The original scan of this document is on the bottom. I'm sorry it isn't in better quality, my scanner is horrible. Instead, I've typed up a recreation of the entire article and inserted the figures from the scan.

A few interesting things from the article to note:

1) Oster's idea was to use the perception of binaural beats as a diagnostic tool because some people are unable to perceive and respond to them. Oster never mentions brainwaves or entrainment as a function of binaural beats. This is interesting since nearly every company advertising binaural beats claims Oster invented binaural beat brainwave entrainment.
2) People with certain neurological conditions, or at certain times of the month (women), vary in their ability to perceive and respond to binaural beats. There is also a gender difference in the ability to process the beats.
3) Binaural beats only form if the two tones are separated by less than 26 hz, 30 at most. This maximum declines as the carrier moves away from 440 hz. Also, binaural beats wane completely past a carrier 1000 hz.
4) According to Oster, the depth of binaural beats is very small (3db). In a test comparison, monaural beats produced a much larger neural response. This seems to follow in line with the research done by David Seiver (Comptronic devices), Transparent Corp and others in regards to monaural and isochronic tones producing stronger entrainment.

Auditory Beats in the Brain

Slow modulations called binaural beats are perceived when tones of different frequency are presented separately to each ear. The sensation may show how certain sounds are processed by the brain.

By Gerald Oster

If two tuning forks of slightly different pitch are struck simultaneously, the resulting sound waves and wanes periodically. The modulations are referred to as beats; their frequency is equal to the difference between the frequencies of the original tones. For example, a tuning fork with a characteristic pitch of 440 hertz, if struck at the same time, will produce beats with a frequency of six hertz.

In modern investigations tuning forks are replaced by electronic oscillators, which can supply tones of precisely controlled pitch, purity, and intensity. Beats are produced when the outputs of two oscillators tuned to slightly different frequencies are combined electrically and applied to a loudspeaker. Alternatively, the signals can be applied individually to separate speakers and the beats will still be heard. The result is the same whether the tones are combined electrically and then converted into sound, or converted into sound separately and then combined.

A quite different phenomenon results when stereophonic earphones are used and the signals are applied separately to each ear. Under the right circumstances beats can be perceived, but they are of an entirely different character. They are called binaural beats, and in many ways they are more interesting than ordinary beats, which in this discussion will be called monaural. Monaural beats can be heard with both ears, but one ear is sufficient to perceive them. Binaural beats require the combined action of both ears. They exist as a consequence of the interaction of perceptions within the brain, and they can be used to investigate some of the brain's processes.

The physical mechanism of monaural beats is a special case of wave interference. At any instant the amplitude of the resulting sound is equal to the algebraic sum of the amplitudes of the original tones. The signals are reinforced when they are in phase, that is, when the peaks and nulls of their waves coincide. Destructive interference diminishes the net amplitude when the waves are in opposition. The pure tones used in these experiments are described by sine waves' the resulting beats are slowly varying functions similar to, but not precisely conforming to, a sine wave.

A beat frequency of about six hertz, as in the example given above, would sound something like vibrato in music (although vibrato is frequency modulation rather than amplitude modulation).
If the interval between frequencies is made smaller, very slow beats can be produced, down to about on per second, to perceive. Rapids beats, up to about 30 hertz, are heard as roughness superimposed on the sound, rather like a Scotsman's burr. With still greater intervals beats are not heard; the two tones are perceived separately.

Beats are rarely encountered in nature because in nature sustained pure tones are rare. They abound, however, in mechanical devices. In an airplane, jet engines operating at slightly different speeds may produce a very strong-beat, often recognized only as a feeling "in the pit of the stomach." Acoustical engineers can filter out the whine of the engines, but the slow vibrations are difficult to suppress. Occupants of apartment houses may be annoyed by beats produced by
machinery, such as two blowers running at different speeds, but they will have a hard time finding the source.

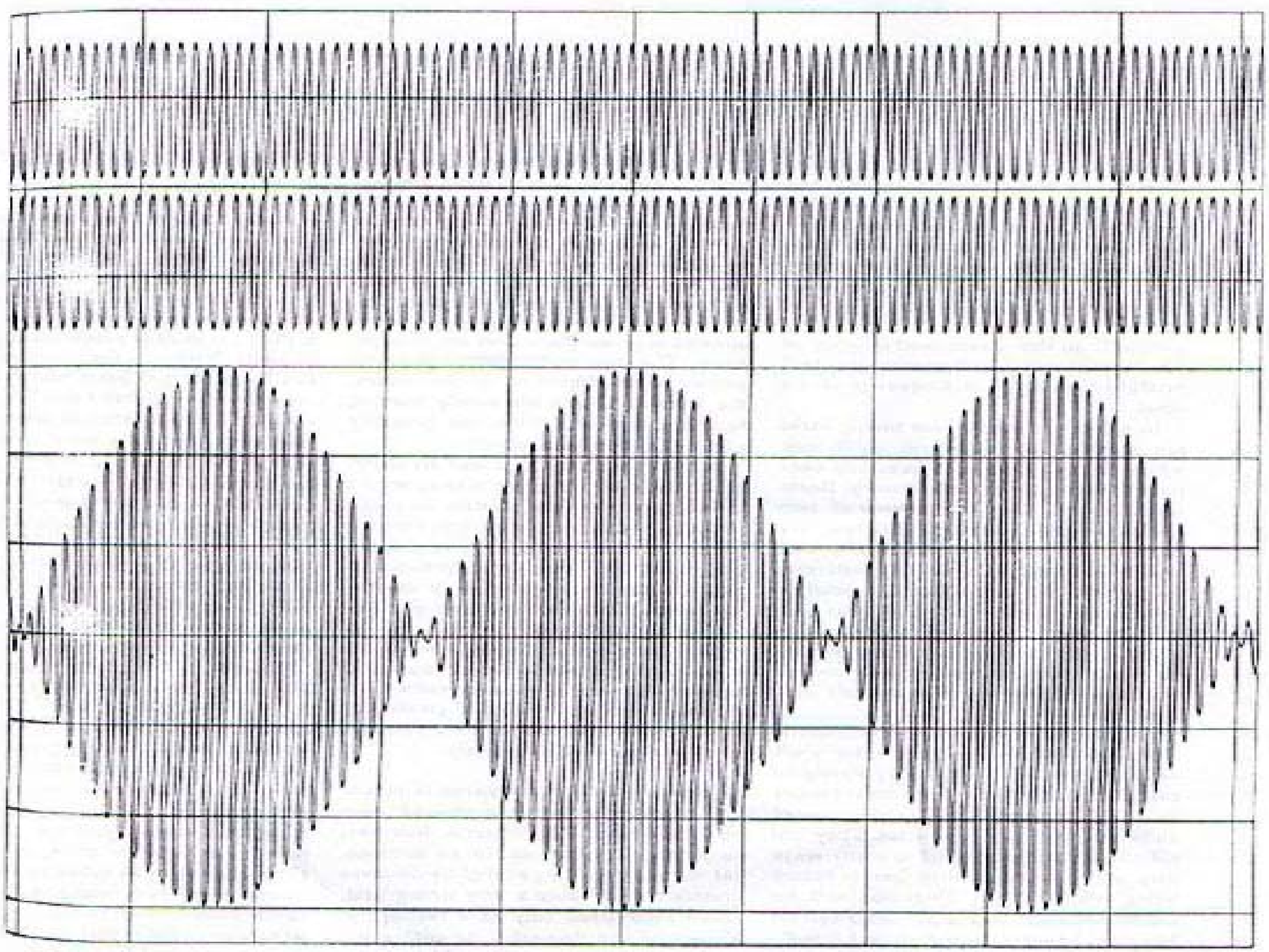
On the other hand, beats are used to advantage where frequencies must be determined precisely. Electrical engineers compare the output of a test oscillator with that of a standard oscillator by detecting the beats produced when their signals are combined. The tuning of pianos is another process that depends on beats. Typically the piano tuner will first listen for the beats produced by a tuning fork of 440 hertz and the A above middle C, and tighten or loosen the A wire until the beats slow to zero. He then strikes the A key and the D key below it and tunes the latter wire until 10 beats per second are heard. That frequency is produced by the interaction of the A string's second harmonic, or second multiple (2 x 440 = 180), and the D string's third harmonic (3 x 290 = 870). In this fashion, key by key, the piano is tuned; in theory it could be done even by someone who is tone-deaf.

Binaural beats were discovered in 1839 by a German experimenter named H. W. Dove, but as late as 1915 they were considered a trivial special case of monaural beats. It was argued that each ear was hearing sounds intended for the other.

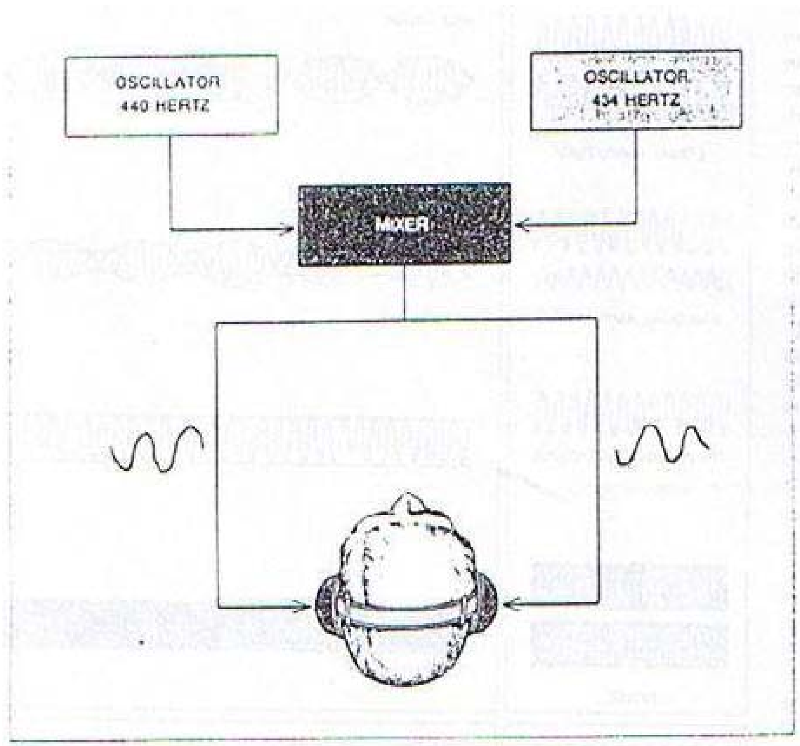
This extraneous result could be eliminated by placing the tuning forks in separate rooms, with the subject in a third room between them, and guiding the sounds through tubes to each ear. It was necessary to carefully seal each tube to the head, however, and another objection was raised; that sound presentation to one ear could be conducted through the skull to the other. Bone conduction is well established, and indeed some hearing aids operate on this principle, although sound is attenuated a thousandfold from ear to ear.

The possible contribution of bone conduction to the perception of binaural beats is eliminated, however, by the use of modern stereophonic earphones. Such earphones have padding, often liquid filled, to insulate the head from the sound source, and are designed explicitly to prevent conduction effects. Indeed, stereophonic recordings played through earphones can sound unnatural because the instruments seem too isolated.

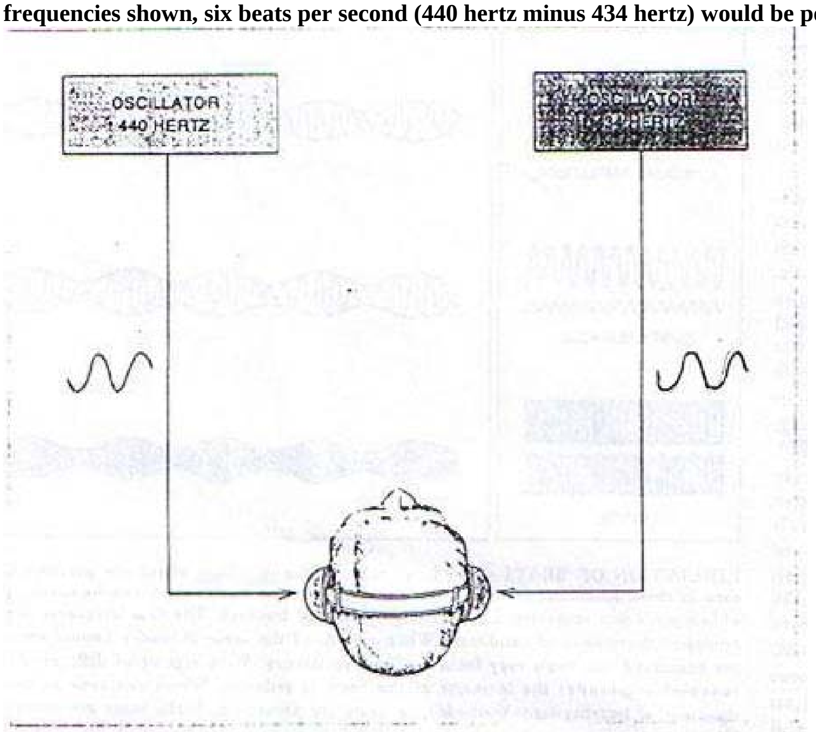
The difference most immediately apparent between monaural and binaural beats is that binaural beats can be heard only when the tones used to produce them are of low pitch. Binaural beats are best perceived when the carrier frequency is about 440 hertz; above that frequency they become less distinct and above about 1,000 hertz they vanish altogether. No person I have tested reports hearing beats for frequencies above 900 hertz. Experimental con-



SINE WAVES COMBINE TO PRODUCE BEATS in this illustration based on oscilloscope traces. The two waves at the top are of slightly different frequency; when they are combined, the resulting wave at the bottom varies slowly in amplitude. The variations are beats and would be perceived acoustically as modulations in loudness. If the two signals were presented separately to each ear, binaural beats would be heard. These differ in character from monaural, or ordinary, beats and are generated within the brain.



