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A binaural beat constructed from a noise

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Abstract

The binaural beat has been used for over one hundred years as a stimulus for generating the percept of motion. Classically the beat consists of a pure tone at one ear (e.g. 500 Hz) and the same pure tone at the other ear but shifted upwards or downwards in frequency (e.g., 501 Hz). An experiment and binaural computational analysis are reported which demonstrate that a more powerful motion percept can be obtained by applying the concept of the frequency shift to a noise, via an upwards or downwards shift in the frequency of the Fourier components of its spectrum.

I. INTRODUCTION

The binaural beat is one of the oldest experimental stimuli in psychoacoustics (Rayleigh, 1907; Stewart, 1917; Licklider et al., 1950). A typical example consists of a 500-Hz pure tone presented to one ear and a 501-Hz pure tone to the other. The listener does not perceive the two tones separately: instead, a single tone is perceived whose lateralization appears to move across the head at a rate of 1 Hz, from centered, to one side, then from the other side back to the center, and so on. If the frequency difference between the two pure tones is increased then the percept of motion disappears, becoming instead one of fluctuations in loudness, then roughness, then of two separate tones at the ears (Licklider et al., 1950; Durlach and Colburn, 1978). Historically, the importance of the binaural beat lies in it being a simple demonstration that the temporal fine structure of the stimulus is encoded by the auditory system and is compared at some point (Licklider et al., 1950). In recent years the binaural beat has enjoyed a resurgence in studies of neurophysiology and neuroscience as a simple stimulus for generating auditory motion (e.g., Karino et al., 2006; Scott et al., 2009; Wallace and Palmer, 2009).

The above example of the binaural beat described it as a 500-Hz pure tone in one ear and a 501-Hz pure tone in the other ear. But it is equally valid to describe a binaural beat as a 500-Hz pure tone in both ears whose spectrum, at one ear, has been shifted upwards by 1 Hz. This immediately suggests that a binaural-beat-like stimulus could be constructed by presenting a band of noise to both ears but with the amplitudes and phases of each component of the noise all shifted up by 1 Hz in one ear. This method is equivalent to heterodyning the spectrum upwards in frequency, or to applying a linearly-varying interaural phase shift simultaneously to each frequency component of the stimulus. Informal listening to this stimulus — conveniently termed a “binaural-beat noise” — demonstrated that it gave a strong percept of motion, which moved around the head at a rate equal to the frequency shift and became more compelling as the bandwidth of the noise was increased. A short

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PACS 43.66.Pn Binaural hearing

43.66.Qp Localization of sound sources

43.66.Nm Phase effects

experiment is reported below that confirms these percepts, along with a computational analysis of the interaural time delays (ITDs) generated.

A binaural-beat noise can also be regarded as an extension of the “phasewarp” stimulus developed by Siveke et al. (2008), which was designed to create a strong, unambiguous percept of motion. The phasewarp stimulus consisted of a wideband noise, identical at the ears except that the phase components were shifted in frequency by a small amount. This partly inspired the present experiment, but it differs from the frequency-shifted noise by not incorporating a shift of the amplitude components. The frequency shift also bears some similarity with a technique developed by Saberi (2004), who noted that applying a Fourier transform to the left waveform to any sound using a different bin spacing to a Fourier transform applied to the right waveform would generate a linear transition in ITD of the sound.

II. METHOD

A one-interval design was used to elicit reports of the presence or absence of auditory motion of a large number of binaural-beat noises. On each trial, one stimulus was presented, and listeners tasked with choosing one of the 10 response options, grouped into three sets: *did not move* (“did not move: compact in center”; “did not move: broad-ish”; “did not move: diffuse across head”; “did not move: at/near left ear”; “did not move: at/near right ear”; “did not move: at/near both ears”), or *move* (“moved from left to right (once or lots)”; “moved from right to left (once or lots)”; “moved, but could not tell which way”), or *did something else*. The options were chosen to cover a wide range of possible choices as to how the motion (if it was there) of the stimuli could be perceived, so that listeners did not feel restricted in their responses. It was stressed to listeners that there was no “correct” response that they should be striving for: they should respond with what they thought they had perceived.

