

# Dichotic Pitch: A new stimulus distinguishes normal and dyslexic auditory function

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**Running head:** Dichotic pitch detection in dyslexia

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**Abstract:** Two patterns of appropriately filtered acoustic white noise can be binaurally fused by the human auditory system to extract pitch and location information that is not available to either ear alone. This phenomenon is called dichotic pitch. Here we present a new method for generating more effective and useful dichotic pitch stimuli. These novel stimuli allow the psychophysical assessment of dichotic pitch detection thresholds. We show that dichotic pitch detection is significantly impaired in individuals with developmental dyslexia, as compared to average readers. These results suggest a low-level auditory deficit associated with dyslexia and also demonstrate the potential value of our new dichotic pitch stimuli for assessment of auditory processing.

**Keywords:** developmental dyslexia, dichotic pitch, binaural masking level difference, interaural time difference, sound localization, auditory perception

Our two eyes get slightly different views of the world. These two different vantage points allow the brain to compute the depth relations between objects based on *retinal disparity*-- the difference in image location in one eye's retina relative to the other. The striking perception of a form floating in depth can be produced by presenting a pattern of random dots to the right eye and a slightly different pattern of random dots to the left eye.<sup>1</sup> This ability to fuse the two patterns to extract form and depth information that is not available to either eye alone is called stereopsis.

The ability to fuse two patterns and extract information that is not available in either alone is not unique to the visual system. Like our eyes, our two ears receive slightly different versions of the soundscape and our brain can exploit this interaural difference to localize and segregate sound sources. Sounds originating on the left reach the left ear first and are louder in the left ear than the right. In addition, as the sound source continues to produce sound waves, each crest of these waves will arrive at the left ear before the right ear. If these sound waves include frequencies whose wavelength is greater than the distance between the ears (i.e., below about 1400 Hz), then the brain can utilize the interaural time difference between crests. This ongoing *interaural time difference* (ITD) can be exploited to create dichotic pitch. This is possible because the brain uses the ongoing ITD to segregate sounds produced by different sources as well as to help localize sounds in 3-dimensional space.

Dichotic pitch is a perception of pitch created by the brain from two noise sequences, neither of which alone contain any cues to pitch. This perceived pitch may be localized to a different spatial location than the background noise, which is heard along with the pitch. Creation of a dichotic pitch stimulus begins with two copies of the same white noise. If played through headphones, the brain will detect that the fine time structure of the noise in each ear is the same and it will fuse the two noises into one perceived sound source. To the listener, this will sound like a "ball of noise" in the middle of the head. If the phases of a narrow band of frequencies, say 490 to 510 Hertz, are shifted in the noise signal going to one ear, that interaural phase-shifted frequency band will perceptually segregate from the ball of noise, and a faint but distinct pitch will be heard along with the noise<sup>2, 3</sup>. For this example, the pitch will sound something like the pitch heard when a 500 Hz tone is played, because it is a narrow band of noise centered on 500 Hz that is segregated from the background noise. A slight variant on this technique, that produces similar pitch sensations, involves an interaural phase-shift of all the frequency components in the noise *except* those in a narrow frequency band. Another variant involves "sparse noise" composed of only a dozen or so frequency components, one of which is phase shifted<sup>4</sup>.

We have created a new technique involving complementary filters and time shifts to produce a more effective and useful dichotic pitch stimulus. For a pure tone, a given phase shift is equivalent to a particular time shift. But, for a sound containing a range of frequencies, a constant phase shift will produce a slightly different time shift for each frequency component. A constant interaural phase shift smears the frequency band in time, which has the effect of smearing the spatial localization of the sound source. Our time-shift technique produces a very robust dichotic pitch percept, and these stimuli are more similar to real localized sound sources than phase-shift based dichotic pitch stimuli because frequency components of real localized complex sounds have constant time shifts rather than constant phase shifts. Further, our technique produces stimuli which are much easier to manipulate. These stimuli can be used to generate compelling perceptual demonstrations of the sophisticated processing in the auditory system. They also open up new avenues of inquiry into both the normal and abnormal function of the human auditory system.