EXPERIMENTAL METHOD for generating monaural beats uses two electronic oscillators and a network, her called a mixer, to combine their outputs. Each ear hears a composite signal; the beats can be heard with one ear or both. With the oscillators tuned to the frequencies shown, six beats per second (440 hertz minus 434 hertz) would be perceived.



BINAURAL BEATS are produced when each oscillator is connected separately to one earphone. Again the beat frequency is six hertz, but in this mode the beats are less distinct. Whereas monaural beats are a result of the interaction of auditory signals occurring within the brain.

ditions, particularly the intensity of the sounds and the type of earphones used can affect the results, however, and other investigators report detecting beats produced by tones up to almost 1,500 hertz. At the other end of the scale beats also become elusive. Below about 90 hertz the subject may confuse the beats with the tones used to produce them.

J. C. R. Licklider of the Massachusetts Institute of Technology developed a technique when he was working at Harvard University to measure a spectrum of binaural beats [*see upper illustration on page 102*]. He adopted the frequency of one oscillator until the interval was large enough so that the beats seemed "rough"; then he noted the frequency of the unchanged reference oscillator. Next he changed the setting of the reference oscillator and repeated the procedure. In this way the range of perception of each subject was recorded.

Another distinguishing characteristic of binaural beats is their muffled sound. Monaural beats produced with sounds of equal intensity pulse from loudness to silence, as their wave form would suggest. Binaural beats, on the other hand, are only a slight modulation of a loud background. I have tried to estimate the depth of the modulation, and it seems to be about three decibels, or about a tenth of the loudness of a whisper. In order to help subjects recognize these relatively faint effects I usually present signals with monaural beats and then suddenly change to the binaural mode. With tones of about 440 hertz it usually takes two or three seconds for the subject to recognize the binaural beats.

To produce a monaural beat that varies from a maximum to complete silence the loudness of the two signals must be identical; if the signals are mismatched, the instantaneous amplitude of the algebraic sum will always be greater than zero. As the difference in intensity increases, the beats become less distinct. Binaural beats, on the other hand, have the same apparent strength regardless of the relative intensities of the two tones. In fact, E. Lehnhardt, at Berlin audiologist, discovered that binaural beats are perceived even if one of the signals is below the threshold of hearing.

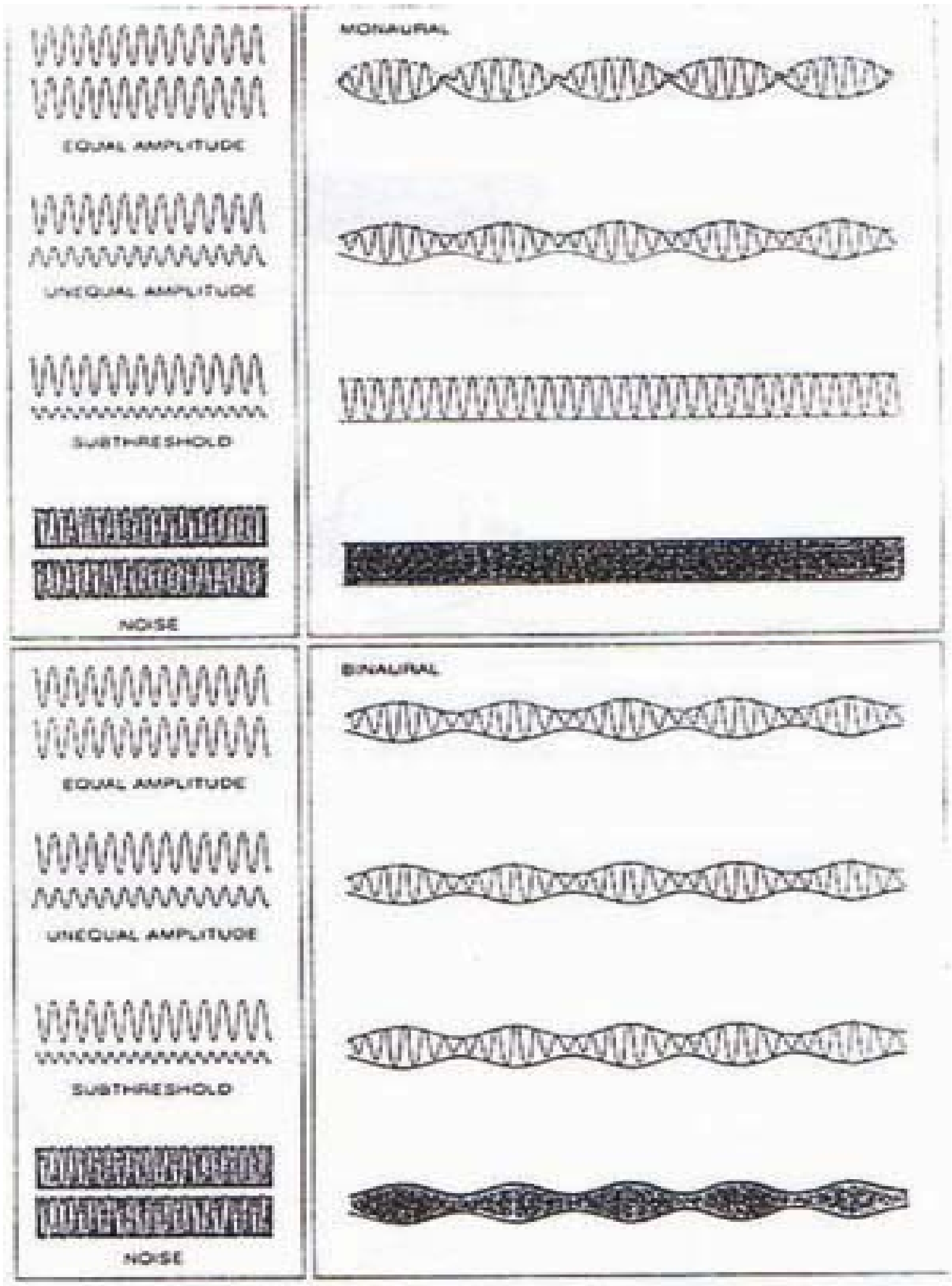
J.J. Groen of the State University of Utrecht has studied this phenomenon. Working with tones of about 200 hertz, he found that beats were perceptible when one signal had a loudness of 40 decibels and the other a loudness of minus 20 decibels, a hundredth the loudness of barely audible sound. Evidently the brain is able to detect and process the signals even though one of them is too weak to impinge on consciousness when the experiment is attempted monaurally, only the louder sound, without beats, is heard.

A perhaps related effect is the interaction of noise and binaural beats. Noise ordinarily masks sounds one wants to hear. For example, "static" sometimes overwhelms a weak radio signal. The perception of binaural beats, however, is enhanced by noise.

When two appropriate tones are presented to the ears so that binaural beats are produced, and are accompanied in each ear by noise just loud enough to obscure the tones, the beats become more distinct. In an analogous experiment with monaural signals only the noise will be heard. In laboratory the source of noise is an electronic device that generates a random signal called white noise, which sounds something like the swish of the wind through swamp grass. When it is added to the signals at the proper loudness, the original tones cannot be heard, but the noise seems to be modulated by the beats. The enhancement of binaural beats by noise is explained by L. A/ Jeffress and his colleagues at the University of Texas in terms of chance reinforcement. AT any instantly the amplitude of the noise will be more likely to be reinforced if the amplitudes of the signals are in coincidence. When the amplitudes of the signals are in opposition, destructive interference is more likely.

Listening to binaural beats produces the illusion that the sounds are located somewhere within the head. This in itself is hardly extraordinary: when music is played through stereophonic earphones, the orchestra seems to be somewhere in the head rather than "out there." It is intriguing, however, that when the beats are very infrequent, fewer than about three per second, they seem to move back and forth in the head. If the intensities of the two tones are different, the motion takes an elliptical path.

This apparent movement may be explained by the connection between binaural beats and the mechanism by which the brain senses the direction of sounds. For low-frequency signals, such as those used to produce binaural beats, sound is localized primarily by detecting the difference in phase between the sounds reaching the two ears [see "Auditory Localization," by Mark R. Rosenzweig; SCEINTIFIC AMERICAN, October, 1961]. Sounds of low frequency have wavelengths much longer than the diameter of the head; as a result the sound travels around the head by diffraction. Lord Raylegh, the 19th century English physicist, calculated that a tone of 256 hertz (middle C) striking the head from the side would reach the far ear with 90 percent of the intensity it had at the near ear. In other



PERCEPTION OF BEATS depends on the manner in which tones are presented to the ears. In these schematic representations the applied tones at the left can be assumed to be of low pitch and separated in frequency by a small interval. The four diagrams at the top represent the monaural condition. When signals of the same intensity (equal amplitude) are combined, the beats vary from loudness to silence. With signals of different loudness (unequal amplitude) the intensity of the beats is reduced. If the tones are accompanied by noise just loud enough to obscure them, again no beats are heard. In the four diagrams at the bottom, representing the binaural condition, the wave forms at the left are the same as those above but are presented to each ear separately. Under these conditions beats are heard whether the signals are of equal or of unequal amplitude and even if one is sub-threshold. If noise masks the tones, binaural beats are still heard, modulating the noise.

words, the head is not an obstruction to sounds of low pitch, and localization by the detection of relative intensity would be inefficient for those frequencies.

Localization by detection of phase differences is highly efficient, however. In an open area with no reflecting structures one can locate a low-pitched sound to within 10 degrees. To do so requires detecting a phase difference of less than one millisecond, a feat accomplished without difficulty by the mechanism of binaural hearing. The same phase difference is present in the tones that produce binaural beats, which is why slow beats seem to be in motion. A source of sound revolving around the head would produce a similar sensation.

For sounds of higher pitch the wavelength is comparable to or smaller than the size of the head, and the head acts as a barrier, so that the ear in its shadow receives almost no sound. Above about 1,000 hertz sound localization is governed primarily by the intensity rather than phase differences. It is significant that the ability to hear binaural beats also wanes when the tones presented approach 1,000 hertz. Direction-finding at the higher frequencies is less accurate than it is for low-pitched tones up to about 8,000 hertz, when the pinna (the external ear) becomes effective as an aid to localization.

The auditory mechanisms manifested in the perception of binaural beats aid human hearing in another way. It has often been observed that the ability to select and listen to a single conversation in a jumble of background noise is a remarkable and valuable human faculty.

This phenomenon, sometimes called "the cocktail party effect,' is dependent on binaural hearing. It is, in fact, an application of the enhancement of phase perception with noise also seen in the perception of binaural beats.