The stimuli were constructed digitally in the Fourier domain, using Matlab and with a sampling rate of 44.1 kHz. First, the real and imaginary components for each spectral frequency within the passband were given random values from a normal distribution; outside the passband, the values were zero. All the passbands were centered on 500 Hz, and the stimuli were 1000 ms in duration, with 25-ms raised-cosine gates applied at the onset and offset; thus the FFT frequencies were stepped at 1-Hz intervals. From the spectra the magnitude and phase components of the spectrum were calculated. This spectrum was kept *as is* for the left channel, but for the right channel each component in the passband was moved upwards (if the frequency shift was positive) or downwards (if the frequency shift was negative); these correspond to rightwards and leftwards motions. The spectra were then inverse Fourier transformed to give the stimuli waveforms. For example, if the frequency shift was 10 Hz, then the magnitude and phase for the left ear at 500 Hz were moved to 510 Hz for the right ear, the magnitude and phase for the left ear at 501 Hz were moved to 511 Hz for the right ear, and so on. Note that this method gives a binaural-beat noise whose IPD at the start is 0 degrees (although if a suitable phase shift is also applied to the shifted frequencies then any other starting IPD can be created). The stimuli were presented via a soundcard (RME DIGI-96/8 PAD), audio amplifier (Arcam A80), and headphones (Sennheiser HD-580). The digital waveforms of the stimuli were set to have the same RMS level, and then the overall level was calibrated such that the 400-Hz bandwidth binaural-beat noise was presented at 70 dB (A) SPL. The listener sat in a small audiological booth.

Each experimental block contained 80 single interval presentations, in a random order: a tonal binaural beat, and binaural-beat noises of 50 Hz, 100 Hz, 200 Hz, or 400 Hz crossed by frequency shifts of 1, 2, 4, 6, 8, 10, 15, 20, -1, -2, -4, -6, -8, -10, -15, or -20 Hz. After

instruction in the task, each listener completed two blocks as training and then 30 experimental blocks.

Five listeners (A-E) participated, from the staff of the Section. All were naïve to the purpose of the experiment and to the construction of the stimuli. Each individual's averages of their audiometric thresholds across 250, 500, 1000, and 2000 Hz were, at the left ear, 4, 4, 15, 3, and 19 dB, and for the right ear 8, 3, 6, 4, and 9 dB (listeners reported in order A to E).

III. RESULTS AND DISCUSSION

Figure 1 plots the number of “move” responses of any kind for each bandwidth — i.e., the sum of the three possible move responses — as a function of the frequency shift. Each listener is plotted individually (panels A-E), with their group mean in the final, bottom-right panel. The results are averaged across upwards and downwards frequency shifts. Four general patterns were consistent across all five listeners: (1) there were remarkably few reports of motion for tonal binaural beats (filled circles); (2) reports of motion were commonplace for the binaural-beat noises (open symbols); (3) the number of motion responses increased with increasing bandwidth (open circles = 50 Hz; hourglasses = 400 Hz), but (4) reduced with increasing frequency shift. The strength of the motion percept is well demonstrated by the number of motion responses for a frequency shift of 1 Hz: as a function of bandwidth from 50 Hz to 400 Hz, they were 58%, 86%, 86%, and 96%. The effect of increasing frequency shift is clear with a comparison to the corresponding values for a shift of 10 Hz: 22%, 27%, 27%, and 27%. A one-way repeated-measures ANOVA was conducted for each value of frequency shift to determine if the effect of bandwidth was statistically significant at $p < 0.05$. It was found to be so for frequency shifts of 1, 2, 4, and 6 Hz (F-ratios were, respectively, 70, 35, 18, 8.7; d.f. = 4, 16), but not for frequency shifts of 8, 10, 15, and 20 Hz (F-ratios of 5.4, 3.0, 1.8, 1.8; for these the results of the sphericity test required that the degrees-of-freedom be corrected to 1.2, 4.6). There are some individual differences — listener E was prone to make far more motion responses than the others, and only listeners D and E made any noteworthy reports of motion for the tonal binaural beats — but they do not affect the overall results: there was a clear percept of motion for binaural-beat noises with relatively small frequency shifts, and that the percept was far stronger for a binaural-beat noise than for a tonal binaural beat.

Figure 2 plots the number of *did not move* responses, categorized as “compact in center” (top-left panel), “broad-ish” (top-right panel), “diffuse across head” (bottom-left panel), and the sum of “at/near left ear”, “at/near right ear”, and “at/near both ears” (bottom-right panel) [as less than 1% of responses were to the miscellaneous category of *did something else*, they are not plotted]. The results are averaged across all listeners; the symbols are the same as in Fig. 1. It can be seen that the responses to the tonal binaural beat were clearly different to those to the binaural-beat noises: there were far more “compact-in-center” responses, substantially less “diffuse across head” responses, and substantially more “at ears” responses. Less than 1 in 5 of any of the stimuli gave “broad-ish” responses. Note that for the binaural-beat noises, the pattern of “diffuse across head” and “at ears” responses approximately mirrored the motion responses illustrated in Fig. 1 (bottom right panel): as one fell with increasing frequency shift, the other rose. There was a similar mirroring in the “compact-in-center” vs. “at ear” responses to the tonal binaural beat. In sum, these results suggest that the tonal binaural beat gave far more “did not move” responses than the binaural-beat noise, although it depended upon the frequency shift whether listeners reported it as being at the center of their heads or at the ears.

