# Can dichotic pitches form two streams?

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The phenomenon of auditory streaming reflects the perceptual organization of sounds over time. A series of "A" and "B" tones, presented in a repeating "ABA-ABA" sequence, may be perceived as one "galloping" stream or as two separate streams, depending on the presentation rate and the A-B frequency separation. The present experiment examined whether streaming occurs for sequences of "Huggins pitches," for which the percepts of pitch are derived from the binaural processing of a sharp transition in interaural phase in an otherwise diotic noise. Ten-second "ABA" sequences were presented to eight normal-hearing listeners for two types of stimuli: Huggins-pitch stimuli with interaural phase transitions centered on frequencies between 400 and 800 Hz, or partially-masked diotic tones-in-noise, acting as controls. Listeners indicated, throughout the sequence, the number of streams perceived. The results showed that, for both Huggins-pitch stimuli and tones-in-noise, two streams were often reported. In both cases, the amount of streaming built up over time, and depended on the frequency separation between the A and B tones. These results provide evidence that streaming can occur between stimuli whose pitch percept is derived binaurally. They are inconsistent with models of streaming based solely on differences in the monaural excitation pattern. © *2005 Acoustical Society of America.* [DOI: 10.1121/1.1945566]

## I. INTRODUCTION

If short bursts of two tones, A and B, separated by only a small frequency difference ($\Delta F$), are concatenated into an ABA-ABA-ABA-··· sequence, then a listener will hear one, "galloping" stream of tones, varying in pitch. In contrast, at wider frequency separations, the listener will hear two separate streams, each with its own, steady pitch, and the tendency to hear two streams increases with presentation rate. Furthermore, for a given $\Delta F$ and presentation rate, the percept will tend to "build-up" from a single stream near the beginning of the sequence to two streams at the end (Anstis and Saida, 1985; Carlyon *et al.*, 2001; Cusack *et al.*, 2004). This phenomenon reflects the process of "auditory streaming," and is important both for our ability to separate one speaker from a background of others and for following the melody of one instrument in an orchestra (van Noorden, 1975; Bregman, 1990).

According to an influential computational model (Beauvois and Meddis, 1991, 1996), the effect of frequency separation on streaming results from its effect on the overlap between the peripheral excitation patterns produced by the A and B tones. However, it appears that streaming based on pitch differences also occurs when produced by complex tones from which the lower (resolved) harmonics have been removed, and where the peripheral excitation patterns produced by the A and B tones do not differ systematically (Vliegen and Oxenham, 1999; Vliegen *et al.*, 1999; Grimault

*et al.*, 2000; for a review see Moore and Gockel, 2002). This suggests that streaming can take place at neural sites which do not receive, or at least do not require, a peripheral tonotopic representation.

In an effort to further constrain the sites at which pitch-based streaming may occur, we investigated streaming produced by "dichotic pitches." Cramer and Huggins (1958) discovered that pitch sensations could be created by the binaural interaction of noise stimuli. A typical stimulus is a white noise, diotic apart from a transition in interaural phase across a narrow band of frequencies around 500 Hz. The waveforms at the two ears differ *only* in the phases of these frequencies. When played monaurally, either of the left and right waveforms sound like white noise, but when played together, a percept of a faint 500-Hz tone is also heard, lateralized to one side or the other (e.g., Raatgever and Bilsen, 1986; Akeroyd and Summerfield, 2000; Zhang and Hartmann, 2004). In many ways this "Huggins pitch" behaves as an ordinary tone, for example, the "octave enlargement" effect occurs for both (Hartmann, 1993), and Huggins pitches are strong enough to form melodies and be easily heard by untrained listeners (Akeroyd *et al.*, 2001). Because a Huggins pitch can *only* be heard when both waveforms are played, its percept must be derived from auditory processing at the brainstem or higher. Modern theories of the creation of the perception of dichotic pitch all postulate an internal spectrum in which there is a peak at the frequency of the center of the transition in interaural phase, although there is as yet no consensus as to quite how the spectrum is generated (e.g., Raatgever and Bilsen, 1986; Culling *et al.*, 1998; Hartmann and Zhang, 2003).

