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Sonic and Rhythmic Knowledge

Listening to single neurons enabled a profoundly new kind of physiological understanding, whose character we now consider in detail. Adrian and his collaborators showed that each neuron conveyed its signal purely through the frequency of its firing. But "frequency" is simply a general term for rhythm.[1] The all-or-nothing principle showed that neural rhythm is the universal language of every nervous system, its binary "machine code" (to borrow a term from computer science). This neural code underlies our thoughts, feelings, perceptions. Among our senses, those that are fundamentally rhythmic—haptic (tactile) awareness and hearing—perceive the neural code as rhythm—its native idiom, as it were. All the other senses represent those binary impulses in other guises, such as visual or olfactory perceptions.

As noted earlier, humans generally perceive vibrational frequencies less than about 20 Hertz as rhythms rather than distinctly audible pitches. Changes in an experimental animal's neural rhythms, when amplified and made audible, can directly affect the experimenters' own neural rhythms and thereby their mental state. These changes then manifest themselves in the experimenters' emerging "awareness" that something happened in the experimental animal. As we will see, both experimenter and subject are joined together by these shared neural rhythms, whose changes mark every aspect of their interaction.

This *rhythmic knowledge* gives access to the phenomena of life *as they unfold in time* more directly than by visual representations. Though the historical path to rhythmic knowledge was opened by *sonic knowledge*, these two forms of knowing should be distinguished as binary is from analog, discrete from continuous. Thus, the sonic turn we have been following since the eighteenth century led to the significantly different rhythmic turn of the twentieth. Subsequently these binary rhythms became digitized data manipulated by computers, themselves designed to mimic the neural networks of animals. This digitization reflected the inherently binary character of neural responses.

My choice of terminology shows the difficulty of finding words to contrast auditory and rhythmic experience with visual or purely numerical thinking. The anthropologist and ethnomusicologist Steven Feld coined *acoustemology* to "suggest a union of acoustics and epistomology, and to investigate the primacy of sound as a modality of knowing and being in the world."[2] Similarly, the term *auditory epistemology* has gained favor with some scholars.[3] Though these terms are helpful and apt, I feel the need to discriminate between sonic and rhythmic modes of knowledge because these words underscore the historical shift between analog and binary phenomena. This has a special importance because the discovery of the all-or-nothing code was not just one "medium" among others but proved to be the common foundation on which all nervous systems operate. Rhythmic knowledge reflected—and revealed—the fundamental rhythms embedded in all neural activity on Earth.

To assess these modes of knowledge, we will consider two episodes from Adrian's later work: his sonification of brain waves and a curious experience he had when experimenting with the retina of a toad. Each turned on neural rhythm, especially its changes at critical moments. Adrian's technique of audio monitoring became common in neurophysiology labs throughout the world. In particular, it played a significant role in the Nobel-prize-winning work of David Hubel and Torsten Wiesel on the visual system. Through these examples, we can compare the fundamental character of rhythmic knowledge to the kinds of objectivity (and subjectivity) Lorraine Daston and Peter Galison described in their analysis of the ways in which vision can mediate knowledge.

The preceding three chapters presented the unfolding evidence that nerves communicate via all-or-nothing impulses encoded purely in the frequency of their firing. Trying to understand this fundamental physiological fact, Helmholtz and du Bois-Reymond had already begun comparing the nerves to a telegraphic system.[4] Though at times he too used this telegraphic metaphor, in 1930 Adrian contrasted neural signals with ordinary codes and telephonic communications:

> A nerve fibre cannot conduct all manner of changes like a telephone wire; it cannot even conduct the dots and dashes of a Morse code. As a rule, with a steady stimulus, the impulses in a sensory discharge are evenly spaced and the only variable is their frequency which gives a measure of the intensity of excitation in the sense organ. This is all the information which a single fibre can convey, but as there are a million or more sensory fibres entering the spinal cord in man, we need not be surprised at the range of our sensations.[5]

Adrian considered frequency to be the true means by which neurons transmit what he called "information," a term he used in a new sense, compared to earlier discourse about the nerves conveying "impulses," "reactions," or "activity." As Justin Garson pointed out, "By using the language of information, nerve physiologists like Adrian posed questions that could not be asked previously, namely, questions about the abstract relationship between impulse and stimulus."[6] Fundamentally, this new approach turned on the concept of frequency, which describes both sound and electric signals, inviting comparisons between them.

