rich in cholesterol ester, and large enough to permit a layered liquid crystal arrangement capable of a cooperative melting behavior.

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Binaural Beats at High Frequencies

Abstract. *Binaural beats have long been believed to be audible only at low frequencies, but an interaction reminiscent of a binaural beat can sometimes be heard when different two-tone complexes of high frequency are presented to the two ears. The primary requirement is that the frequency separation in the complex at one ear be slightly different from that in the other—that is, that there be a small interaural difference in the envelope periodicities. This finding is in accord with other recent demonstrations that the auditory system is not deaf to interaural time differences at high frequencies.*

For decades it has been known that the auditory system is provided with two binaural cues for localizing sound sources—interaural time differences and interaural intensity differences—and on the basis of certain physical and psychophysical facts it has been commonly asserted that the two cues are functional in different spectral regions. Interaural intensity differences have been thought to be of value only for high frequencies and interaural time differences only for low frequencies. In part, this belief (sometimes expressed as the duplex theory of sound localization) stemmed from psychophysical research using sinusoidal signals as the waveforms to be localized. For these simplest of waveforms, there is no argument—the auditory system is insensitive to interaural time differences above about 1200 to 1500 hertz (*1*)—but many psychoacousticians applied duplex theory to other listening situations as well, and this has recently been shown to have been an error. Recent research (*2, 3*) shows that more complex waveforms provide the system with a processable time cue in addition to the cycle-by-cycle time differences available with sinusoids. That is, a complex waveform that is time-delayed to one ear provides the auditory system with interaural time differences in the envelope of the waveform, and it is now clear that the auditory system can lateralize (*4*) just as accurately at high frequencies working on this cue as it can at low frequencies working on cycle-by-cycle time differences—only a few microseconds are required for excellent performance.

The realization that the auditory system is not deaf to interaural time differences at high frequencies led us to wonder if there might be any other time-based phenomena that were known not to occur with high-frequency tones, but that might be detectable using more complex waveforms. Among the first to come to mind was binaural beats. It has long been known that if one low-frequency tone is presented to one ear only and a second tone, slightly different in frequency, to the other ear only, a beat will be heard whose rate is equal to the difference in frequency between the tones. Since the two waveforms are not being mixed acoustically, this beat must be the result of an interaction somewhere in the auditory nervous system, and the system must have preserved the "fine structure" (the cycle-by-cycle periodicities) of the two waveforms for this interaction to have occurred. The fact that a binaural beat cannot be heard if the two tones exceed about 1000 hertz (*5*) implies that the auditory nervous system preserves cycle-by-cycle periodicities with diminishing accuracy beyond this point, and this view is reinforced by the fact that sound localization on the basis of cycle-by-cycle time differences also begins to deteriorate beyond this frequency region (*1*). But while all this is true for tonal stimuli, might not an interaction similar to binaural beats be possible for the complex high-frequency waveforms for which time-based lateralization is now recognized to be possible?

We found that it is possible to hear a binaural beat at high frequencies by using complex waveforms whose envelope periodicities are slightly different at the two ears. For example, if 3000 hertz is presented to both ears, 3100 hertz only to the left, and 3101 hertz only to the right, then the envelope periodicities in the two ears differ by 1 hertz, and a faint, one-per-second beat is detectable. To our knowledge, this binaural beat at high frequencies has not been previously reported.

We have done several things to convince ourselves that the effect does involve an interaction between the envelopes in the two ears. One of our first concerns was with combination tones or distortion products (*6*), for if low-frequency products were being generated by nonlinearity in the auditory periphery, it could well have been their interaction—that is, a "real" binaural beat—that was being detected. The first step to counter this possibility is to use frequency components of low amplitude. Most of our listening has been at 50 to 60 db SPL (sound-pressure level referred to 0.0002 μbar), but with a little practice most listeners are able to hear these binaural beats with even weaker components. It is noteworthy that even relatively intense components do not enhance the effect, that a colleague with severe hearing loss at high frequencies had difficulty hearing both the two-tone complexes and the binaural beat even at high intensities, and that an intense low-pass noise does not mask the beat. Thus, any contribution to the effect by combination or distortion products would appear to be negligible.