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The primary motivation of the present study was to ascertain if stream segregation occurred with ABA-ABA-ABA-⋯ sequences of dichotic pitches. A secondary aspect of the design tested if two of the factors that influence the streaming of pure tones—namely, $\Delta F$ and the build-up over time—also affected the streaming of dichotic pitches. If stream segregation can indeed operate on pitch information that has been derived from binaural interactions, then listeners should report one stream at the beginning of the sequence, but, over the course of about 10 s, would report two. They should also report two streams more often for larger than for smaller $\Delta F$s.

## II. METHODS

### A. Stimuli

Four conditions were tested. The stimuli were 10-s sequences of either Huggins-pitch stimuli or tone-in-noise control stimuli (see below), with an A frequency of 400 or 800 Hz. For the 400-Hz A tones, the B frequencies were, in different subconditions, either 4, 6, or 8 semitones higher, whereas for the 800-Hz A tones the B frequencies were 4, 6, or 8 semitones lower. Each Huggins-pitch stimulus in a sequence was constructed in the frequency domain, as described by Akeroyd *et al.* (2001). Two matched spectral buffers, representing the left and right channels of a diotic Gaussian noise sampled at 22050 Hz, were created and then rectangular filtered (0–4000 Hz passband) in the spectral domain. The interaural phase shift was implemented by modifying the phases of the frequency components in the spectral buffer representing one channel: a linear shift of 0 to $2\pi$ radians was added to the phases for frequency components from 10% below to 10% above the frequency of the note. Subsequently the signal waveforms for the left and right channels were created by applying an inverse discrete Fourier transform to the two spectral buffers, giving waveforms of 125-ms duration. They were then concatenated into a 10-s sequence of "ABA" triplets, each separated by 125 ms of diotic noise. Each sequence was bandpass filtered between 100 and 2000 Hz, in order to remove the transients from the concatenation of each 125-ms segment, and finally given a smoothed onset and offset of 30-ms duration. The spectrum level of the noise used in this and in the following control condition was 40 dB SPL.

In order to compare the results obtained with Huggins-pitch stimuli to those occurring when monaural excitation-pattern cues are available, we included control conditions with sequences of pure tones. To produce a pitch percept that was similar to the Huggins-pitch sequences, the tones were presented diotically against a continuous background noise (i.e., NoSo), lowpass filtered at 2000 Hz. The NoSo configuration was chosen so that any streaming could only have been attributable to *monaural* processing; although other configurations (e.g., NoS$\pi$) would have created localizations similar to those of the Huggins-pitch stimuli, these would have been strongly influenced by binaural processes. The following procedure was adopted in an attempt to match, roughly, the strength of the pure tones in these diotic (NoSo) stimuli to those of the Huggins-pitch stimuli. First, we computed the mean interaural correlation at the output of a gammatone filter placed at the center frequency of the Huggins-pitch transition band; for example, at 400 Hz it was approximately 0.02. Second, we found the level of a 125-ms duration NoS$\pi$ tone which gave the same amount of interaural decorrelation; at 400 Hz and for a noise spectrum level of 40 dB, it was found to be 57 dB. Third, from the data of Blodgett *et al.* (1958), we estimated the detection threshold for such an NoS$\pi$ tone to be 47 dB.[1] Accordingly, we estimated the sensation level of the Huggins pitches to be $57-47=10$ dB. Finally, we noted from Blodgett *et al.*'s data that the threshold of a 125-ms NoSo tone was about 63 dB, and so we set the level of the pure tones in the NoSo control stimuli to be $63+10=73$ dB.

### B. Procedure

In the main part of the experiment we presented 10-s sequences of ABA stimuli, and asked our listeners to report throughout how many streams they heard. They did so by clicking with a mouse on one of two virtual buttons on a computer screen, marked "one stream" and "two streams." They were told to press one of these buttons whenever their percept changed, and their responses therefore map out what each listener perceived at each point during each sequence. For statistical convenience, we quantized the responses into nonoverlapping, 1-s bins. The first two bins were excluded from the analysis because subjects did not always make their first response within the first 2 s of each sequence (Carlyon *et al.*, 2001; Cusack *et al.*, 2004).