To illustrate the sonic investigation of these frequencies, consider Adrian's pioneering work on listening to brain waves. This research he and Bryan Matthews conducted shortly after Hans Berger published his discovery (1929–1933) of the basic brain rhythms:

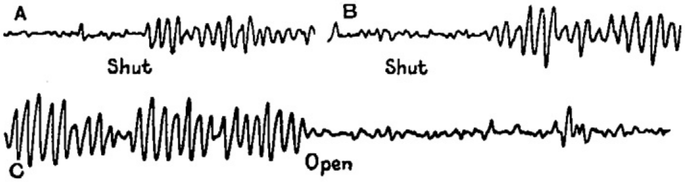

Figure 18.1
"The development of the [alpha] rhythm in the absence of visual activity. (a) E. D. A. The rhythm appears when the eyes are closed; (b) B. H. C. M. Ditto; (c) E. D. A. The rhythm disappears when the eyes are opened." From Adrian and Matthews, "The Berger Rhythm: Potential Changes from the Occipital Lobes in Man" (1934).

alpha (7–14 Hertz) and beta (15–30 Hertz).[7] Adrian and Matthews confirmed Berger's work and brought it to wide attention; though they differed with his interpretation on some points, Adrian nominated Berger for a Nobel prize.[8] In their initial 1934 work on animals, they used no fewer than three Matthews oscillographs to record brain waves, noting that "a loudspeaker was not often used, as the cortical potentials often rise and subside too slowly to give clearly audible sounds."[9] Evidently these very low frequencies were not rendered usefully by ordinary loudspeakers. In their subsequent work on the human brain, they again used the Matthews oscillograph but added that "it is sometimes an advantage to be able to hear as well as see the rhythm; although its frequency is only 10 a second it can be made audible by using a horn loud speaker with the diaphragm set very close to the pole pieces and a condenser in parallel to cut out high frequencies."[10] In this way, they rigged up a sort of subwoofer and filter that could do better with the low frequencies they were hearing from their own brains (figure 18.1). They also noted the differences between them: "One of us (E. D. A.) gives the [alpha] rhythm as soon as the eyes are closed, and maintains it with rare and brief intermissions as long as they remain closed. The other (B. H. C. M.) is better in the role of observer than of subject, for in him the rhythm may not appear at all at the beginning of an examination, and seldom persists for long without intermission."[11] Such striking rhythmic changes could readily be heard even when the experimenter's eyes were closed.

In 1941, Adrian described further refinements of his listening to the electrical impulses coming to the cerebral cortex from peripheral sense organs:

> An essential feature of the method has been the use of a loud-speaker and amplifier system giving a faithful reproduction over a wide range of frequencies. The electrical changes in the cortex include both the very brief axon potentials due to impulses in nerve fibres and the much slower waves which are the characteristic product of the cortex. An optical system making a photographic record can be adapted to show one or the other but can rarely do justice to both simultaneously, whereas with a good loud-speaker it is easy to detect both impulses and waves.[12]

In this paper, Adrian used the term *noise* both to describe what he heard from the loudspeaker as well as to characterize the neural impulses themselves, one of the earliest uses of "noise" in this context.[13] He also characterized the impulses as "signals," well before others used that term in this context.[14] Thus, his listening informed his categorization of the nerve signals in relation to noise. To do so, he attended to "faithfulness" or "fidelity," which Sterne has called "sound's own 'dismal science'—it was ultimately about deciding the values of competing and contending sounds."[15] By devising more "faithful" loudspeakers, Adrian could directly hear the interplay of global brain waves and local impulses in real time, as he or Matthews produced them. This important discrimination depended on hearing's ability to counterpoint the local and global without blurring them together.