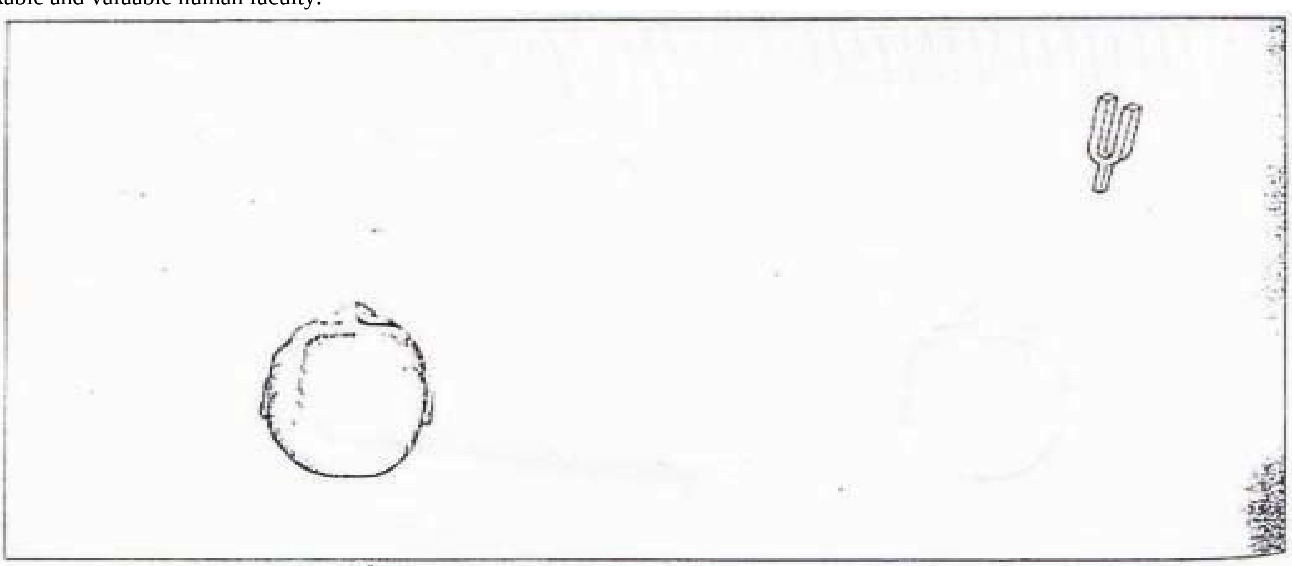
Hearing generally deteriorates with age. Yet I have found that older people are able to detect binaural beats and to locate sounds almost as well as the young. At 5,000 hertz the auditory acuity of a man of 60 is, on the average, 40 decibels below that of a man of 20, and the highest pitch he can hear, 8,000 hertz, is half that heard by the younger man. His acuity for low tones, however, is barely affected, and evidently his phase perception is also undiminished.

What is the neurological basis of binaural beats? The simplest explanation is that the number of nerve impulses from each ear and the route they travel to the brain are determined by the frequency of the incident sound, and that the two nerve signals interact somewhere in the brain.

One theory of perception of pitch, call the telephone theory, was proposed by W. Butherford in 1886, it postulated that the ear converts acoustic vibrations into electrical signals much as a microphone does, emitting one nerve impulse for each cycle of the tone. Single nerve fibers can respond to such stimuli only up to about 500 hertz, however, so that the telephone theory could describe the behavior of the ear only for the lowest frequencies. In 1865 Herman von Helmholtz proposed the place theory which ascribed pitch discrimination to the mechanical properties of the cochlea, or inner ear. The cochlea is a cone-shaped, fluid-filled vessel, rich in nerve endings and coiled like a snail shell. ("Chochlea" is a Latin for snail.) the coiled tube of the cochlea is divided in half along its length by the basilar membrane, which vibrates in response to sound. George von Bekesy found by direct visual observation that a sound of a certain frequency will make the basilar membrane bulge most noticeably in a certain place [see "The Ear," by George von Bekesy; Scientific American, August, 1957]. This local stimulation, it is believed, excites receptor cells in the vicinity of the bulge and thus excites the nerve fibers connecting the receptor cells to the auditory area of the brain. According to the place theory, the impulses transmitted by the auditory nerves reflect the intensity of the sound but not the frequency. What pitch is perceived is determined by the place on the cochlea where the nerve originates.

Above about 5,000 hertz the place theory seems to be adequate to describe pitch perception. At lower frequencies, however, the mechanical response of the basil membrane is too unspecific to account for the precision with which the ear identifies tones. Furthermore, attempts to test the theory by excising in experimental animals those nerve fibers that should be the sole carriers of low frequency tones have been unsuccessful.

For the frequencies between 500 and 5,000 hertz, Ernest Glen Wever of Princeton University in 1939 proposed the volley theory. Although the individual nerve fibers cannot fire more than 500 times per second, a group of



LOCATION OF THE SOURCE of a sound is determined for lower pitched tones by detecting the difference in phase between signals arriving at each ear. In this illustration a compression wave has reached the left ear while the right is near a maximum of rarefaction. By detecting such a phase difference the ears can find the direction of a low-frequency tone to an accuracy of about 10 degrees. At these frequencies little sound is blocked by the head; the wavelength is larger than the head and the sound is diffracted around it.

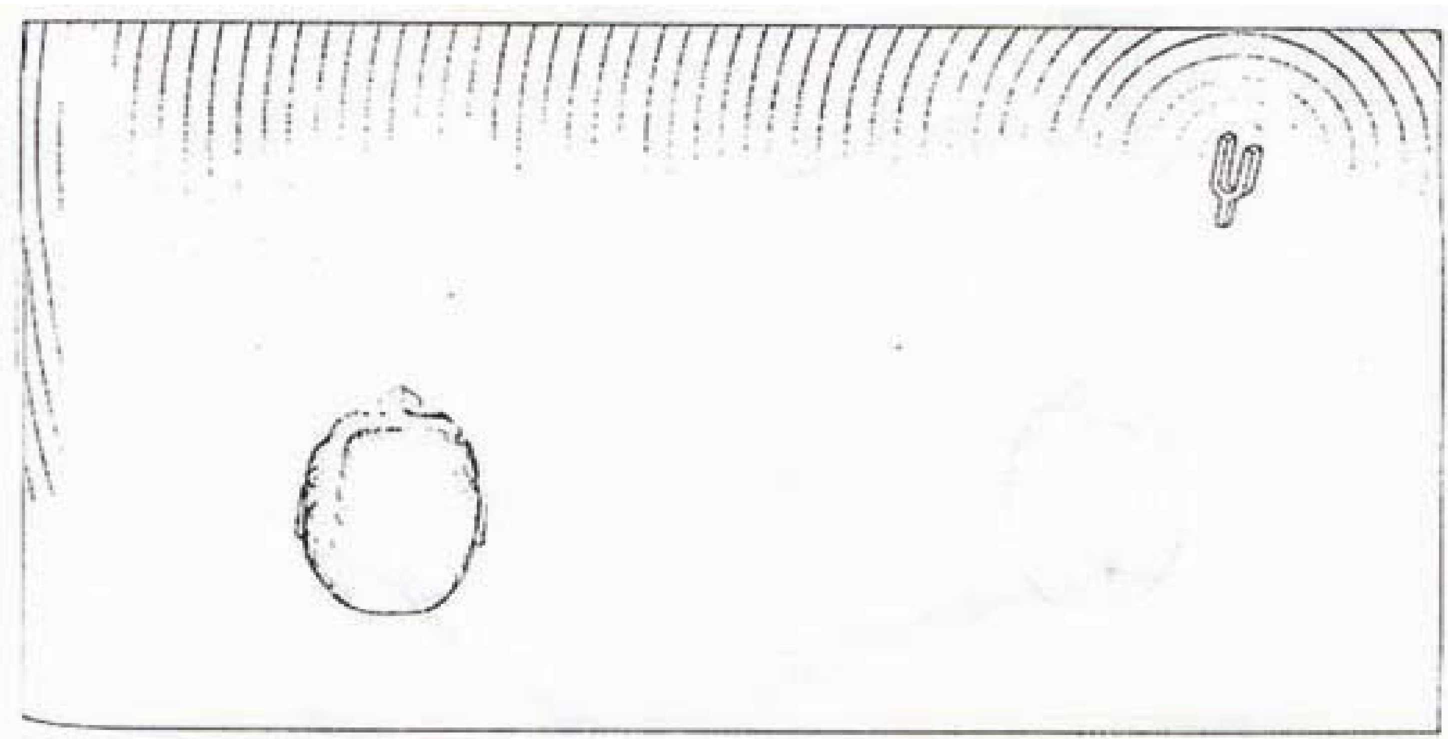
nerve cells could exceed this rate by firing in succession, Wever suggested, much as platoons in an infantry company could fire their weapons in successive volleys. Thus while some nerve cells area in their refractory period others are producing pulses. The fading of binaural beats at frequencies between 500 and 1,000 hertz suggests that the mechanism of the beats follows the telephone theory and, at the higher frequencies, follows the related volley theory.

Interaction of the signals from the two ears probably occurs at the brain center named the superior olivary nucleus. As the messages ascend to the auditory pathways to be processed and interpreted at the high er centers, this is the first center in the brain to receive signals from both ears [*see illustration on page 101*]. Actually there are two superior olivary nuclei; they are arrayed symmetrically on each side of the brain, and each is a terminus for nerve fibers from both ears. They have long been considered likely sites for the neural processing of low-frequency sound impulses.

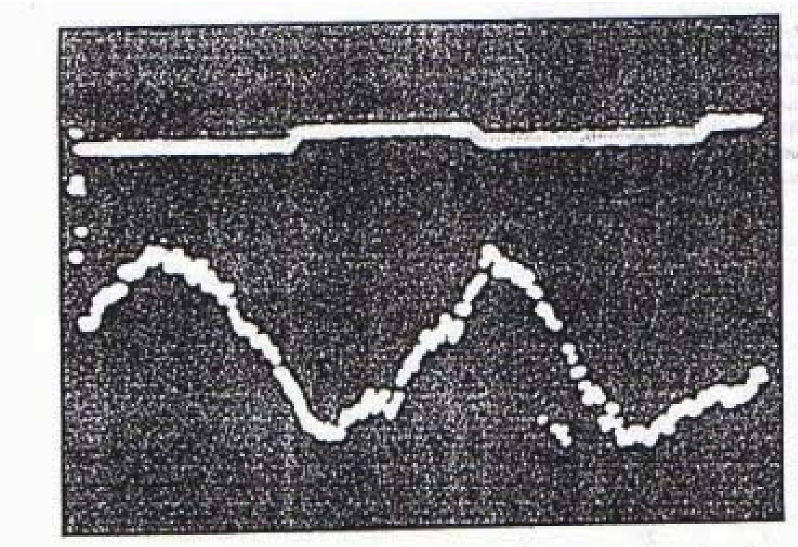
In experiments with cats, Robert Galambos showed in 1959 that loud clicks stimulating both ears generate nerve impulses that meet in the superior olivary nucleus. When the clicks are simultaneous, the signals are reinforced at some site in the superior olivary nucleus. When a slight delay is introduced, however, the resulting signal is inhibited. Thus a small phase shift gives rise to a weaker perception of sound. It is presumably for this reason that one tends to turn toward the source of a sound and eliminate the phase difference. When one is listening through earphones, of course, turning the head has no effect on the phase of the signals.

Nerve potentials at the superior olivary nucleus of the cat have been measured directly. With human subjects it is possible to measure these signals by recording evoked potentials: small changes in the electrical properties of the scalp produced as a result of activity of the brain. Because they are objective indicators of certain brain functions evoked potentials have clinical applications. For example, in cases of possible hysterical blindness evoked potentials from the scalp above the occipital lobes can determine whether or not the brain is receiving visual information. Similarly, evoked potentials can be used to detect deafness in infants, which is otherwise quite difficult to diagnose. The potentials are very small (measured in microvolts) and are obscured by many random signals not associated with the stimulus. They can be measured on an oscilloscope, but special procedures must be followed.

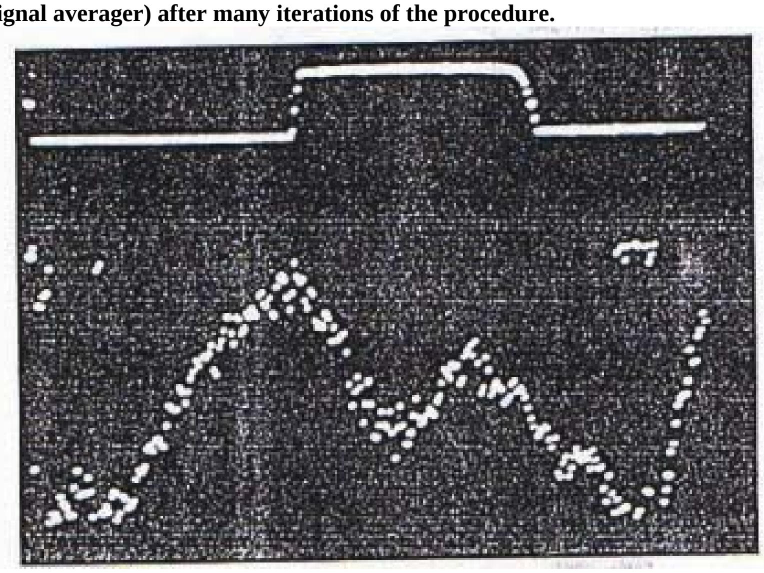
First, the horizontal sweep of the oscilloscope must be synchronized with the stimulus; this is done by using the stimulus current to trigger the start of the sweep. In addition, a great many tracings must be made in order to obtain unambiguous data. A computer known as a signal averager stores a series of tracings electronically, then on command adds the instantaneous potentials to produce a composite signal. Because the extraneous random potentials have no lived phase relation to the



HIGH FREQUENCY SOUND LOCALIZATION also requires binaural hearing, but differences in intensity rather than phase are detected. The wavelength of a high-pitched tone is smaller than the diameter of the head and a distinct sonic shadow is formed; thus one ear receives more sound than the other. This mode of sound localization is less accurate than phase detection except at very high freqeucies. The transition takes place at about 1,000 hertz; at this frequency too the perception of binaural beats wanes.