Perhaps the most remarkable aspect of this phenomenon is that the components in one ear do not have to be similar in frequency to those in the other to produce the beat. That is, 2000 and 2050 hertz in one ear will beat once per second against 3000 and 3051 hertz in the other. And the perception is essentially unchanged as the two frequency components in one ear are changed over a wide frequency range, as long as a constant difference in the envelope periodicities is maintained (*7*). This aspect of the effect gives us additional confidence that the binaural beat at high frequencies is not based on any simple interaction of combination or distortion products and that a cross-channel "leak" in the audio is not the basis. The most obvious and the most parsimonious explanation is that there is an interaction in the nervous system between the envelope extracted from one ear and that extracted from the other.

There are several ways in which this high-frequency binaural beat resembles the binaural beat heard with two low-frequency sinusoids. First, the maximum interaural difference that can produce beats is about 3 to 5 hertz for tones or envelope periodicities below about 200 hertz. Second, slowing the beat to about one per 2 seconds, or slower, produces an impression of movement of an intracranial image when there is spectral similarity in the waveforms at the two ears. Third, a masker is less effective when the envelope periodicities are slightly different interaurally than when they are the same. Listeners were first presented with identical two-tone complexes in the two ears and were asked to adjust the intensity of a wideband diotic noise until the complex was masked. Changing just one of the tones by 2 hertz produced a two-per-second binaural beat that was itself not masked until the noise was increased by about 3 to 5 db. Said differently, there is a masking-level difference between the no-beat and the beat conditions (*8*).

Table 1. Percentage of correct discriminations between beat and no-beat conditions in a two-interval, forced-choice task. The binaural beat rate was two per second throughout, and the observation intervals were 1.5 seconds each. The envelope periodicity (monaural frequency separation) was varied. One tone in each ear was always 3550 hertz; the other was either lower in frequency by the amount indicated in both ears (no-signal interval), or by the amount indicated in one ear and by 2 hertz more in the other ear (signal interval). These are median values from six 40-trial blocks. Fifty percent correct represents chance performance. The two tones were each 47 db SPL. In all conditions there was continuously present a masking noise low-passed at 1000 hertz and of overall level 70 db SPL. Initials denote subjects.

Frequency separation (hertz)	Correct discriminations (%)			
	A.W.	D.M.	C.M.	E.P.
25	100	94	96	99
75	93	85	80	100
125	78	92	84	97
175	62	74	64	95
225	55	63	68	84
275	52	65	60	79
325	62	66	51	82

The high-frequency binaural beat also differs in certain respects from that at low frequencies. For example, it is more faint; a naive listener is less likely to spontaneously report the beat at high frequencies without its being called to his attention than he is at low frequencies. Also, it is subject to "fatigue" in a way that binaural beats at low frequencies are not; after several minutes of continuous listening, uncertainty can arise about whether there is a beat, but this uncertainty can be erased or reduced by a brief rest (*9*).

Because of these facts, an oscilloscopic display of the stimuli is valuable to both naive and experienced listeners. The naive listener is more quickly alerted to the presence of the beat, and both he and the experienced listener are better able to recapture the beat after it is lost when there is available for consultation a visual stimulus from which to gain temporal information. For these purposes, the best display mode seems to be "A – B"—the difference between the complex waveforms at the two ears—but a Lissajous or a simple amplitude versus time display is also helpful for certain stimulus configurations.

There are at least two other ways in which binaural beats at high frequencies differ from those at low frequencies. The more important is that they are heard over a quite different range of frequencies (envelope periodicities). With weak, low-frequency tones, binaural beats cannot be heard below about 150 to 200 hertz and they are best heard around 500 hertz (*5*), but at high frequencies, envelope periodicities as slow as 10 hertz are capable of beating against a slightly different envelope periodicity in the opposite ear. This is strong additional evidence that the effect is not based on simple distortion products, for an audible difference tone of 10 to 50 hertz is difficult to imagine. At the other extreme, envelope periodicities greater than about 300 to 400 hertz are incapable of interacting binaurally with a slightly different envelope periodicity. This is presumably a reflection of the width of the critical band (*10*) in the frequency regions we have studied; once the monaural frequency separation is too great the two tones in each ear are apparently processed more or less separately, and inside the nervous system there are no "envelopes" to interact—just two high-frequency tones in each ear. Most observers agree that a further difference between binaural beats at high and low frequencies is that with a slow binaural beat at high frequencies, there is a cyclic change in pitch not obvious at low frequencies; the pitch perception is best described as changing from simple to complex.