Adrian continued to use loudspeakers as an essential tool of his work, registering the signal and helping him find a single neuron. For instance, in his very next paper, after introducing this technique (1929), Adrian mentioned using "the additional amplifier and loud speaker arrangement" along with a Matthews oscillograph, an instrument he apparently viewed "with some considerable awe."[16] In a 1938 paper, he noted that "a loudspeaker was particularly valuable and discharges could often be detected by ear although the oscillograph record was too confused to show them."[17] By 1942, Adrian's paper on the olfactory response of hedgehogs described sonic monitoring "in the usual way," as if the technique had become so routine as to be unremarkable.[18]

Still, in 1947 he recounted an incident that happened "not long ago" that indicated how listening to neurons calls for further thought. He began by noting that though neural response is "best studied" through the photographic record, "the timing of the impulses can be made more intelligible by reproducing them as a series of sounds," for each impulse is "brief enough to be turned into a sharp click in a telephone or loudspeaker or to be recorded permanently on a gramophone disk." Through hearing the impulses, "the changes in frequency are reproduced directly and there is no need to infer them from a still picture."[19]

Then Adrian contemplated the curious "vicissitudes through which the sensory message must pass when we listen to such a recording," beginning with the experimental animal's muscle twitching, whose neural impulses he then recorded on a gramophone disk:

> When a copy of the disk is played, the sounds fall on the ear-drum of the listener and set up a succession of impulses in the auditory nerve corresponding to those set up originally by the stretched muscle-spindle. Thus the message ultimately reaches a central nervous system, though not the central nervous system which was its original destination, and it has been curiously changed *en route*.[20]

Through hearing, the animal's nervous system had been "curiously" connected to Adrian's with a kind of directness not possible for a visual reading of the galvanometer. This directness meant that Adrian was hearing—and thus feeling—what the animal saw:

> I had arranged electrodes on the optic nerve of a toad in connection with some experiments on the retina. The room was nearly dark and I was puzzled to hear repeated noises in the loudspeaker attached to the amplifier, noises indicating that a great deal of impulse activity was going on. It was not until I compared the noises with my own movements around the room that I realized I was in

> the field of vision of the toad's eye and that it was signaling what I was doing, for the slight shadow movements which I was making on the toad's retina were (and ought to have been) quite enough to send messages to the brain, if it had been there to receive them.[21]

Having previously removed the toad's brain, Adrian realized that in effect, he had put his own brain in its place. In that dark room, Adrian heard the toad seeing *him*. The hail of nerve impulses in the toad's optic nerve responded to Adrian's movement, thereby evoking an exactly similar hail of impulses in his own brain, registered as his sudden realization. This moment of rhythmic crisis opened a passage from one brain to the other. Compared to vision, hearing generally connects more primally to the brain; as Nietzsche put it, the ear is "the organ of fear," always open to alert an animal to imminent danger.[22] For scientists, Daston and Galison assert that "all epistemology begins in fear"—the fear of succumbing to delusions, bias, or the deceptive allure of pet theories.[23] Because of its exquisite sensitivity, hearing can offer critical help at the moment of discovery.

In particular, perception of rhythmic changes marked the work of David Hubel and Torsten Wiesel on how the brain processes visual perception. During the late 1950s, they investigated how visual signals are encoded by the visual system.[24] They projected various shapes onto a screen that would be viewed by an animal and monitored the response of a single neuron in the animal's brain. As Bevil Conway, one of their collaborators, explains, "One listens to the neurons with limited filtering of the signal, which allows one to hear all the neurons in the population. One can then isolate a cell, by ear, and use that auditory isolation to help guide the electrical isolation of the trace."[25]

This depends on an extraordinary fact that Conway pointed out: because "neurons have distinctive waveforms, they each have a distinctive sound quality." Thus, *each neuron is a distinct individual identifiable by its "voice," its individual rhythm*. Therefore, listening to neurons "is akin to the way the auditory system can solve the 'cocktail party' problem: among dozens of speaking voices, one can pick out by ear one voice and track almost everything that voice says." As a result, listening "makes it actually much easier to identify and distinguish a neuron from the population noise than by oscilloscope." We return to this special kind of listening in the final chapter.