EVOKED POTENTIALS for subjects listening to monaural beats are shown in a photograph of an oscilloscope screen made by the author with Adam Atkin and Neil Wetherspoon at the Mount Sinai School of Medicine. Tones of 300 hertz and 303 hertz were presented to each ear; an electrode attached to the scalp was used to measure electric potentials in the skin evoked by underlying electrical activity in the brain. By synchronizing the horizontal sweep of the oscilloscope with the beat frequency it was possible to correlate these small potentials (measured in microvolts) with the stimulus. The steplike wave form at the top of the screen is a signal used to time the oscilloscope sweep; the rise of each pulse corresponds to the moment of maximum loudness of the beat. The periodic wave below it records the evoked potentials. It consists of the average values for each point on the curve, determined by a small computer (a signal averager) after many iterations of the procedure.



BINAURAL EXPERIMENT was conducted under the same conditions, except that the tones were presented separately to each ear. Evoked potentials were once again successfully recorded, but they differed from those detected under monaural conditions in amplitude, in wave form and in timing with respect to the stimulus. These differences suggest that binaural beats are processed in another way or at another site in the brain than monaural beats are. In the illustration the amplitude of the evoked potentials appears to be about the same as it is for monaural beats; it is actually much smaller. For clarity the vertical scale of the oscilloscope has been expanded, as can be seen by comparing the apparent amplitudes of the timing signals. In both illustrations bright areas not associated with the main wave form are extraneous signals produced by residual noise generated in the recording apparatus.

stimulus they are progressively suppressed as the number of tracings increases.

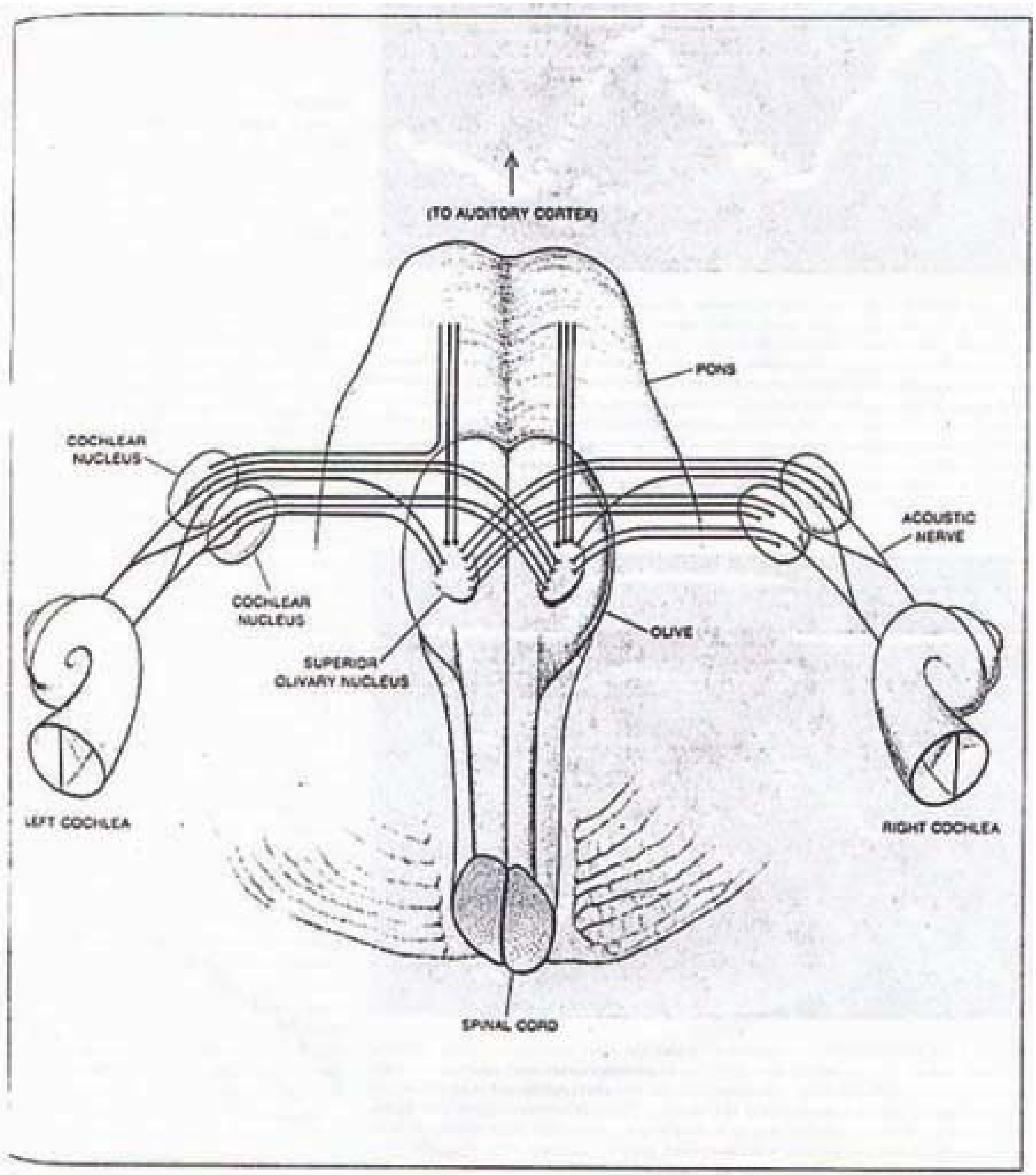
If binaural and monaural beats are indeed processed at different sites in the brain, it should be possible to detect this difference by measuring the evoked potentials. With my colleagues at the Mount Sinai School of Medicine, Adam Atkin and Neil Wetherspoon, I set out to test this hypothesis. Because the stimulus was continuous tone rather than a brief click, it proved particularly difficult to obtain clear tracings. Eventually we learned that for effective results the subject must concentrate on the beats while in total darkness. This is a boring task, since binaural beats indistinct and many tracings must be averaged. Often the subject experiences auditory hallucinations imposing a spurious pattern on the sound, which spoils the results. Nevertheless, after many iterations of this procedure we were able to demonstrate that the evoked potentials produced by binaural and monaural beats differ qualitatively and quantitatively, indicating that they are processed differently [*see illustration at left*].

Binaural beats my have clinical applications. With some of my students I examined a number of neurological patients and discovered that a few could not hear binaural beats. Among these patients a few could not localize sounds produced by the examiner’s snapping his fingers). It may be significant that some of those who could not hear the beats suffered from Parkinson’s disease, a disorder that the central nervous system characterized by a lack of spontaneous muscular activity, an immobile facial expression and tremor. One patient, a violinist, was unable to hear binaural beats when he entered the hospital. As his treatment continued he began to perceive the beats produced by the very lowest level tones, and gradually he progressed to the higher frequencies. At the end of the week, when his condition was considered satisfactory, he could hear beats produced by tones up to about 650 hertz.

A sex related variation in ability to hear binaural beats has also been discovered. J.V.

Tobias of the Federal Aviation Administration in Oklahoma City studied the binaural-beat spectrum of a number of volunteers and found that the upper limit of the applied frequencies is higher for men than for women [see lower illustration on next page]. He went on to monitor the perceptions of three women over a period of six weeks and found that the spectrum extended to the highest tones at the beginning of menstruation, then declined before reaching a second peak 15 days aft the onset of menstruation. The latter peak may correspond to the time of ovulation, when a women is most fertile.

I have tested a few women of reproductive age, with results that tend to confirm Tobias' findings. It appears that some women do show marked variations in the perception of binaural



LOWER AUDITORY CENTERS of the brain are in the medulla oblongata, viewed here schematically from the back of the nceck. Nerve impulses from the right (color) and the left (black) ears first meet in the left or right superior olivary nucleus. These structures are part of the olive, an organ that in this view lies behind the brain stem. It is probable that binaural beats are detected here.

beats during the menstrual cycle. When the beats are not heard, the women often hear two separate tones. Men, on the other hand, show no extended to the highest tones at the beginning of menstruation, then declined before reaching a second peak 15 days aft the onset of

Binaural beats have been widely regarded as a mere curiosity. A recent textbook on hearing does not mention them at all. Yet the variation during the month. These results suggest that the binaural-beat spectrum may be influenced by the level of estrogen in the blood.

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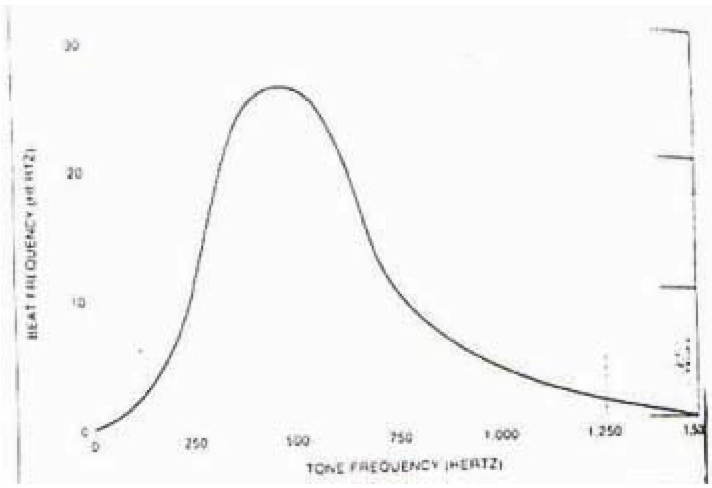
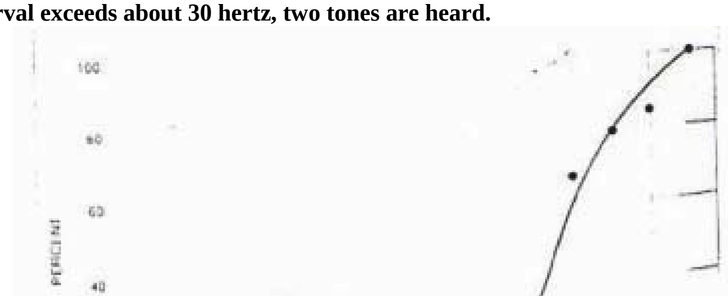
measurement of binaural beats can explain the processes by which sounds are located, a crucial aspect of perception. The enhancement of the beats by noise is a model of the mechanism by which auditory messages are sorted from a noisy background. That sub- threshold sounds are effectively rendered audible by binaural beats suggests that there may be other stimuli processed by the brain of which we are not aware. Finally, it is possible that hormonally induced physiological or behavioral changes too subtle to detect by ordinary means may be made apparent by measuring the binaural beat spectrum.



SPECTRUM OF BINAURAL BEATS was measured by J.C.R. Licklider, J.C. Webster and J.M. Hedlum. Rapid beats, up to about 26 per second, can be heard when the tones used to produce them are about 440 hertz. With tones of higher or lower pitch the maximum beat frequency declines. When the interval exceeds about 30 hertz, two tones are heard.



SEX-RELATED VARIATION in the perception of binaural beats is plotted from data compiled by J.V. Tobias. As the pitch of the tones used to produce beats increases, both men and women cease to perceive them. Women, however, lose the ability at lower frequencies. Some female subjects also report variations during the menstrual cycle.

Below is the original scan of the Scientific American article by Oster

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by Gerald Oster

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In modern investigations tuning forks are replaced by electronic oscillators, which can supply tones of precisely controlled pitch, purity and intensity. Beats are produced when the outputs of two oscillators tuned to slightly different frequencies are combined electrically and applied to a loudspeaker. Alternatively, the signals can be applied individually to separate speakers and the beats will still be heard. The result is the same whether the tones are combined electrically and then converted into sound, or converted into sound separately and then combined.

A quite different phenomenon results when stereophonic earphones are used and the signals are applied separately to each ear. Under the right circumstances beats can be perceived, but they are of an entirely different character. They are called binaural beats, and in many ways they are more interesting than ordinary beats, which in this discussion will be called monaural. Monaural beats can be heard with both ears, but one ear is sufficient to perceive them. Binaural beats require the combined action of both ears. They exist as a consequence of the interaction of perceptions within the brain, and they can be used to investigate some of the brain's processes.

The physical mechanism of monaural beats is a special case of wave interference. At any instant the amplitude of the resulting sound is equal to the algebraic sum of the amplitudes of the original tones. The signals are reinforced when they are in phase, that is, when the peaks and nulls of their waves coincide. Destructive interference diminishes the net amplitude when the waves are in opposition. The pure tones used in these experiments are described by sine waves; the resulting beats are slowly varying functions similar to, but not precisely conforming to, a sine wave.

A beat frequency of about six hertz, as in the example given above, would sound something like vibrato in music (although vibrato is frequency modulation rather than amplitude modulation). If the interval between frequencies is made smaller, very slow beats can be produced, down to about one per second, but at this speed the beats may be difficult to perceive. Rapid beats, up to about 30 hertz, are heard as roughness superimposed on the sound, rather like a Scotsman's burr. With still greater intervals beats are not heard; the two tones are perceived separately.