Developmental dyslexia is a specific developmental disorder in reading despite normal intellectual function, sensory acuity, motivation, and educational opportunity. Dyslexia affects 2 to

8 percent of the population<sup>5</sup>. It has long been known that individuals with dyslexia often have difficulty with phonological processing tasks, such as rhyming.<sup>6, 7</sup> A large number of recent studies have shown that many individuals with developmental dyslexia also show deficits on visual tasks that selectively activate the magnocellular system.<sup>8-14</sup> (The magnocellular system is one of several anatomically and functionally distinct visual processing streams; see<sup>15</sup> for a review). Several groups have reported low-level auditory deficits in psychophysical tasks such as detection of frequency modulation<sup>16, 17</sup>, the binaural masking level difference<sup>18</sup>, frequency discrimination, and the perception of illusory auditory motion based on small interaural time differences<sup>19</sup>. An electrophysiological study measuring the frequency following response (which results from the synchronous discharge of phase-locked neurons in the brainstem) also suggests a low level auditory deficit in dyslexia<sup>18</sup>. One recent study has found a strong correlation between visual deficits (motion detection) and low-level auditory deficits (frequency modulation detection), suggesting a common underlying mechanism<sup>17</sup>.

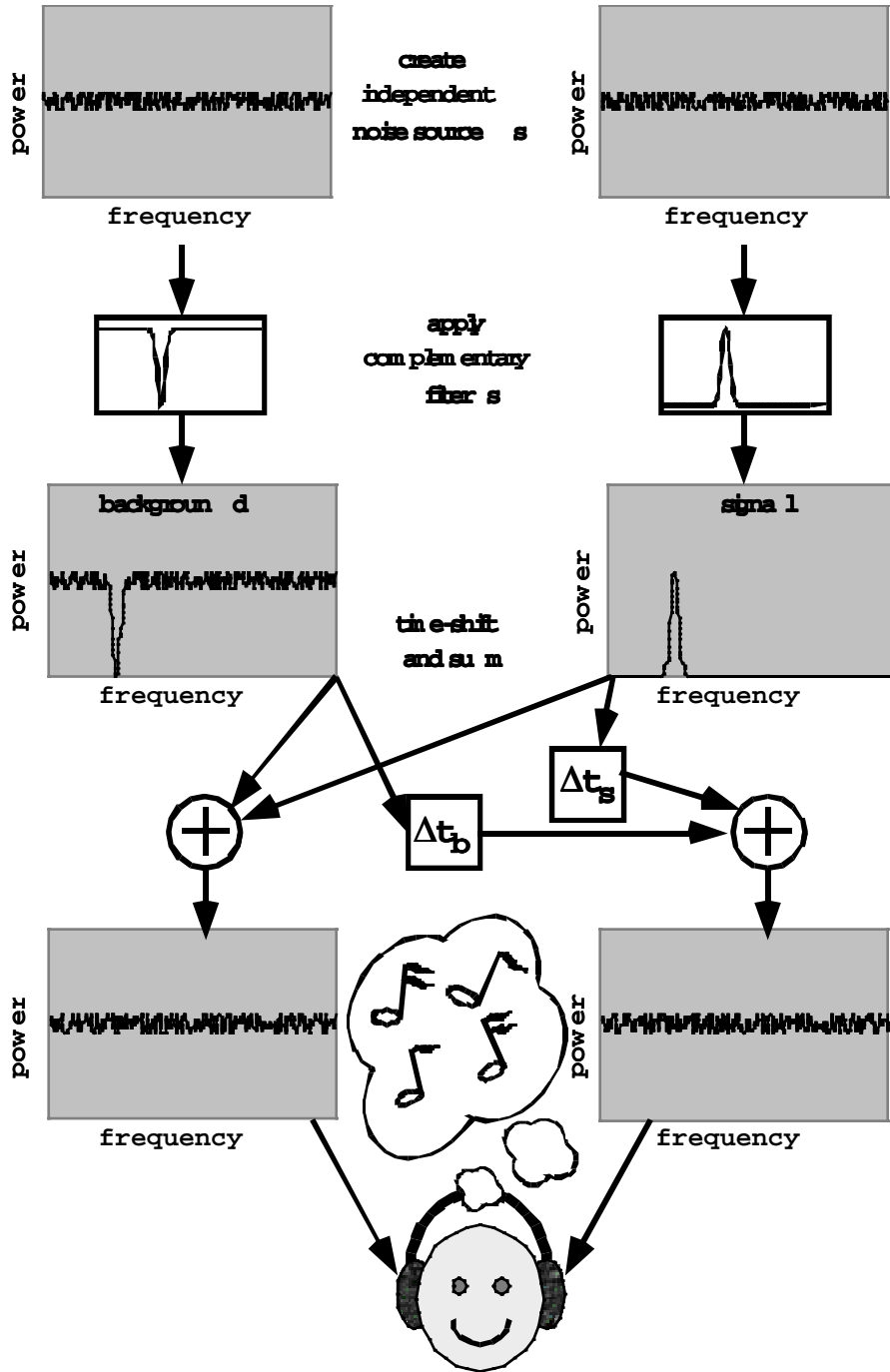
We expected individuals with dyslexia to show deficits in dichotic pitch detection because all the low-level auditory deficits in dyslexia cited above involve precise timing relationships between stimuli and detection of dichotic pitch requires very precise interaural timing. Perhaps most relevant to the present study, individuals with dyslexia have been found to have a smaller binaural masking level difference<sup>18</sup>. In its most common form, the binaural masking level difference is a measure of the increased detectability of a signal in noise when the signal's interaural phase configuration differs from that of the noise (see<sup>20</sup> for a review). It is closely related to dichotic pitch and may tap into the same auditory processing mechanisms, but we propose that our dichotic pitch stimulus is an even more sensitive measure of the auditory system's ability to extract signals from background noise with binaural timing cues.