Prior to the main test, subjects were first played eight simple Huggins-pitch melodies, to confirm that they could indeed perceive a dichotic pitch (Akeroyd *et al.*, 2001). All eight listeners reported hearing the appropriate melodies, with six listeners hearing the melodies to the left of the center of the head, and two to the right. Next, they were shown a diagram illustrating the two possible perceptual organizations, told that these could change during a sequence, and performed some training runs with demonstration versions of the pure-tone sequences. The demonstration versions used $\Delta F$s of 3 and 12 semitones, to illustrate percepts of one and two streams, respectively. Their frequencies were increased by a factor of 2.25 relative to those used in the main experiment, and there was no background noise. Listeners were encouraged to concentrate on the rhythm instead of the overall pitch of the stimuli. Third, they practiced making streaming judgements for about 10 min on the experimental stimuli. They were told that the pitches of these stimuli would be lower in frequency and fainter than in the demonstration stimuli, and so they should continue making their judgments on the rhythm. The main test followed, in which each experimental sequence was presented 20 times per listener. The listeners were not instructed to try to keep the stimuli into one "galloping" stream nor to try to separate them into two streams; instead, they were encouraged to listen naturally and to report what they perceived (Carlyon *et al.*, 2001).
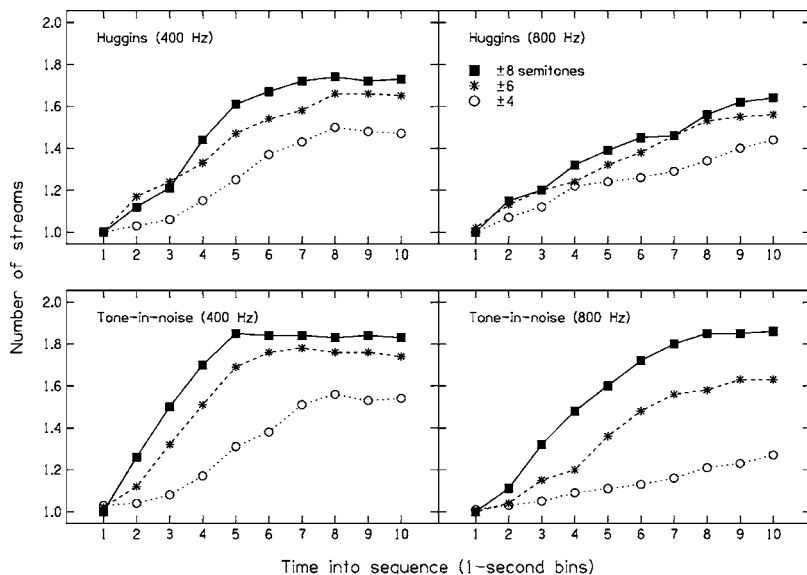
FIG. 1. Mean number of streams perceived by the listeners as a function of time into each 10-s sequence of stimuli. The top panels are for the Huggins-pitch stimuli, and the bottom panels are for the tone-in-noise control stimuli. The left panels are for an A frequency of 400 Hz, and the right panels are for an A frequency of 800 Hz. The parameter is the frequency separation ($\Delta F$) between the A and B tones; 4 semitones (circles), 6 semitones (asterisks), and 8 semitones (squares). The results were quantized into 1-s bins and then averaged across the eight listeners.

## C. Listeners

Eight normal-hearing listeners participated. Four of them completed all the Huggins-pitch conditions before starting any of the tones-in-noise conditions, while the other four did the tones-in-noise conditions first.

## III. RESULTS

The results are plotted in Fig. 1. Each panel shows the number of streams reported, averaged across the listeners, for $\Delta F = \pm 4$, $\pm 6$, or $\pm 8$ semitones (shown by circles, asterisks, and squares, respectively). The upper panels show the results for the Huggins-pitch stimuli, and the lower panels show the results for the tone-in-noise control stimuli; the left panels are for the A=400 Hz stimuli, and the right panels are for the A=800 Hz stimuli.

The primary result is that listeners did indeed report stream segregation for the Huggins-pitch stimuli. Furthermore, the build-up and $\Delta F$ effects occurred for Huggins-pitch stimuli almost as much as for the tone-in-noise control stimuli; the number of reported streams increased towards the end of the sequence, and they were more likely to report two streams in the higher $\Delta F$ sequences than in the lower $\Delta F$ sequences.