Beats are rarely encountered in nature because in nature sustained pure tones are rare. They abound, however, in mechanical devices. In an airplane, jet engines operating at slightly different speeds may produce a very strong beat, often recognized only as a feeling "in the pit of the stomach." Acoustical engineers can filter out the whine of the engines, but the slow vibrations are difficult to suppress. Occupants of apartment houses may be annoyed by beats produced by machinery, such as two blowers running at different speeds, but they will have a hard time finding the source.

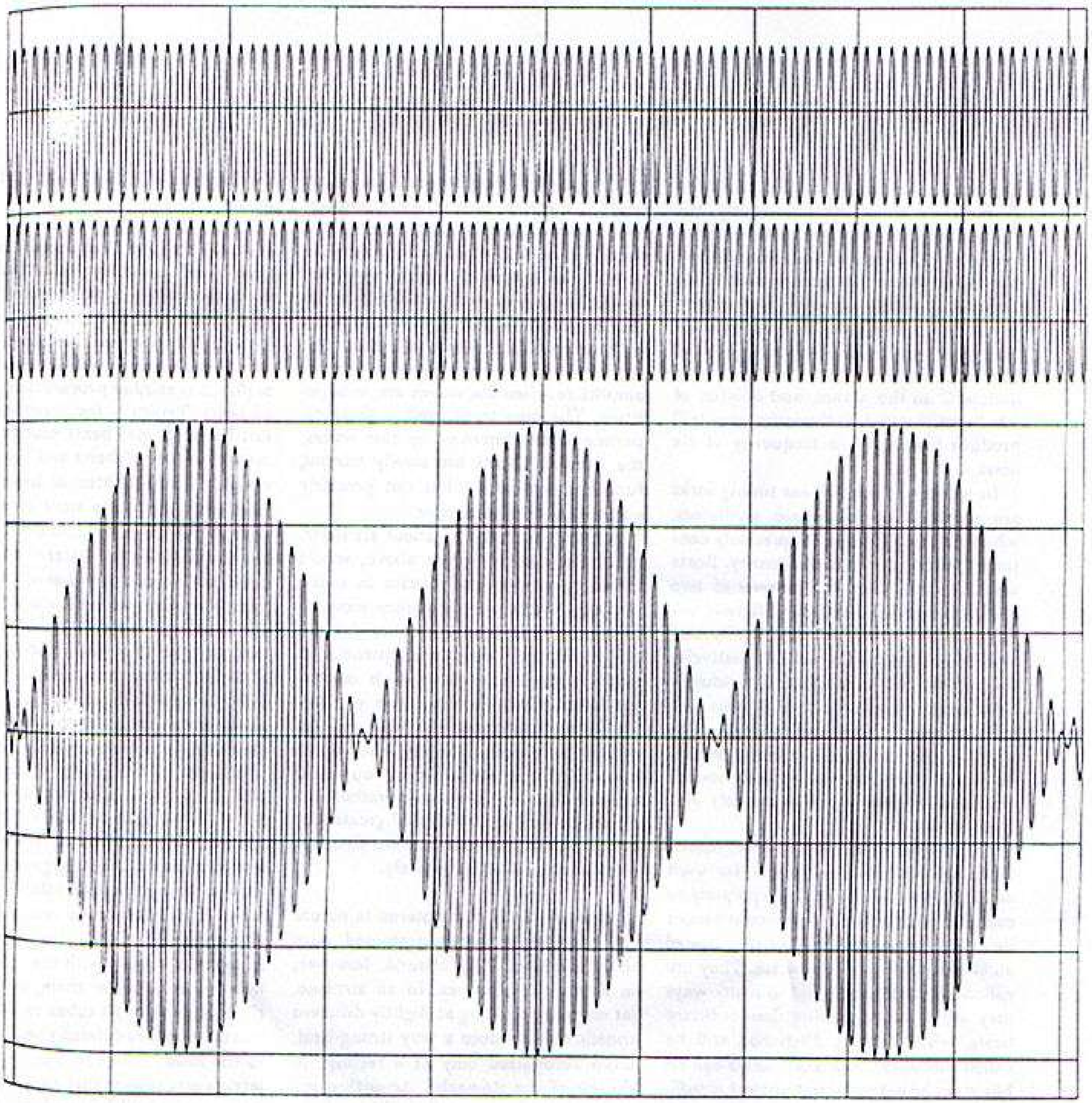
On the other hand, beats are used to advantage where frequencies must be determined precisely. Electrical engineers compare the output of a test oscillator with that of a standard oscillator by detecting the beats produced when their signals are combined. The tuning of pianos is another process that depends on beats. Typically the piano tuner will first listen for the beats produced by a tuning fork of 440 hertz and the *A* above middle *C*, and tighten or loosen the *A* wire until the beats slow to zero. He then strikes the *A* key and the *D* key below it and tunes the latter wire until 10 beats per second are heard. That frequency is produced by the interaction of the *A* string's second harmonic, or second multiple ($2 \times 440 = 880$), and the *D* string's third harmonic ($3 \times 290 = 870$). In this fashion, key by key, the piano is tuned; in theory it could be done even by someone who is tone-deaf.

Binaural beats were discovered in 1839 by a German experimenter named H. W. Dove, but as late as 1915 they were considered a trivial special case of monaural beats. It was argued that each ear was hearing sounds intended for the other. This extraneous result could be eliminated by placing the tuning forks in separate rooms, with the subject in a third room between them, and guiding the sounds through tubes to each ear. It was necessary to carefully seal each tube to the head, however, and another objection was raised: that sound presented to one ear could be conducted through the skull to the other. Bone conduction is well established, and indeed some hearing aids operate on this principle, although sound is attenuated a thousandfold from ear to ear.

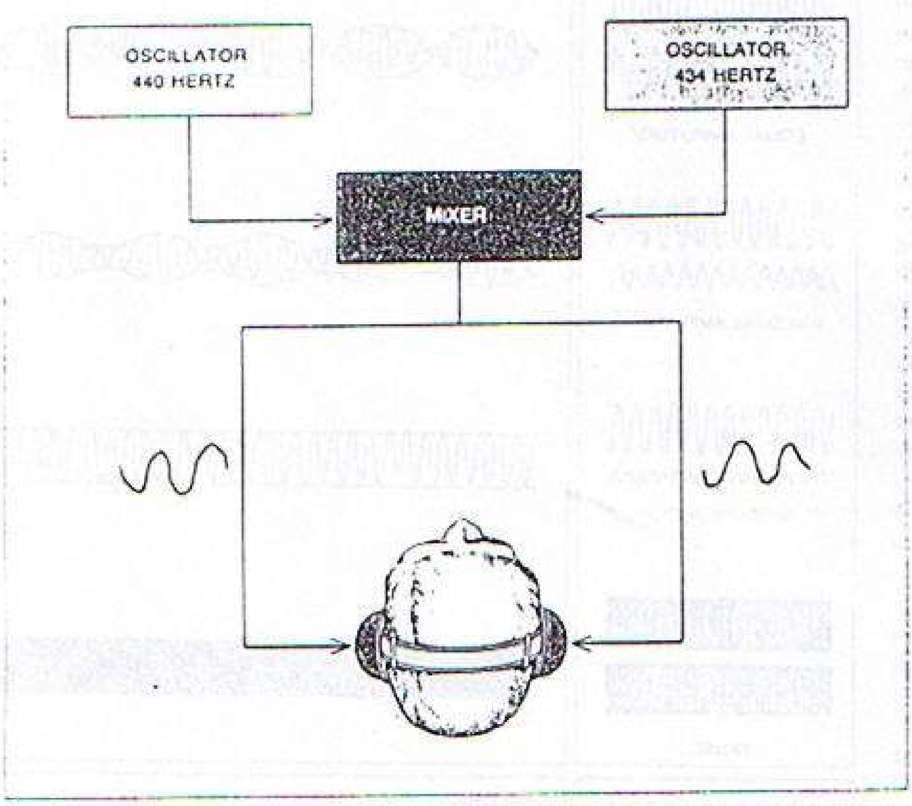
The possible contribution of bone conduction to the perception of binaural beats is eliminated, however, by the use of modern stereophonic earphones. Such earphones have padding, often liquid-filled, to insulate the head from the sound source, and are designed explicitly to prevent conduction effects. Indeed, stereophonic recordings played through earphones can sound unnatural because the instruments seem too isolated.

The difference most immediately apparent between monaural and binaural beats is that binaural beats can be heard only when the tones used to produce them are of low pitch. Binaural beats are best perceived when the carrier frequency is about 440 hertz; above that frequency they become less distinct and above about 1,000 hertz they vanish altogether. No person I have tested reports hearing beats for frequencies above 900 hertz. Experimental conditions, particularly the intensity of the signals and the type of earphones used, can affect the results, however, and other investigators report detecting beats produced by tones up to almost 1,500 hertz. At the other end of the scale beats also become elusive. Below about 90 hertz the subject may confuse the beats with the tones used to produce them.

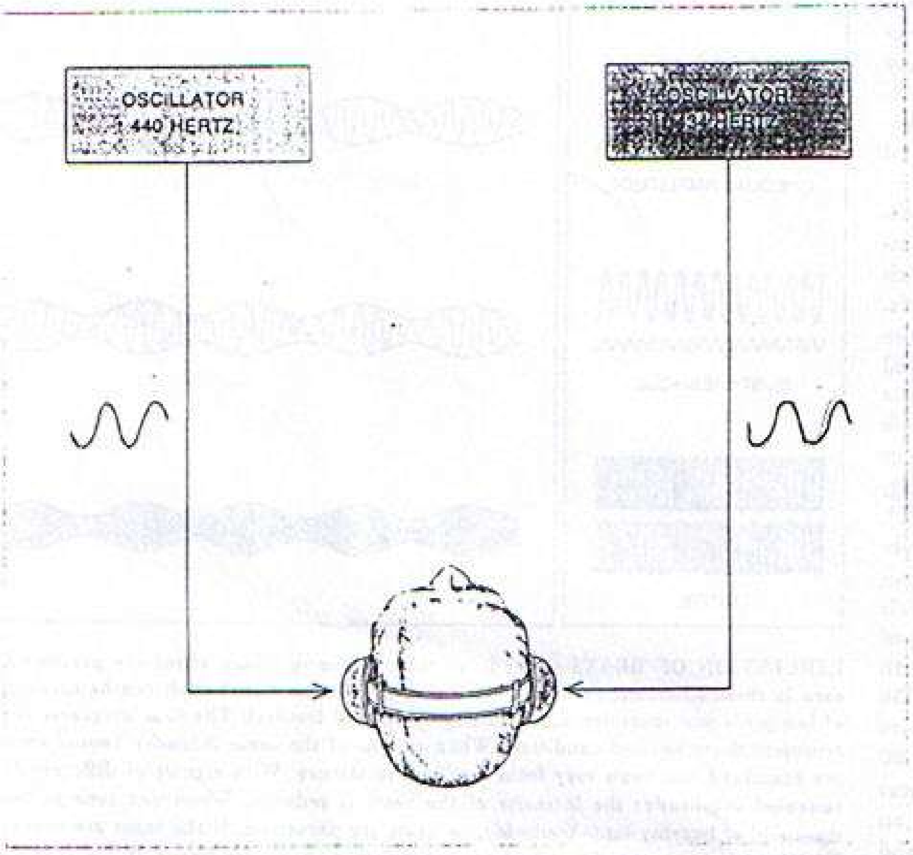
J. C. R. Licklider of the Massachusetts Institute of Technology developed a technique when he was working at Harvard University to measure a spectrum



SINE WAVES COMBINE TO PRODUCE BEATS in this illustration based on oscilloscope traces. The two waves at the top are of slightly different frequency; when they are combined, the resulting wave at the bottom varies slowly in amplitude. The variations are beats and would be perceived acoustically as modulations in loudness. If the two signals were presented separately to each ear, binaural beats would be heard. These differ in character from monaural, or ordinary, beats and are generated within the brain.



EXPERIMENTAL METHOD for generating monaural beats uses two electronic oscillators and a network, here called a mixer, to combine their outputs. Each ear hears a composite signal; the beats can be heard with one ear or both. With the oscillators tuned to the frequencies shown, six beats per second (440 hertz minus 434 hertz) would be perceived.



BINAURAL BEATS are produced when each oscillator is connected separately to one earphone. Again the beat frequency is six hertz, but in this mode the beats are less distinct. Whereas monaural beats are produced by the physical interference of two sound waves, binaural beats are a result of the interaction of auditory signals occurring within the brain.

of binaural beats [*see upper illustration on page 102*]. He adjusted the frequency of one oscillator until the interval was large enough so that the beats seemed "rough"; then he noted the frequency of the unchanged reference oscillator. Next he changed the setting of the reference oscillator and repeated the procedure. In this way the range of perception of each subject was recorded.