## Methods and Materials

### *Stimuli*

Figure 1 illustrates our stimulus generation technique. The *signal-to-background ratio* (SBR) is easily adjusted from 0 (no signal present) to 1 (full dichotic pitch signal) by changing the height of the signal filter, with a corresponding change in the depth of the complementary background filter. In fact, the SBR can be set greater than 1 to produce cues to pitch that are monaurally detectable (i.e., peaks in the amplitude spectra). The adjustable SBR of this stimulus is very useful for assessing individual listener's sensitivities to dichotic pitch. The monaurally audible SBR levels are necessary because some listeners may be completely insensitive to true dichotic pitch (just as some individuals lack stereopsis). With our stimulus, however, such listeners may still have a measurable pitch detection threshold. Their threshold SBR will simply be above the true dichotic pitch cut-off of one.

**Figure 1. Dichotic pitch stimulus generation schematic.** Creation of our dichotic pitch stimulus begins with two independent noise sources: one will become the signal (the perceived dichotic pitch) and the other the background noise. The complementary filters may be modified to adjust the signal-to-background ratio (SBR). For any SBR equal to or less than one (the dichotic pitch region), the power spectra for both binaural channels are flat, providing no monaural cues to pitch. However, if the SBR is greater than one (not shown), these power spectra will have peaks at the signal frequency, providing monaural cues to pitch.