Conway notes that "the use of auditory information was for Hubel and Wiesel a prominent, and distinguishing feature, evident in how they disseminated their work," including Hubel's Nobel lecture (1981) and various videos they made documenting their experiments. We focus on the crux of their work: their discovery of the receptive fields of single neurons in the primary visual cortex (1959). Hubel and Wiesel set up their experiment so that an anesthetized cat or monkey would continuously view a visual image, composed of simple shapes and lines, that they could manipulate. In order to record the response of a single neuron in the visual cortex, Conway notes that "they used their own eyeballs to guide the placement of the electrodes. And then they recorded every cell that they encountered as they pushed the electrode ever deeper into the brain," noting their individual waveforms (rhythms). Their main problem was how to present the animal's eye

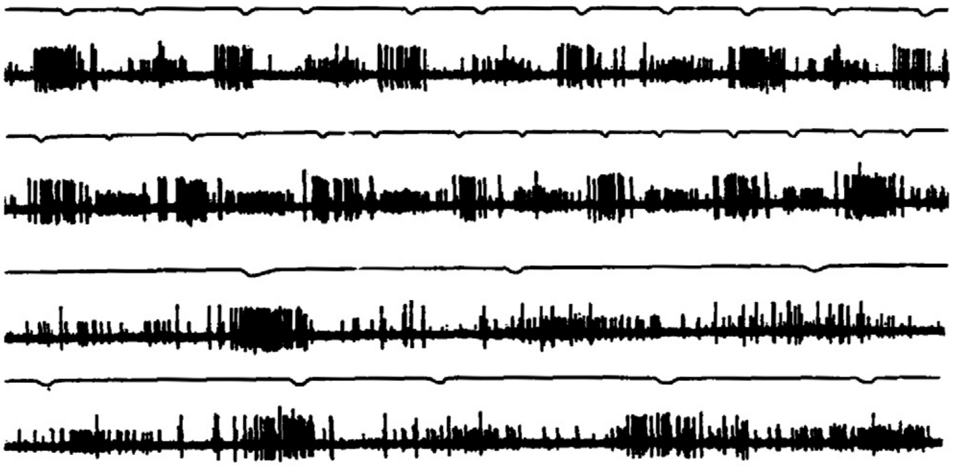

Figure 18.2
David Hubel's 1958 experiments on an unrestrained cat with a microelectrode in the striate cortex. There are two pairs of records, shown as four panels separated by horizontal lines: top to bottom: panels 1 and 2 show the first pair of records (faster hand movements), 3 and 4 the second pair (slower). In each pair, the upper line shows the stimulus: a hand movement interrupted a light beam falling on a photoelectric cell. The lower line shows the cat's neural response on an oscilloscope. Each line represents 4 seconds.

with various images that could be altered or changed while at the same time monitoring the neuron's response.

By the time of their experiments, cathode-ray oscilloscopes had become standard for observing neural impulses; nevertheless, Conway notes that "they rarely photographed action potentials on the oscilloscope, and when they did, they needed to dodge and burn the background of the photographic paper to make the traces visible." Hubel and Wiesel's challenge was to find a nimble and responsive way to use the neural signal to inform how the visual stimuli should most informatively be deployed or altered. This flexibility was especially necessary because initially it was not at all clear what (if any) structures or patterns of response were "hard-wired" in the visual cortex, as opposed to being learned or random behavior; as Hubel put it in his Nobel lecture, "It is hard, now, to think back and realize just how free we were from any idea of what cortical cells might be doing in an animal's daily life."[26]

The problem was how to make the neural signal as easily comprehensible as possible. For comparison, consider earlier experiments by Hubel in 1958 on an unrestrained cat, stimulated by small to-and-fro hand motions in front of the animal.[27] Figure 18.2 shows the stimulus and response as purely visual images, one above the other, the stimulus recorded via a photocell, the response via oscilloscope. The caption clarifies the details of the images, but the overall impression shows the difficulty of understanding what at first looks like a forest of lines; discerning their relation visually would take considerable practice.

Though the oscilloscope indeed showed the tracings of the neural response, it was far easier for Hubel and Wiesel just to listen to the amplified nerve sounds over a loudspeaker—an audio monitor, as Hubel called it—leaving their eyes free to watch the visual display they were presenting to the cat, whose neural output they were also hearing. This simultaneous hearing and seeing allowed them to mediate readily between the visual display and the hearing of the neural signal.

