaporation, and mutation—are central to this new approach to musical organization.

Upon reading a draft of this paper, the composer and psychologist Dr. Gerard Pape made the following suggestion: Why rule out so-called non-scientific research that would ask individual listeners to describe what they hear when they are listening to microsounds, how grains or pulsars make them feel...?

I might point out that I run such experiments as often as I can, in the form of concerts. Although I have not yet handed out questionnaires to be filled out by the subjects, I have definitely noted a variety of reactions!

ACKNOWLEDGMENTS

I would like to credit Dr. Gerard Pape (Centre de Composition Musicale "Iannis Xenakis," Paris) and my colleague Stephen Pope, University of California at Santa

Barbara, for insightful comments on a draft of this manuscript, which led to many improvements and clarifications. I would also like to thank the Mariani Foundation and my colleagues at the conference on the neurosciences and music for the opportunity to learn more about this fascinating area of scientific inquiry.

REFERENCES

1. GABOR, D. 1946. Theory of communication. J. Inst. Elect. Eng. Pt. 3, **93:** 429–457.
2. GABOR, D. 1947. Acoustical quanta and the theory of hearing. Nature **159:** 591–594.
3. GABOR, D. 1952. Lectures on communication theory. Technical Report 238. Research Laboratory of Electronics. Massachusetts Institute of Technology. Cambridge, MA.
4. ROADS, C. 1978. Automated granular synthesis of sound. Comput. Music J. **2**: 61–62. Granular synthesis of sound. 1985. *In* Foundations of Computer Music. C. Roads & J. Strawn, Eds. :145–159. The MIT Press. Cambridge, MA.
5. ROADS, C. 2001. Sound composition with pulsars. J. Audio Eng. Soc. **49:** 134–147.
6. ROADS, C. 2002. Microsound. Book and audio compact disc. MIT Press. Cambridge, MA.
7. GORDON, J. 1996. Psychoacoustics in computer music. *In* The Computer Music Tutorial. C. Roads, Ed. :1053–1069. MIT Press. Cambridge, MA.
8. HELMHOLTZ, H. 1850. On the velocity of propagation of nerve impulses. Comptes Rendus 30, 33. Cited in H. Margenau's introduction to H. Helmholtz. 1885. On the Sensations of Tone. Translated by A. Ellis. New edit. 1954. Dover Publications. New York. The cited page is not numbered.
9. GALAMBOS, R. 1962. Nerves and Muscles. Anchor Doubleday. New York.
10. WINCKEL, F. 1967. Music, Sound, and Sensation. Dover Publications. New York.
11. DOUGHTY, J. & W. GARNER. 1947. Pitch characteristics of short tones I: two kinds of pitch thresholds. J. Exp. Psychol. **37:** 351–365.
12. BUSER, P. & M. IMBERT. 1992. Audition. MIT Press. Cambridge, MA.
13. MEYER-EPPLER, W. 1959. Grundlagen und Aufwendungen der Informationstheorie. Springer-Verlag. Berlin.
14. WHITFIELD, J. 1978. The neural code. *In* Handbook of Perception, vol. IV, Hearing. E. Carterette & M. Friedman, Eds. Academic Press. Orlando, FL.
15. JONES, E.G. 2002. Anatomical and physiological pathways to sound perception. Presented at the conference on the Neurosciences and Music. Venice, Italy. Ann. N.Y. Acad. Sci., this volume.
16. ZATORRE, R.J., P. BELIN & V. PENHUNE. 2002. Structure and function of auditory cortex: music and speech. Trends Cognit. Sci. **6:** 37–46.
17. BREGMAN, A. 1990. Auditory Scene Analysis. MIT Press. Cambridge, MA.
18. BREGMAN, A. 1997. When will we hear separate events in a sequence of sounds? Preprint 4582. Presented at the 103rd Conference of the Audio Engineering Society. Audio Engineering Society. New York.
19. BREGMAN, A. & J. CAMPBELL. 1971. Primary auditory stream segregation and perception of order in rapid sequences of tones. J. Exp. Psychol. **89:** 244–249.
20. MCAULAY, R. & T. QUATIERI. 1986. Speech analysis/synthesis based on a sinusoidal representation. IEEE Trans. on Acoustics, Speech, and Signal Processing **34:** 744–754.
21. MALLAT, S. & Z. ZHENG. 1993. Matching pursuit with time-frequency dictionaries. IEEE Trans. Signal Processing **41:** 3397–3415.
22. DAVIS, G., S. MALLAT & Z. ZHENG. 1994. Adaptive time-frequency decompositions with matching pursuit. Optical Eng. **33:** 2183–2191.
23. KURTZ, M. 1992. Stockhausen: A Biography. Faber and Faber. London.
24. BUTLER, D. 1992. The Musician's Guide to Perception and Cognition. Schirmer Books. New York.
25. HELMHOLTZ, H. 1885. On the Sensations of Tone. Translated by A. Ellis. New edit. 1954. Dover Publications. New York.
26. GREEN, D. 1971. Temporal auditory acuity. Psychol. Rev. **78:** 540–551.