A tonal binaural beat generates a continuous transition in interaural phase difference (IPD), from 0° to $+90^\circ$ to $\pm 180^\circ$ to -90° to 0° , and so on. The change of side occurs at $\pm 180^\circ$. This

corresponds to a continuous transition in ITD at each frequency component of the stimulus. The same occurs for each frequency component of the binaural-beat noise, except that the ITDs are slightly different at each frequency because the ITD resulting from a given IPD is frequency dependent. To illustrate this, a binaural model was applied to one example of a 4-Hz binaural-beat noise that had a passband from 400 to 600 Hz. First, the stimulus was filtered using a gammatone filter centered at 400 Hz (Patterson et al., 1995). Next, the “instantaneous ITD” at time t was calculated by taking a 4-ms Hanning-windowed segment of the filtered left waveform centered at time t , taking a 4-ms Hanning-windowed segment of the filtered right waveform centered at time $t + \Delta t$, and then finding the value of Δt that minimized the mean square difference between the two segments (note that if the slight differences in power between the left and right segments are ignored then this is equivalent to maximizing the cross-correlation of the segments). This method finds the best time delay that aligns the two segments, to a resolution in Δt of 1 sample (22.05 μ s). The values of Δt were restricted to $\pm 1250 \mu$ s, being half the period of the lowest frequency in the passband; this value was chosen to avoid problems due to the overall periodicity of around 2 ms in the stimuli (remember that the center frequency of the stimuli was 500 Hz). The segment duration of 4 ms was chosen pragmatically as a compromise between something very short but still longer than the periodicity. The measurements were made at 8-ms intervals in t . The process was repeated with gammatone filters centered at 500 and 600 Hz. The results are shown in the left panel of Figure 3, with the results for the three channels represented as open circles (400 Hz), filled circles (500 Hz), and stars (600 Hz). The stimulus shows a sawtooth pattern: a linearly increasing ITD from zero until at $t = 125$ ms the ITD reverts to the other ear (i.e., where the IPD is $\pm 180^\circ$), and then the ITD increases again, and so on. The pattern repeats every 250 ms, matching the frequency shift of 4 Hz. The slight variation across symbol that can be observed is due to the frequency dependence of ITD on IPD. It would be expected from this plot that the stimulus would give a strong percept of motion.

The right-hand panel shows the corresponding plot for one example of a 4-Hz rate, 200-Hz bandwidth phasewarp noise (Siveke et al., 2008). The overall trend of the sawtooth pattern of a continuously-varying ITD is still discernable, but the variability and instability in ITD is far larger. This can also be noted in informal listening: the phasewarp stimulus gives a percept of motion, but against a background of a slight diffuseness that is not present with the binaural-beat noise.

The plot of instantaneous ITDs for the binaural-beat noise would suggest that the direction of motion would be reported reliably. This was occasionally found: for example, for a frequency shift of +1 Hz and a bandwidth of 400 Hz, three listeners (A, B, D) reported the correct direction 17, 38, and 34 times more than they reported the reverse direction in their 60 responses. But listener E only reported the correct direction 5 more times than the reverse direction, and listener C reported the reverse direction 54 more times than the correct direction. These biases were consistent across frequency shift for the 400-Hz bandwidth, but for frequency shifts of 2 Hz or more the biases towards the correct direction were much reduced (though listeners C and E had a bias to the reverse direction up to about 8-10 Hz). It is likely that these effects were due to the change of sides at $\pm 180^\circ$: it should be remembered that the listeners were given no formal instruction as to what they should be listening for or when in the stimulus to listen, as it was desired to obtain their own judgments as to what was happening. The author’s introspection is that as the frequency shift is reduced to around 1 Hz or less, the direction of instantaneous ITD becomes increasingly easy to follow.

In summary, this experiment has demonstrated the clarity of the percept of motion of a frequency-shifted binaural noise in comparison to a tonal binaural beat. It may therefore be of interest to those studying auditory motion or the binaural aspects of temporal fine structure.

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FIGURE 1.

Results from the experiment: the number of “motion” responses for each binaural-beat noise, as a function of frequency shift (abscissa) and bandwidth (parameter). Each individual’s responses are plotted separately, with their mean in the bottom-right panel. The symbols are for tonal binaural beats (filled circles) or for binaural-beat noises with bandwidths of 50 Hz (open circles), 100 Hz (open triangles), 200 Hz (open diamonds), and 400 Hz (open hourglasses).

FIGURE 2.

Further results from the experiment: the number of “did not move” responses as a function of frequency shift (abscissa) and bandwidth (parameter). The results are averaged across listener. The panels are for the four options of “did not move” response; the symbols are the same as in Fig. 1

FIGURE 3.

The instantaneous ITDs computed for one example each of a 200-Hz bandwidth binaural-beat noise (left panel) and a 200-Hz bandwidth “phasewarp” noise (right panel). Each have a frequency shift of 4 Hz. The three sets of symbols are for ITDs calculated in frequency channels centered on 400 Hz (open circles), 500 Hz (filled circles), and 600 Hz (stars).