Hubel later recalled that "we set up our first experiments and they did not go well because at the beginning we could not make the cells fire at all. We'd shine light all over the screen and nothing seemed to work."[28] During his live Nobel lecture, Hubel described the monitor in detail for the benefit of nonspecialists:

> In order to make a record, we take a video camera and direct it at the screen so that when we play back the tape, we can see what the animal would have seen, if it had been awake. And in order to make a record of the responses, we take the output of the microelectrode, which is connected to amplifiers and an oscilloscope, and we connect that to the soundtrack of the tape so that when we play back we can hear the cells firing. When one records from a single cell, one hears a single impulse as a click and if the cell is firing very vigorously, the clicks tend to merge and one hears a noise.[29]

He went on to play an experiment recorded on film; not hearing the soundtrack play, he told the projectionist, "We need sound," thus underlining its importance for what he wanted to present. During the film, he gave no spoken commentary, trusting that the audience would immediately understand what they were seeing and hearing: a spot of light on the screen seen by the cat would be registered by a hail of clicks, the evidence of a neuron firing in response.

In the text of his lecture, Hubel recounted that

> our first real discovery came about as a surprise. We had been doing experiments for about a month. We were still using the Talbot-Kuffler ophthalmoscope and were not getting very far: the cells simply would not respond to our spots and annuli. One day we made an especially stable recording. . . . The cell [neuron] in question lasted nine hours, and by the end we had a very different feeling about what the cortex might be doing. For three or four hours we got absolutely nowhere. Then gradually we began to elicit some vague and inconsistent responses by stimulating somewhere in the midperiphery of the retina. We were inserting the glass slide with its black spot into the slot of the ophthalmoscope when suddenly over the audio monitor the cell went off like a machine gun. After some fussing and fiddling we found out what was happening. The response had nothing to do with the black dot. As the glass slide was inserted its edge was casting onto the retina a faint but sharp shadow, a straight dark line on a light background. That was what the cell wanted, and it wanted it, moreover, in just one narrow range of orientations. This was unheard of.[30]

Clearly, the audio monitor going "off like a machine gun" alerted the researchers that something significant had happened, though it took longer to clarify exactly what: not the black dot, as they first thought, but rather the edge of the slide, which they had not initially considered to be part of the intended "real" stimulus (as heard in ♪ video example 18.1). The rhythmic knowledge evoked by moving the slide revealed that it was the edge that really turned that neuron on. In Conway's description, "Listening to a neuron over the audio monitor is thrilling, much more like listening to a great pianist performing a beloved piece of music: a combination of delight at understanding something through hearing, and pleasure."

In his lecture, Hubel went on to show how the different kinds of cortical neurons (which he and Wiesel named simple, complex, and hypercomplex) were differentiated by the relation between the sound from the audio monitor and the visual stimulus, including the exact location, orientation, and direction sensitivity of each kind of neuron. This finding "was unheard of. . . . That the retinas mapped onto the visual cortex in a systematic way was of course well known, but it was far from clear what this apparently unimaginative remapping was good for. It seemed inconceivable that the information would enter the cortex and leave it unmodified," yet their correlations between sound and stimulus helped them find just such surprisingly simple mappings.[31] Their work showed that vision discerns outlines, edges, and thereby shapes. Yet that visual realization emerged through the thrill of hearing the neuron's "machine gun" firing. As with Adrian's encounter with the toad, the ear's ability to register critical changes in *time* enabled the neuroscientists to discern the activity of life through changing rhythms.

The power of such practices of listening indicates that they provide a kind of knowledge fundamentally different from the various forms of objectivity sought through visual means. In 1666, Hooke had already observed that whereas the eye could discover "Conveniences and Inconveniences at a great Distance as well as near at hand," the ear could receive "Warning or Information from Sound, where the Eye could not assist."[32] Indeed, research by Ernst Mach in 1865 showed that the ear responded more quickly to stimuli than the eye.[33]

In scientific atlases of images, whether of snowflakes, galaxies, or neurons, Daston and Galison delineated various kinds of objectivity they called *truth-to-nature* (idealized images of types), *mechanical objectivity* (seeking to avoid any such idealization or interpretation, for instance through photography), and *trained judgment*, which is "a capacity of both maker and user of atlas images to synthesize, highlight, and grasp relationships in ways that were not reducible to mechanical procedure."[34] One might surmise that practices like audio monitoring move immediately to the phase of trained judgment, not having modalities comparable to the idealizations of truth-to-nature or mechanical objectivity.