The aspects of the phenomenon described to this point have been documented for dozens of listeners, both experienced and naive, in various formal and informal experiments and demonstrations held over a period of months. In these situations, the details differed, but basically the psychophysical technique was simply careful listening. The effect is so robust that to us this is adequate to demonstrate both the existence and the limits of the effect, but in addition, some "hard" psychophysical data were obtained using a two-interval forced-choice technique. The procedure was as follows: on each trial two observation intervals were indicated by lights; during one of them, the same two-tone complex was presented to both ears, and during the other, the complex at one ear differed by 2 hertz in periodicity from that in the opposite ear; the subject indicated on each trial which observation interval contained the latter pair of waveforms, and he received immediate feedback as to the correctness of his response. The duration of each observation interval was 1.5 seconds, and the rise-decay time was 25 msec. For each block of 40 trials, all stimulus parameters were the same for each trial; the only difference was which observation interval contained the waveforms capable of beating binaurally. Proportion correct was calculated for each block of trials, and the median of six blocks of trials was used to estimate performance for that condition.

Table 1 shows the outcome of an experiment in which the envelope periodicity was varied. There are individual differences in subjects' abilities to discriminate between the beat and no-beat conditions, but all subjects show diminishing discrimination as envelope periodicity (monaural frequency separation) increases. Relatively weak tones were used for this experiment, and while this choice produced generally less proficient discrimination than is possible at higher intensities, it is a more rigorous test of the effect.

Table 2 shows data taken for a single envelope periodicity in the presence of low-pass background noises of three different intensities. A separate noise generator was used for each ear, so the masker was uncorrelated binaurally. Reducing the noise level improved performance for only one of the four subjects, and the improvement was slight. Had the perception of beats been based on an interaction between difference tones in the two ears, performance would have improved markedly as the noise level was reduced (*11*).

For a time we considered the possibility that the effect is not based on interaural time differences, as are beats at low frequencies, but on a kind of dichotic loudness summation. That is, as the envelope maximums and minimums in the two ears slide in and out of temporal alignment, the beat may be due not to the resulting maximums and minimums in interaural time difference, but to the maximums and minimums in the opportunity for dichotic summation of loudness. We thought this interpretation might account for some of the differences between binaural beats at high and low frequencies, and the fact that dichotic loudness summation can occur across large differences in frequency (*12*) was in accord with the idea. However, we are now less inclined toward such an explanation, and the reason is based on the following demonstration: if 3000 and 3002 hertz, say, are *both* led to *both* ears perfectly in phase interaurally, the perception is of a two-per-second beat that is centered and stationary in the head. (This is not a binaural beat; it is a monaural beat presented diotically.) Now if *one* of the tones at one ear is inverted (a phase shift of 180°), the envelopes at the two ears are put out of phase, creating an interaural intensity difference that alternately favors first one ear and then the other. The perception now is of an auditory image that "jumps" back and forth between the ears at a rate of two per second. If the frequency difference (monaural beat rate) between the two tones is increased, the rate of alternation of this image increases, and it is easily heard as a rapid alternation at monaural beat rates of 10 to 15 hertz. Thus, the auditory system can "follow" an alternating intensity difference which is much more rapid than the fastest high-frequency binaural beats we have been able to observe (3 to 5 hertz), and this makes it unlikely that these beats are based on fluctuations in dichotic loudness summation.