27. Moore, B. 1989. An Introduction to the Psychology of Hearing. Academic Press. London.
28. Blauert, J. 1997. Spatial Hearing. Revised edition. MIT Press. Cambridge, MA.
29. Boerger, G. 1965. Die Lokalisation von Gausstönen. Ph.D. thesis. Technische Universität, Berlin.
30. Rabiner, L. & B. Gold. 1975. Theory and Application of Digital Signal Processing. Prentice-Hall. Englewood Cliffs, NJ.
31. Freeman, W. 1995. Chaos in the central nervous system. *In* Neural Modeling and Neural Networks. F. Ventriglia, Ed. :185–216. Pergamon Press. New York.
32. Oohashi, T., E. Nishina, N. Kawai, *et al*. 1991. High frequency sound above the audible range affects brain electric activity and sound perception. Preprint 3207(W-1). Presented at the 91st convention of the Audio Engineering Society. Audio Engineering Society. New York.
33. Oohashi, T., E. Nishina, Y. Fuwamoto & N. Kawai. 1993. On the mechanism of hypersonic effect. *In* Proceedings of the 1993 International Computer Music Conference. S. Ohteru, Ed. :432–434. International Computer Music Association. San Francisco.
34. Thaut, M.H. 2002. Neurophysiology of neural timing networks in musical rhythm and rhythmic synchronization: basic science and clinical data. Presented at the conference on the Neurosciences and Music. Venice, Italy.
35. Thaut, M., T. Bin & M. Azimi-Sadjadi. 1998. Rhythmic finger-tapping sequences to cosine-wave modulated metronome sequences. Hum. Mov. Sci. **17:** 839–863.
36. Molinari, M. 2002. The neurobiology of rhythmic motor entrainment: a neurorehabilitation perspective. Presented at the Conference on the Neurosciences and Music. Venice, Italy.
37. Molinari, M., M. Thaut, C. Gioia, *et al*. 2001. Motor entrainment to auditory rhythms is not affected by cerebellar pathology. Proceedings of the Society for Neuroscience 950.2. Society for Neuroscience. Washington, DC.
38. Reder, L. & J.S. Gordon. 1995. Subliminal perception: nothing special, cognitively speaking. *In* Cognitive and Neuropsychological Approaches to the Study of Consciousness. J. Cohen & J. Schooler, Eds. Lawrence Erlbaum Associates. Hillsdale, NJ.
39. Marin, O.S.M. 1982. Neurological aspects of music perception and performance. *In* The Psychology of Music. D. Deutsch, Ed. :453–477. Academic Press. New York.
40. Tippett, M. 1978. Foreword. *In* Music and the Brain. M. Critchley & R. Henson, Eds. W. Heinemann Medical Books. London.
41. Apel, K. 1972. Harvard Dictionary of Music. Harvard University Press. Cambridge, MA.
42. Wallin, N. 1991. Biomusicology. Pendragon Press. Stuyvesant, NY.
43. Toop. R. 1982. A note—new music and neurobiologic research: can they meet? *In* Music, Mind, and Brain. M. Clynes, Ed. :387–398. Plenum. New York.
44. Wenger, E. & E. Spiegel. 1999. MetaSynth Manual. U&I Software. San Francisco.
45. Goodwin, M. & M. Vetterli. 1997. Atomic decompositions of audio signals. Proceedings of the IEEE ASSP Workshop on Audio Signal Processing. :4–7. IEEE. New York.
46. Einstein, A. 1952. Relativity: The Special and the General Theory. 15th edit. of the original published in 1916. Three Rivers Press. New York.
47. Homer, W.I. 1964. Seurat and the Science of Painting. MIT Press. Cambridge, MA.