The two white noise sources at the top of figure 1 were filtered with Gaussian filters parameterized by the peak frequency ( $p$ ) and the spread ( $s$ ; typically set to 5-10 % of the peak frequency). The signal filter,  $S(f)$ , and the background filter,  $B(f)$ , (both functions of frequency,  $f$ ) are given by:

$$S(f) = \text{SBR} \cdot \exp\left[-\left(\frac{f-p}{s}\right)^2\right] \quad B(f) = 1 - S(f) \text{ for } S(f) < 1, \quad B(f) = 0 \text{ otherwise.}$$

For all stimuli, the background had an ITD of 0 ms, so it was perceived to be in the center of the head while the signal was perceived to be either to the right (pitch identification task) or randomly to the left or right of center (melody localization task). The signal melody in the melody localization task consisted of four sequential 200 ms harmonic complexes (330 & 660 Hz; 220, 440, 660 & 880 Hz; 330 & 660 Hz; 440 & 880 Hz). Half-height bandwidth of the Gaussian signal frequency bands was 5% of center frequency. All stimuli were digitally low-pass filtered with a 1200 Hz cut-off before delivery and were ramped on and off with a 50 ms half-Gaussian. Stimuli were delivered through Sennheiser HD-265 headphones via the built-in 16-bit, 44.1 KHz, stereo sound output of an Apple PowerMac 8500. Sound pressure level was 80 dB.

### *Subjects*

All procedures involving human observers were approved by the University of British Columbia's Clinical Screening Committee for Research Involving Human Subjects and all subjects provided informed consent.

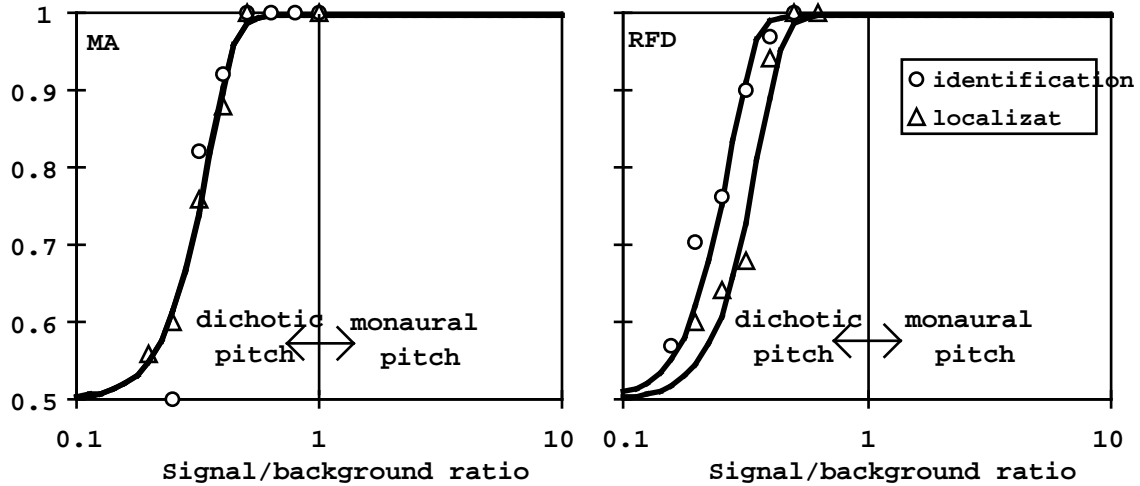
For the results presented in figure 2, the subjects were 2 adult males (aged 22 and 29 years) with normal audiometric assessments. One of the subjects was the first author, the other was naive as to the goals of the study.

For the results presented in figure 3, children were assigned to the control or dyslexic group based on psychometric testing. The dyslexic group consisted of children with reading skills at least 1.5 standard deviations below the age norms for the reading tests used, while the control group consisted of children with reading skills within 0.75 standard deviations of the norm. All the children had at least average intelligence and a normal neurologic exam (e.g., no attention-deficit/hyperactivity disorder).