Another distinguishing characteristic of binaural beats is their muffled sound. Monaural beats produced with sounds of equal intensity pulse from loudness to silence, as their wave form would suggest. Binaural beats, on the other hand, are only a slight modulation of a loud background. I have tried to estimate the depth of the modulation, and it seems to be about three decibels, or about a tenth the loudness of a whisper. In order to help subjects recognize these relatively faint effects I usually present signals with monaural beats and then suddenly change to the binaural mode. With tones of about 440 hertz it usually takes two or three seconds for the subject to recognize the binaural beats.

To produce a monaural beat that varies from a maximum to complete silence the loudness of the two signals must be identical; if the signals are mismatched, the instantaneous amplitude of the algebraic sum will always be greater than zero. As the difference in intensity increases, the beats become less distinct. Binaural beats, on the other hand, have the same apparent strength regardless of the relative intensities of the two tones. In fact, E. Lehnhardt, a Berlin audiologist, discovered that binaural beats are perceived even if one of the signals is below the threshold of hearing.

J. J. Groen of the State University of Utrecht has studied this phenomenon. Working with tones of about 200 hertz, he found that beats were perceptible when one signal had a loudness of 40 decibels and the other a loudness of minus 20 decibels, a hundredth the loudness of barely audible sound. Evidently the brain is able to detect and process the signals even though one of them is too weak to impinge on consciousness. When the experiment is attempted monaurally, only the louder sound, without beats, is heard.

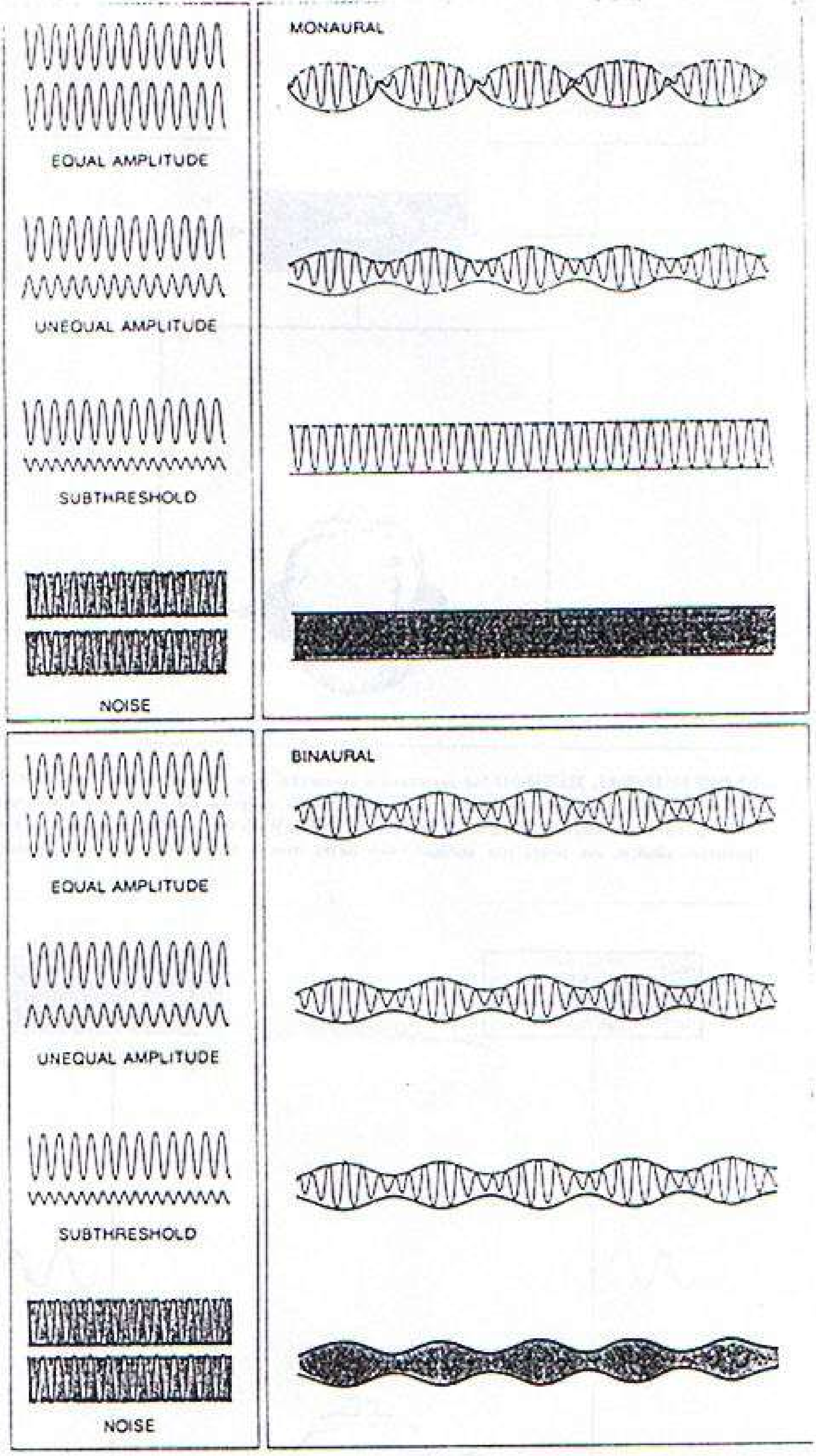
A perhaps related effect is the interaction of noise and binaural beats. Noise ordinarily masks sounds one wants to hear. For example, "static" sometimes overwhelms a weak radio signal. The perception of binaural beats, however, is enhanced by noise.

When two appropriate tones are presented to the ears so that binaural beats are produced, and are accompanied in each ear by noise just loud enough to obscure the tones, the beats become more distinct. In an analogous experiment with monaural signals only the noise will be heard. In the laboratory the source of noise is an electronic device that generates a random signal called white noise, which sounds something like the swish of the wind through swamp grass. When it is added to the signals at the proper loudness, the original tones cannot be heard, but the noise seems to be modulated by the beats. The enhancement of binaural beats by noise is explained by L. A. Jeffress and his colleagues at the University of Texas in terms of chance reinforcement. At any instant the amplitude of the noise will be more likely to be reinforced if the amplitudes of the signals are in coincidence. When the amplitudes of the signals are in opposition, destructive interference is more likely.

Listening to binaural beats produces the illusion that the sounds are located somewhere within the head. This in itself is hardly extraordinary: when music is played through stereophonic earphones, the orchestra seems to be somewhere in the head rather than "out there." It is intriguing, however, that when the beats are very infrequent, fewer than about three per second, they seem to move back and forth in the head. If the intensities of the two tones are different, the motion takes an elliptical path.

This apparent movement may be explained by the connection between binaural beats and the mechanism by which the brain senses the direction of sounds. For low-frequency signals, such as those used to produce binaural beats, sound is localized primarily by detecting the difference in phase between the sounds reaching the two ears [see "Auditory Localization," by Mark R. Rosenzweig; SCIENTIFIC AMERICAN, October, 1961]. Sounds of low frequency have wavelengths much longer than the diameter of the head; as a result the sound travels around the head by diffraction. Lord Rayleigh, the 19th-century English physicist, calculated that a tone of 256 hertz (middle C) striking the head from the side would reach the far ear with 90 percent of the intensity it had at the near ear. In other words, the head is not an obstruction to sounds of low pitch, and localization by the detection of relative intensity would be inefficient for those frequencies.

Localization by detection of phase dif-



PERCEPTION OF BEATS depends on the manner in which tones are presented to the ears. In these schematic representations the applied tones at the left can be assumed to be of low pitch and separated in frequency by a small interval. The four diagrams at the top represent the monaural condition. When signals of the same intensity (*equal amplitude*) are combined, the beats vary from loudness to silence. With signals of different loudness (*unequal amplitude*) the intensity of the beats is reduced. When one tone is below the threshold of hearing (*subthreshold*), no beats are perceived. If the tones are accompanied by noise just loud enough to obscure them, again no beats are heard. In the four diagrams at the bottom, representing the binaural condition, the wave forms at the left are the same as those above but are presented to each ear separately. Under these conditions beats are heard whether the signals are of equal or of unequal amplitude and even if one is subthreshold. If noise masks the tones, binaural beats are still heard, modulating the noise.

ferences is highly efficient, however. In an open area with no reflecting structures one can locate a low-pitched sound to within 10 degrees. To do so requires detecting a phase difference of less than one millisecond, a feat accomplished without difficulty by the mechanism of binaural hearing. The same phase difference is present in the tones that produce binaural beats, which is why slow beats seem to be in motion. A source of sound revolving around the head would produce a similar sensation.

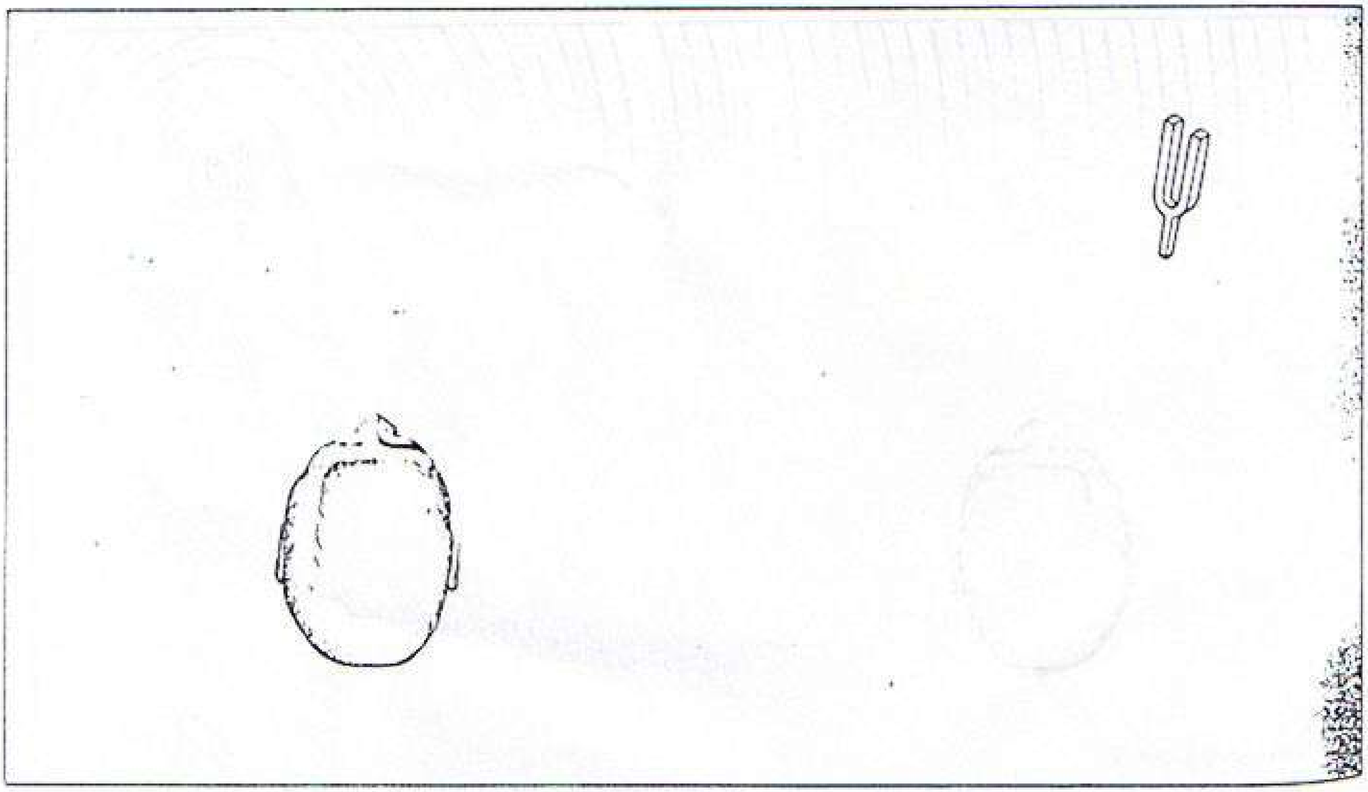
For sounds of higher pitch the wavelength is comparable to or smaller than the size of the head, and the head acts as a barrier, so that the ear in its shadow receives almost no sound. Above about 1,000 hertz sound localization is governed primarily by intensity rather than phase differences. It is significant that the ability to hear binaural beats also wanes when the tones presented approach 1,000 hertz. Direction-finding at the higher frequencies is less accurate than it is for low-pitched tones up to about 8,000 hertz, when the pinna (the external ear) becomes effective as an aid to localization.