Yet none of these visually oriented terms really fit the sonic and rhythmic experiences we have been considering. A collection of sound recordings differs profoundly from a photographic atlas, which invites the different kinds of interpretation that Daston and Galison discuss. Where the viewer of an atlas must learn to interpret subtle visual differences, rhythmic knowledge provides the far more direct thrill of hearing a cat's neurons going "off like a machine gun." Because it operates directly on the felt sense of time, rhythmic knowledge has a force and felt immediacy notably different from visual scrutiny

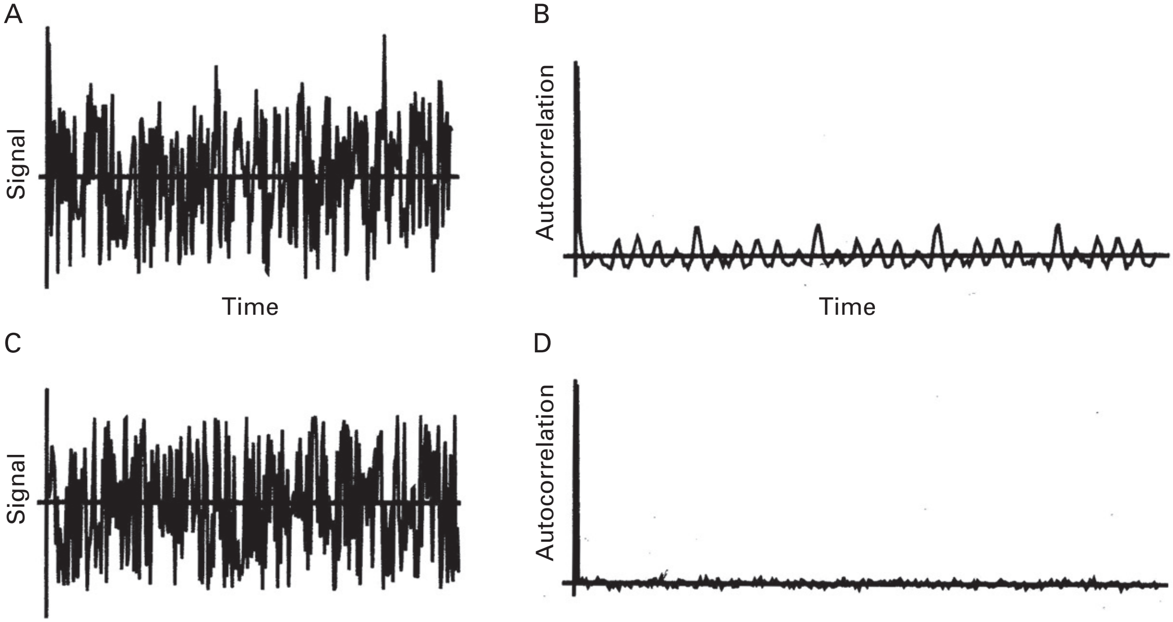

Figure 18.3
Signal and noise, shown with their calculated autocorrelation functions in Eric J. Heller's *Why You Hear What You Hear* (2012). Top: (a) a pure noise signal plus a "clean" signal (♪ sound example 18.2a); (b) the "clean" signal, shown by its computed autocorrelation (♪ sound example 18.2b). Bottom: (c) the noise by itself (♪ sound example 18.2c); (d) the autocorrelation verifying that this is pure noise. Visually, one cannot discriminate between pure noise (c) and noise plus clean signal (a), yet the ear can distinguish between them.

of phenomena in space, which often requires complex acts of interpretation. Summarizing their findings about scientific images, Daston and Galison proposed the provocative formulation "*seeing is being*"; by comparison, the examples we have been considering suggest that *hearing is living.*[35]

In due course, rhythmic knowledge led to the representation and manipulation of binary neural signals as digital data in computers, themselves modeled on artificial nervous systems.[36] Yet even the development of ever more powerful modes of data storage and analysis has not superseded the utility of hearing (or seeing) the result. Data analysis can take instrumental readings and give them a precise numerical form—bearing witness to the heritage of Herophilus and the Pythagoreans—but not with the immediacy of hearing or the graphic clarity of seeing. The very richness, density, and sheer volume of numerical data often require careful consideration how best to bin, organize, and analyze this material, each stage of which has many possibilities and pitfalls. The story of ultrasound has shown the power of combining acoustic data with visual representation; the final chapter presents other examples.