To assess the significance of these effects, we conducted a three-way within-subjects ANOVA, contrasting the effect of frequency of the A tone, $\Delta F$, and time-in-sequence upon the number of reported streams.[2] For the Huggins-pitch stimuli, there was a significant effect of time-in-sequence $[F(7,49)=13.9,p<0.001]$ and $\Delta F$ $[F(2,14)=6.5,p=0.01]$, but not of A frequency $[F(1,7)=0.8,p>0.1]$. The A-frequency by time-in-sequence interaction was found to be marginally significant $[F(7,49)=2.7,p=0.07]$. The other interactions were found to be insignificant. A separate ANOVA was conducted for the tones-in-noise stimuli. It showed that the three factors all gave significant effects: time-in-sequence $[F(7,49)=30.6,p<0.001]$, $\Delta F$ $[F(2,14)=59.0,p<0.001]$, and A-frequency $[F(1,7)=21.8,p=0.002]$. Two of the three two-way interactions were, at least, marginally significant: time-in-sequence by $\Delta F$ $[F(14,98)=2.5,p=0.03]$, and $\Delta F$

by A-frequency $[F(2,14)=3.5,p=0.07]$, but time-in-sequence by A frequency was not significant $[F(7,49)=2.1,p=0.1]$. Finally, the three-way interaction was also significant: time-in-sequence by $\Delta F$ by A-frequency $[F(14,98)=10.7,p<0.001]$. The interaction between $\Delta F$ and time-in-sequence occurred because listeners always reported one stream at the beginning of each sequence, but the number of "two stream" judgements at the end was lower for small $\Delta F$s. The interaction between $\Delta F$ and A-frequency occurred because, although fewer two-stream responses were made for the 800-Hz than for the 400-Hz A tones at most $\Delta F$s, this difference was smaller at the largest $\Delta F$ due to ceiling effects. This was especially true later in the stream, so accounting for the 3-way interaction between $\Delta F$, A-frequency, and time-in-sequence.

We conducted a multiple-regression analysis to rank the importance of the various factors in determining the data. The quantitative factors of "time-in-sequence" and $\Delta F$ were coded as $1,2,3,\dots10$ s, and 4, 6, or 8 semitones, respectively, whilst the binary factors of A-frequency and stimulus type were coded as 1=400 Hz, 2=800 Hz, or 1=tones-in-noise, 2=Huggins-pitch stimulus. The analysis was applied to the mean data plotted in Fig. 1. It showed that the most-important factor was time-in-sequence $(r^2=0.58)$, followed, at some remove, by $\Delta F$ $(r^2=0.19)$. The factors of the A-frequency $(r^2=0.05)$ and type-of-stimulus $(r^2=0.02)$ were the least important predictors of the data.

The small effect of type-of-stimulus is shown in the figure by the curves for different $\Delta F$s being lower for the Huggins-pitch stimuli than for the tone-in-noise stimuli. This was confirmed by a four-way ANOVA with factors of stimulus type, A-tone frequency, $\Delta F$, and time-in-sequence, which revealed a main effect of stimulus type $[F(1,7)=6.2,p=0.04]$. There was also a significant interaction between stimulus type and $\Delta F$ $[F(2,14)=7.8,p=0.005]$; this is reflected in Fig. 1 by the fact that the separation between the curves for different $\Delta F$s differ for the Huggins than for the tone-in-noise stimuli. The reason for the smaller effect of $\Delta F$ for the Huggins-pitch stimuli is not certain. It may be a result of the "sluggish" response of the binaural system in response

to dynamic changes (e.g., Grantham and Wightman, 1978; Culling and Summerfield, 1998, Akeroyd and Summerfield, 1999), which could impair the ability to follow the frequency changes between successive Huggins pitches (although we note that not all monaural analyses of pitch are fast: some, such as the pitch of unresolved harmonics, are sluggish; e.g., White and Plack, 2003). A second possibility is that the internal representation of dichotic pitches may be less accurate in frequency than for typical, monaural pitches. Henning and Wartini (1990) have shown that the frequency difference limen is larger for a tone presented dichotically in a noise (NoS$\pi$) than diotically (NoSo) at an equal sensation level, and Hartmann's (1993) direct measurements of the accuracy of pitch matching of a Huggins-pitch stimulus found an average value of 0.5%, whilst the value for a diotic pure-tone stimulus in silence is approximately 0.1% (Kohlrausch and Houtsma, 1992). This conjecture is consistent with Grimault *et al.*'s (2000) study of the effect of harmonic resolvability on the stream segregation of complex tones. They observed fewer "two-stream" responses when the harmonics were highly unresolvable than when they were highly resolvable (see also Vliegen *et al.*, 1999). As other data (e.g., Houtsma and Smurzynski, 1990; Carlyon and Shackleton, 1994) shows that the detectability of changes in fundamental frequency is considerably worse for a set of unresolved harmonics than for a set of resolved harmonics; it may well be the case that a larger $\Delta F$ is needed to induce streaming for stimuli with a relatively indistinct, imprecise, representation of pitch or pitch strength.