The auditory mechanisms manifested in the perception of binaural beats aid human hearing in another way. It has often been observed that the ability to select and listen to a single conversation in a jumble of background noise is a remarkable and valuable human faculty. This phenomenon, sometimes called "the cocktail party effect," is dependent on binaural hearing. It is, in fact, an application of the enhancement of phase perception with noise also seen in the perception of binaural beats.

Hearing generally deteriorates with age. Yet I have found that older people are able to detect binaural beats and to locate sounds almost as well as the young. At 5,000 hertz the auditory acuity of a man of 60 is, on the average, 40 decibels below that of a man of 20, and the highest pitch he can hear, 8,000 hertz, is half that heard by the younger man. His acuity for low tones, however, is barely affected, and evidently his phase perception is also undiminished.

What is the neurological basis of binaural beats? The simplest explanation is that the number of nerve impulses from each ear and the route they travel to the brain are determined by the frequency of the incident sound, and that the two nerve signals interact somewhere in the brain.

One theory of the perception of pitch, called the telephone theory, was proposed by W. Rutherford in 1886. It postulated that the ear converts acoustic vibrations into electrical signals much as a microphone does, emitting one nerve impulse for each cycle of the tone. Single nerve fibers can respond to such stimuli only up to about 500 hertz, however, so that the telephone theory could describe the behavior of the ear only for the lowest frequencies. In 1863 Hermann von Helmholtz proposed the place theory, which ascribed pitch discrimination to the mechanical properties of the cochlea, or inner ear. The cochlea is a cone-shaped, fluid-filled vessel, rich in nerve endings and coiled like a snail shell. ("Cochlea" is Latin for snail.) The coiled tube of the cochlea is divided in half along its length by the basilar membrane, which vibrates in response to sound. Georg von Békésy found by direct visual observation that a sound of a certain frequency will make the basilar membrane bulge most noticeably in a certain place [see "The Ear," by Georg von Békésy; SCIENTIFIC AMERICAN, August, 1957]. This local stimulation, it is believed, excites receptor cells in the vicinity of the bulge and thus excites the nerve fibers connecting the receptor cells to the auditory area of the brain. Accord-



LOCATION OF THE SOURCE of a sound is determined for low-pitched tones by detecting the difference in phase between signals arriving at each ear. In this illustration a compression wave has reached the left ear while the right is near a maximum of rarefaction. By detecting such a phase difference the ears can find the direction of a low-frequency tone to an accuracy of about 10 degrees. At these frequencies little sound is blocked by the head; the wavelength is larger than the head and sound is diffracted around it.

ing to the place theory, the impulses generated by the auditory nerves reflect the intensity of the sound but not the frequency; what pitch is perceived is determined by the place on the cochlea where the nerve originates.

Above about 5,000 hertz the place theory seems to be adequate to describe pitch perception. At lower frequencies, however, the mechanical response of the basilar membrane is too unspecific to account for the precision with which the ear identifies tones. Furthermore, attempts to test the theory by excising in experimental animals those nerve fibers that should be the sole carriers of low-frequency tones have been unsuccessful.

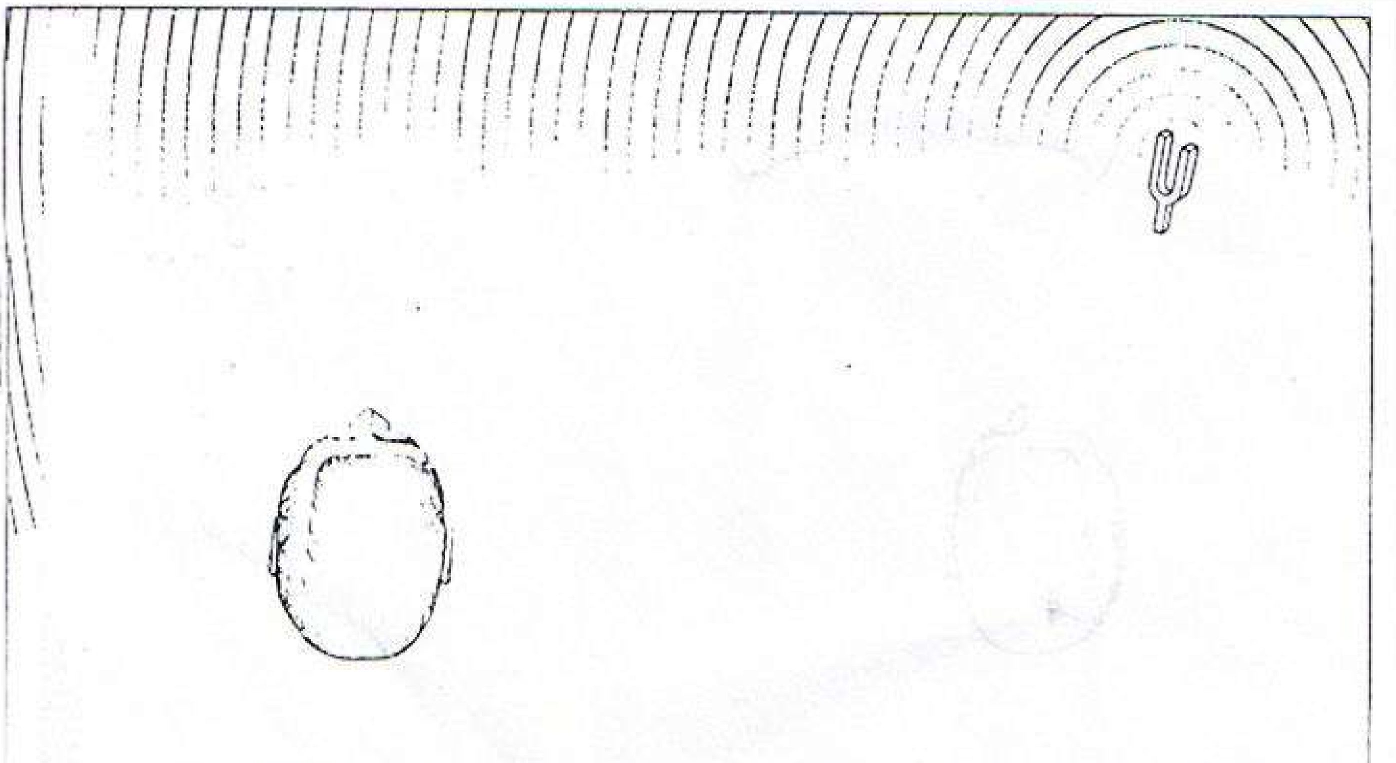
For the frequencies between 500 and 5,000 hertz Ernest Glen Wever of Princeton University in 1939 proposed the volley theory. Although individual nerve fibers cannot fire more than 500 times per second, a group of nerve cells could exceed this rate by firing in succession, Wever suggested, much as platoons in an infantry company could fire their weapons in successive volleys. Thus while some nerve cells are in their refractory period others are producing pulses. The fading of binaural beats at frequencies between 500 and 1,000 hertz suggests that the mechanism of the beats follows the telephone theory and, at the higher frequencies, follows the related volley theory.

Interaction of the signals from the two ears probably occurs at the brain center named the superior olivary nucleus. As the messages ascend the auditory pathways to be processed and interpreted at higher centers, this is the first center in the brain to receive signals from both ears [*see illustration on page 101*]. Actually there are two superior olivary nuclei; they are arrayed symmetrically on each side of the brain, and each is a terminus for nerve fibers from both ears. They have long been considered likely sites for the neural processing of low-frequency sound impulses.

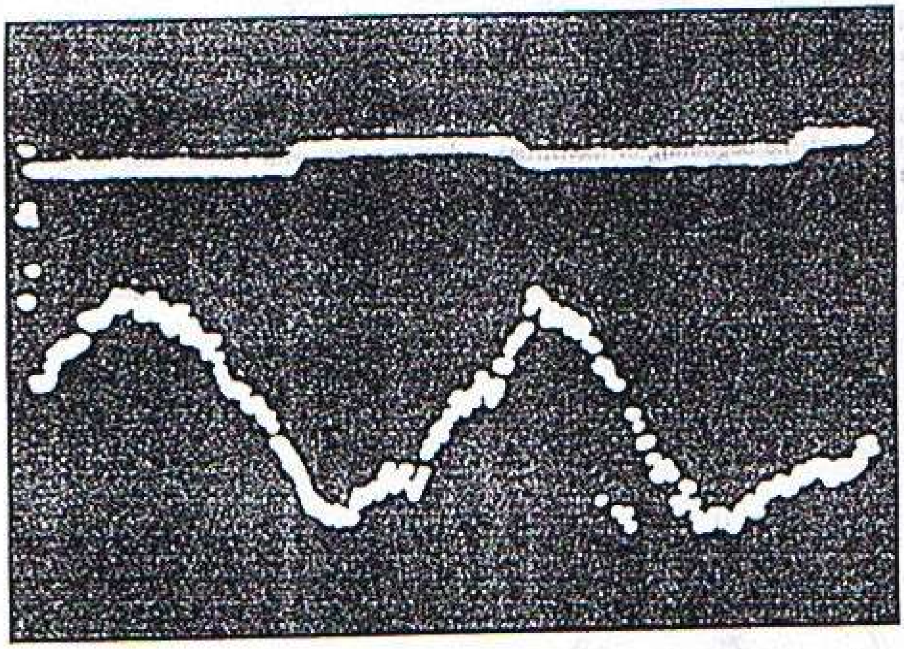
In experiments with cats Robert Galambos showed in 1959 that loud clicks stimulating both ears generate nerve impulses that meet in the superior olivary nucleus. When the clicks are simultaneous, the signals are reinforced at some site in the superior olivary nucleus. When a slight delay is introduced, however, the resulting signal is inhibited. Thus a small phase shift gives rise to a weaker perception of sound. It is presumably for this reason that one tends to turn toward the source of a sound and eliminate the phase difference. When one is listening through earphones, of course, turning the head has no effect on the phase of the signals.

Nerve potentials at the superior olivary nucleus of the cat have been measured directly. With human subjects it is possible to measure these signals by recording evoked potentials: small changes in the electrical properties of the scalp produced as a result of activity of the brain. Because they are objective indicators of certain brain functions evoked potentials have clinical applications. For example, in cases of possible hysterical blindness evoked potentials from the scalp above the occipital lobes can determine whether or not the brain is receiving visual information. Similarly, evoked potentials can be used to detect deafness in infants, which is otherwise quite difficult to diagnose. The potentials are very small (measured in microvolts) and are obscured by many random signals not associated with the stimulus. They can be measured on an oscilloscope, but special procedures must be followed.

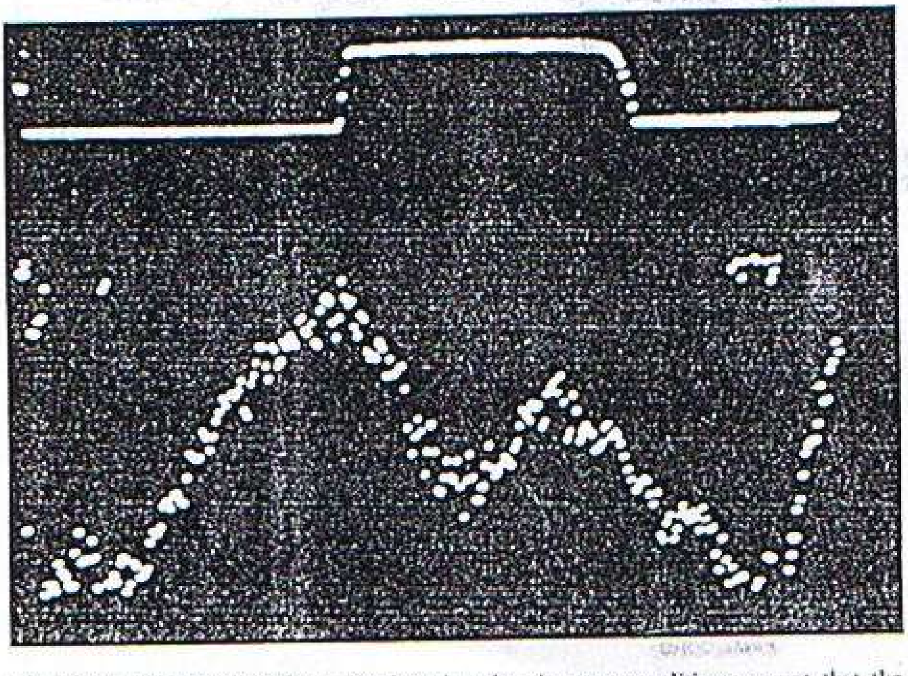
First, the horizontal sweep of the oscilloscope must be synchronized with the stimulus; this is done by using the stimulus current to trigger the start of



HIGH-FREQUENCY SOUND LOCALIZATION also requires binaural hearing, but differences in intensity rather than phase are detected. The wavelength of a high-pitched tone is smaller than the diameter of the head and a distinct sonic shadow is formed; thus one ear receives more sound than the other. This mode of sound localization is less accurate than phase detection except at very high frequencies. The transition takes place at about 1,000 hertz; at this frequency too the perception of binaural beats wanes.