Table 2. Percentage of correct discriminations between beat and no-beat conditions in a two-interval, forced-choice task. The binaural beat rate was two per second throughout, and the observation intervals were 1.5 seconds each. The intensity of a continuous masking noise low-passed at 1000 hertz was varied; the noise values shown are overall levels. The two tones were each 47 db SPL; they were 175 hertz apart, centered at 3460 hertz. The values are medians from six 40-trial blocks. Initials denote subjects.

Noise level (db SPL)	Correct discriminations (%)			
	A.W.	D.M.	C.M.	E.P.
70	62	74	64	95
55	86	73	68	97
40	82	78	70	94

Having discounted this alternative explanation of binaural beats at high frequencies, we are brought back to the idea that motivated our search for them in the first place: the auditory system is apparently able to extract envelope periodicities monaurally and compare their temporal relations binaurally, and this ability gives rise not only to time-based lateralization performance at high frequencies, but also to a binaural beat similar in many respects to that heard with low-frequency sinusoids.

Extraction of envelope periodicities is thought to be involved in certain pitch phenomena (*6*), and it is generally thought to be accomplished by neural autocorrelation networks (*13*). It has been suggested (*14*) that the autocorrelation mechanism follows binaural interaction in the processing sequence, but the present demonstration implies that it is possible for autocorrelation to precede binaural interaction. The fact that it is possible for a periodicity present at one basilar membrane region in one ear to beat against a slightly different periodicity present at a distant spectral region in the other ear seems to require that the two envelope periodicities be extracted before the binaural interaction occurs. Since binaural interaction occurs initially at the superior olivary complex, it may be that autocorrelation of the sort necessary for the phenomena described here is first performed in the immediately preceding center—the cochlear nucleus. A straightforward test of this possibility would be single-unit recording from animals stimulated with the appropriate waveforms. Also of interest, of course, is the response of cells in the olivary complex, and other sites of binaural interaction, when exposed to high-frequency waveforms that produce binaural beats.

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3. J. C. R. Licklider and J. C. Webster, *J. Acoust. Soc. Am.* **22**, 191 (1950).
4. The term lateralization is used to describe psychophysical data taken with headphones; localization is reserved for data taken with free-field stimulation.
5. J. C. R. Licklider, J. C. Webster, J. M. Hedlun, *J. Acoust. Soc. Am.* **22**, 468 (1950). But it should be noted that E. G. Wever [*Theory of Hearing* (Wiley, New York, 1949)] has reported hearing binaural beats with single frequency components as high as 3000 hertz.
6. See A. M. Small, in *Foundations of Modern Auditory Theory*, J. V. Tobias, Ed. (Academic Press, New York, 1970), vol. 1, p. 3; R. Plomp and G. F. Smoorenburg, Eds., *Frequency Analysis and Periodicity Detection in Hearing* (Sijthoff, Leiden, 1970).
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8. J. P. Egan [*J. Acoust. Soc. Am.* **37**, 1143 (1965)] was the first to demonstrate this effect for binaural beats at low frequencies. For a discussion of masking-level differences see D. M. Green and G. B. Henning, *Annu. Rev. Psychol.* **20**, 105 (1969).
9. Licklider and Webster (*3*) reported a similar fatigue effect with high-frequency waveforms.
10. B. Scharf, in *Foundations of Modern Auditory Theory*, J. V. Tobias, Ed. (Academic Press, New York, 1970), vol. 1, p. 159.
11. We present these forced-choice data primarily to dispel concern about the "reality" of the phenomenon. We do not believe that such psychophysical procedures are the best for studying the effect, for a number of reasons. First, even with our long observation intervals, no subject reported actually hearing a beat in the forced-choice procedure. The phenomenology is different for different subjects—some base their decisions on whether there is a fused intracranial image, some use a loudness criterion, some use pitch-associated differences, and so forth. Second, it is possible to establish stimulus configurations that appear to be natural extensions of some of those used here—configurations for which discrimination performance is excellent—and yet find that a binaural beat cannot be heard when the signal waveform is observed continuously. For example, this would occur with a 100-hertz periodicity in one ear and a 125-hertz periodicity in the other. The potential for a similar problem exists whenever changes along a single physical dimension produce not only changes in the magnitude of a psychological experience, but qualitatively different experiences in different regions of that physical dimension.
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