A final analysis was performed to test for a potential alternative explanation for the build-up observed in our mean data for the Huggins-pitch stimuli. As all listeners received initial practice with high-frequency tones in quiet before the experiment started, it is possible that they learned to expect a switch from one stream to two as the sequences progressed. This may have caused them to adopt a similar strategy when listening to the Huggins-pitch stimuli. Furthermore, four of our listeners were tested with the Huggins-pitch sequences only *after* being tested on the tones-in-noise sequences. We reasoned that if the build-up observed with the Huggins-pitch stimuli were due to subjects having learnt "what to expect" from the diotic stimuli, it should be greater in those subjects tested with the Huggins-pitch stimuli last, compared to those tested with Huggins-pitch stimuli first. We therefore conducted another ANOVA, with the order in which subjects were tested entered as a between-subjects factor. This factor was not significant [$F(1,6)=0.8, p>0.1$], and did not interact with A-frequency, $\Delta F$, or time-in-sequence [respectively, $F(1,6)=1.0, p>0.1$; $F(2,12)=0.0, p>0.1$; $F(7,42)=0.4, p>0.1$]. We conclude that the data were not compromised by a learning effect.[3]

## IV. DISCUSSION

Overall, the results demonstrate that Huggins-pitch stimuli can form two streams, like partially-masked tones-in-noise do. A build-up of streaming was observed in the Huggins-pitch condition; listeners were often reporting two streams at the end of the ABA-ABA-$\cdots$ sequences. The A-B

frequency difference $\Delta F$ had a similar, albeit slightly smaller, effect to that which it has for pure tones; the larger the frequency difference between the A and B tones, the more two-stream reports were made. Thus, pitch information derived from binaural processing is sufficient for streaming to occur.

The results are inconsistent with the predictions of the model of Beauvois and Meddis (1991, 1996), according to which streaming arises solely from monaural peripheral processes, and they add to others that show that binaurally-derived lateralization information—from ear-of-presentation or interaural-time-differences—can help in the segregation of pure-tone melodies (Hartmann and Johnson, 1991). Our results are consistent with Moore and Gockel's (2002) hypothesis that streaming can stem from a variety of cues, including both spectral and purely temporal differences, and that the amount of streaming depends on the strength of the perceptual differences between stimuli. A complete account of streaming would have to include what those loci are, how the operations interact, and, given recent evidence for a strong effect of attention on streaming (Carlyon *et al.*, 2001; Carlyon *et al.*, 2003; Cusack *et al.*, 2004), how they are modified by attentional input. The results described here make a small contribution towards this endeavor by demonstrating that streaming based on pitch differences can occur solely as the result of binaural interactions.

[1]Although Blodgett *et al.*'s (1958) data were obtained for a signal frequency of 500 Hz, we assumed that they would not have differed substantially for the 400- or 800-Hz frequencies of our A tones.

[2]For this and the following statistical analyses, we applied the Huyhn-Feldt sphericity correction to account for the fact that the response in any bin will be unlikely to be independent of the response in the preceding bin. The effect of the Huyhn-Feldt correction is to reduce the effective degrees of freedom in the $F$-ratio test and to increase the $p$ value for any given $F$; we report the corrected $p$ values and the uncorrected degrees of freedom.

[3]Furthermore, it is worth noting that the amount of build-up was not significantly smaller for the Huggins-pitch stimuli than for the tones-in-noise stimuli, as one might expect if the former were simply a side-effect of the latter. The earlier four-way ANOVA showed that the interaction between stimulus type and time-in-sequence was not significant [$F(7,49)=0.66, p>0.5$].

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