EVOKED POTENTIALS for subjects listening to monaural beats are shown in a photograph of an oscilloscope screen made by the author with Adam Atkin and Neil Wotherspoon at the Mount Sinai School of Medicine. Tones of 300 hertz and 303 hertz were presented to each ear; an electrode attached to the scalp was used to measure electric potentials in the skin evoked by underlying electrical activity in the brain. By synchronizing the horizontal sweep of the oscilloscope with the beat frequency it was possible to correlate these small potentials (measured in microvolts) with the stimulus. The steplike wave form at the top of the screen is a signal used to time the oscilloscope sweep; the rise of each pulse corresponds to the moment of maximum loudness of the beat. The periodic wave below it records the evoked potentials. It consists of the average values for each point on the curve, determined by a small computer (a signal-averager) after many iterations of the procedure.



BINAURAL EXPERIMENT was conducted under the same conditions, except that the tones were presented separately to each ear. Evoked potentials were once again successfully recorded, but they differed from those detected under monaural conditions in amplitude, in wave form and in timing with respect to the stimulus. These differences suggest that binaural beats are processed in another way or at another site in the brain than monaural beats are. In the illustration the amplitude of the evoked potentials appears to be about the same as it is for monaural beats; it is actually much smaller. For clarity the vertical scale of the oscilloscope has been expanded, as can be seen by comparing the apparent amplitudes of the timing signals. In both illustrations bright areas not associated with the main wave form are extraneous signals produced by residual noise generated in the recording apparatus.

the sweep. In addition, a great many tracings must be made in order to obtain unambiguous data. A computer known as a signal-averager stores the tracings electronically, then it adds the instantaneous potentials of all the tracings to produce a composite signal. Because the extraneous random potentials have no fixed phase relation to the stimulus they are progressively suppressed as the number of tracings increases.

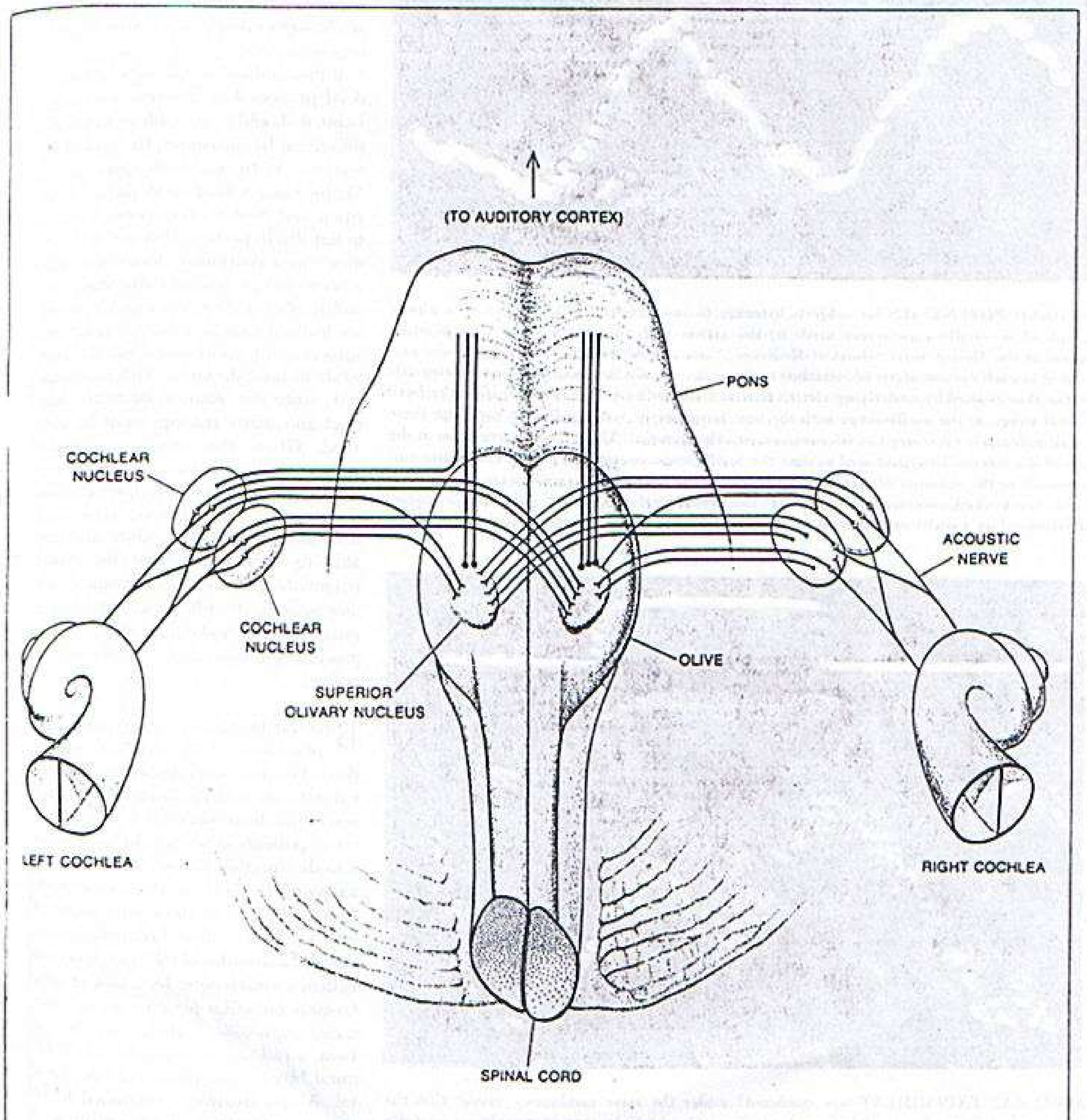
If binaural and monaural beats are indeed processed at different sites in the brain, it should be possible to detect the difference by measuring the evoked potentials. With my colleagues at the Mount Sinai School of Medicine, Adam Atkin and Neil Wotherspoon, I set out to test this hypothesis. Because the stimulus was a continuous tone rather than a brief click, it proved particularly difficult to obtain clear tracings. Eventually we learned that for effective results the subject must concentrate on the beats while in total darkness. This is a boring task, since the binaural beats are indistinct and many tracings must be averaged. Often the subject experiences auditory hallucinations imposing a spurious pattern on the sound, which spoils the results. Nevertheless, after many iterations of this procedure we were able to demonstrate that the evoked potentials produced by binaural and monaural beats differ qualitatively and quantitatively, indicating that they are processed differently [see illustration at left].

Binaural beats may have clinical applications. With some of my students I examined a number of neurological patients and discovered that a few could not hear binaural beats. Among these patients a few could not localize sounds (produced by the examiner's snapping his fingers). It may be significant that some of those who could not hear the beats suffered from Parkinson's disease, a disorder of the central nervous system characterized by a lack of spontaneous muscular activity, an immobile facial expression and tremor. One patient, a violinist, was unable to hear binaural beats when he entered the hospital. As his treatment continued he began to perceive the beats produced by the very lowest tones, and gradually he progressed to higher frequencies. At the end of a week, when his condition was considered satisfactory, he could hear beats produced by tones up to about 800 hertz.

A sex-related variation in the ability

to hear binaural beats has also been discovered. J. V. Tobias of the Federal Aviation Administration in Oklahoma City studied the binaural-beat spectrum of a number of volunteers and found that the upper limit of the applied frequencies is higher for men than for women [*see lower illustration on next page*]. He went on to monitor the perceptions of three women over a period of six weeks and found that the spectrum extended to the highest tones at the beginning of menstruation, then declined before reaching a second peak 15 days after the onset of menstruation. The latter peak may correspond to the time of ovulation, when a woman is most fertile.

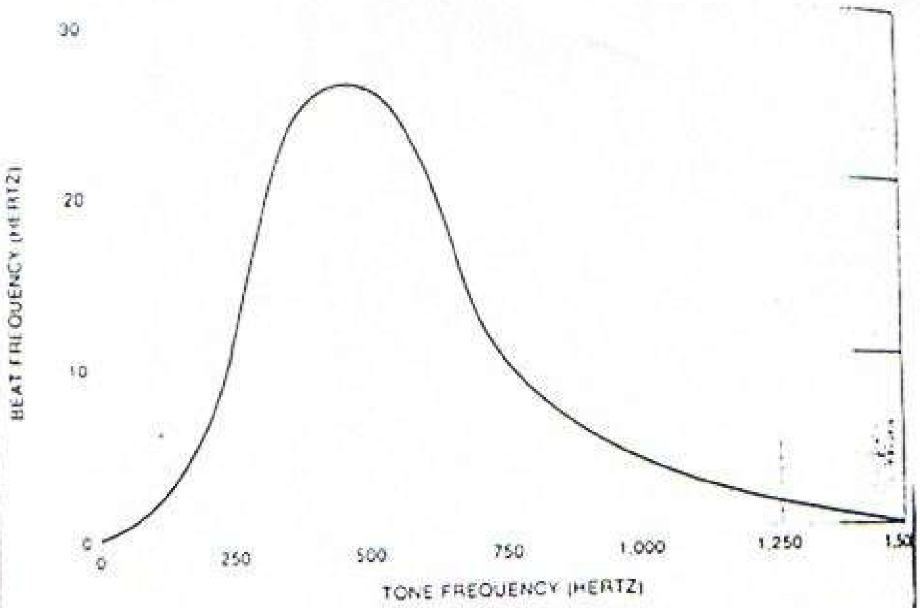
I have tested a few women of reproductive age, with results that tend to confirm Tobias' findings. It appears that some women do show marked variations



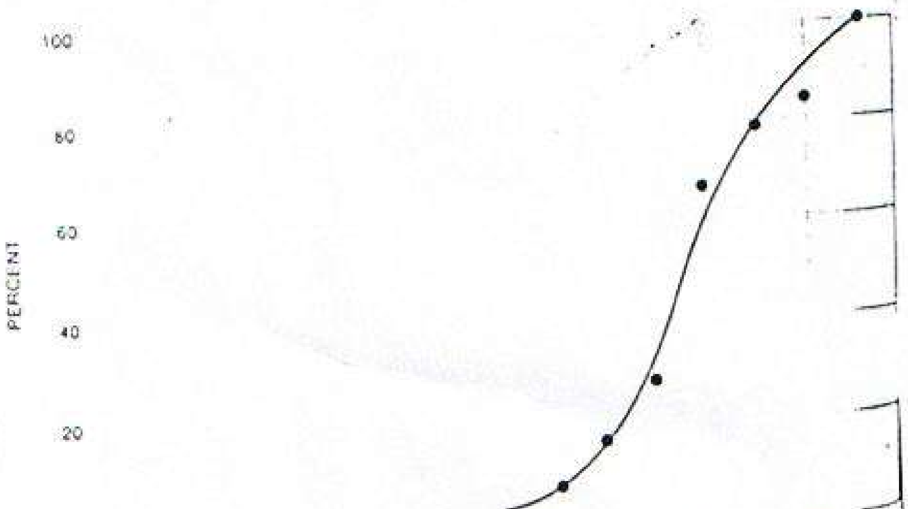
LOWER AUDITORY CENTERS of the brain are in the medulla oblongata, viewed here schematically from the back of the neck. Nerve impulses from the right (*color*) and left (*black*) ears first meet in the left or right superior olivary nucleus. These structures are part of the olive, an organ that in this view lies behind the brain stem. It is probable that binaural beats are detected here.

in the perception of binaural beats during the menstrual cycle. When the beats are not heard, women often hear two separate tones. Men, on the other hand, show no variation during the month. These results suggest that the binaural-beat spectrum may be influenced by the level of estrogen in the blood.

Binaural beats have been widely regarded as a mere curiosity. A recent textbook on hearing does not mention them at all. Yet the measurement of binaural beats can explain the processes by which sounds are located, a crucial aspect of perception. The enhancement of the beats by noise is a model of the mechanism by which auditory messages are sorted from a noisy background. That subthreshold sounds are effectively rendered audible by binaural beats suggests that there may be other stimuli processed by the brain of which we are not aware. Finally, it is possible that hormonally induced physiological or behavioral changes too subtle to detect by ordinary means may be made apparent by measuring the binaural-beat spectrum.



SPECTRUM OF BINAURAL BEATS was measured by J. C. R. Licklider, J. C. Webster and J. M. Hedlum. Rapid beats, up to about 26 per second, can be heard when the tones used to produce them are about 440 hertz. With tones of higher or lower pitch the maximum beat frequency declines. When the interval exceeds about 30 hertz, two tones are heard.



SEX-RELATED VARIATION in the perception of binaural beats is plotted from data compiled by J. V. Tobias. As the pitch of the tones used to produce beats increases, both men (color) and women (black) cease to perceive them. Women, however, lose the ability at lower frequencies. Some female subjects also report variations during the menstrual cycle.