Whether through automated procedures or by direct inspection, the mind must distinguish signal from noise, a procedure in which hearing has advantages over sight. If some noise is added to a "clean" signal, the result is a ragged-looking wave (figure 18.3a). Calculating the autocorrelation function can extract the signal from the noise purely numerically (figure 18.3b). But the eye alone cannot really tell the difference between pure noise and signal plus noise (compare figures 18.3a and 18.3c), which both look equally ragged. On the other hand, Eric J. Heller points out that "we may be able to hear the original clean signal buried in the noise even if we cannot visually detect its presence" (♪ sound examples 18.2a, 18.2b, and 18.2c).[37] The ear can lock on to salient differences that are far less clear to the eye. To be sure, such statistical tools as autocorrelation can provide robust and quantitative measures important for careful analysis of any experiment. Yet such analysis is a heavily mediated process that depends on how it is done. Hearing gives a thrill that (in the case of Hubel and Wiesel) was important in the process of discovery, requiring (as Conway notes) subtle aural discrimination of the neural rhythms from the high background noise.

The Pythagorean program worked for hearing in ways it scarcely could have for sight. It is hard to imagine Pythagoras coming into an artist's studio and having an epiphany about the relation between colors and numbers that would have paralleled his legendary realization after hearing the hammers in the smithy. This stems from deep factors differentiating these senses: human hearing can span ten octaves of frequency, whereas our vision spans only about a major sixth in terms of color (a ratio of 400:700 in wavelength between violet and red).[38] That is, humans have never seen an octave in color, which would be the experience of two colors of wavelengths in a 2:1 ratio seen as "the same," in the way we hear two adjacent octave Cs on the piano as "the same note." We seem to have a diffuse awareness of ultraviolet light of wavelength 350 nanometers (though that would cause serious injury to our eyes); still, we do not register that as a "color" that could be compared with the red of light at 700 nanometers, an octave lower.[39] Thus, Pythagorean arguments connecting octaves with 2:1 ratios do not address our experience of colors.[40] All of these factors indicate why sonification—using hearing to access data—has proved an important tool in many fields and can enable insights into data that may go beyond what looking at graphs or what computers can provide.[41]

With this in mind, let us return briefly to Nagel's argument that we will never know what it is like to be a bat.[42] His conclusion that we will never penetrate the bat's subjectivity—its inner world of feeling—is persuasive, but we also cannot penetrate the subjectivity of other human beings, their unique inner world. Still, we extrapolate to other humans a considerable amount of sympathetic understanding based on our own inner experience and feelings. Nagel's assertion of the utter alienness of bats does not acknowledge that they and we share the same universal neural code. Though they use much higher frequencies for echolocation than we do for hearing, their neurons fire at comparable frequencies to ours. What, then, prevents us from entering into their world in the way Adrian (at least for a moment) saw through a toad's eye, both organisms sharing the same rhythms? The practice of audio monitoring is a kind of way-finding: like a bat flying in the dark, an experimenter listens for the individual voices of the neurons to navigate the darkness of the brain.

The Pythagorean project of understanding the body via rhythms expressed as numbers has come full circle. Herophilus began mathematizing (and musicalizing) the felt pulse; the responses to his idea eventually led to the actual hearing of the body's "analog" soundscape, eventually also its "ultrasoundscape." Going further into the nervous system, Adrian and others transduced single neural impulses into binary rhythms, first heard over loudspeakers, later recorded and processed as digital data—a stream of binary numbers. What began with numbers eventually returned to numbers. Yet the other side of the Pythagorean project remains important—not just numbers by themselves, but the connection between sounding bodies and sounding numbers as rhythm and music. As computers' growing power enables us to analyze physiological data, they also offer new powers of rendering that data visible and audible. Developments underway at the beginning of the twenty-first century show the growing reach and availability of those powers.

Sounding Bodies

Music and the Making of Biomedical Science

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