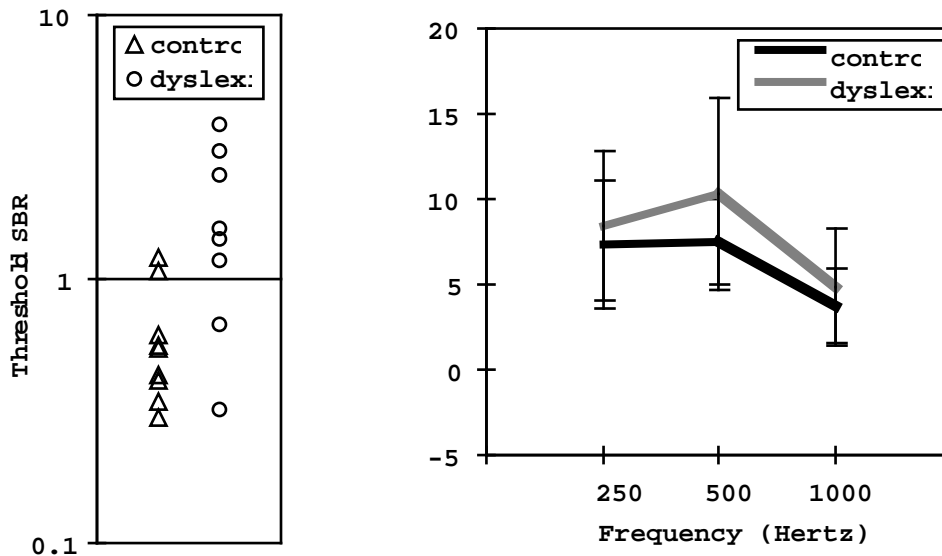
### *Procedures*

For the melody localization task, subjects pressed one of two response buttons to indicate on which side they perceived the melody. The pitch identification task required subjects to indicate whether the pitch was rising or falling. In sessions involving children, animated visual feedback was provided, as was reinforcement in the form of an incremental score. For both tasks, the SBR was adjusted by a simple adaptive staircase with log steps and thresholds were estimated by fitting a psychometric function to the data. Subjects were practiced and the staircase began with high SBRs so that the pitches were initially clearly monaurally audible for all subjects.

Monaural tone detection thresholds were measured for each ear by a standard yes/no audiometric technique using a Beltone model 119 calibrated audiometer (dB SPL reference = 20  $\mu$ Pa).



**Figure 2. Dichotic pitch psychometric functions for two listeners.** Dichotic pitch detection was measured by two-alternative, forced choice with feedback. Pitch identification involved discrimination of a 400-500-600 Hz “rising pitch” sequence from a 600-500-400 Hz “falling pitch” sequence. Melody localization involved localizing a melodic signal that was time-shifted to lead either the left ear or the right ear by 0.6 ms. For both tasks, SBR values equal to or less than one indicate stimuli which produce dichotic pitch. Curves shown are maximum likelihood fits of a Weibull function <sup>21</sup> with slope four.



**Figure 3. Dichotic pitch (left) and monaural tone detection (right) thresholds for 10 to 12 year olds with and without dyslexia.** The dichotic pitch task reveals that 6 out of the 8 dyslexic subjects do not hear dichotic pitch, while only 2 of the 8 controls had SBR thresholds above one. Monaural tone detection shows no significant difference between the two groups. (Error bars indicate the 95% confidence intervals.) Also, there was no correlation between monaural tone detection and dichotic pitch detection. Regression analysis indicated that monaural pure tone detection explained less than 1% of the dichotic pitch threshold variance, and this value was not significantly different than zero. (There were no significant differences between ears; the data shown were collapsed across ears.)

## Results

Figure 2 shows dichotic pitch psychometric functions for two listeners and two different tasks. These results demonstrate that the SBR is a well-behaved psychophysical parameter that provides meaningful threshold estimates.

Figure 3 demonstrates that the SBR proves useful in uncovering subtle low-level auditory deficits in developmental dyslexia. The data show that the dichotic pitch thresholds for the dyslexic subjects are, as a group, substantially higher than those of the control subjects (control mean = 0.61, dyslexic mean = 1.82;  $t=3.1$ , 1-tailed  $p<0.01$ ,  $df = 14$ ). In fact, six of the eight dyslexic subjects had SBR thresholds greater than one, indicating that they were unable to extract the pitch in the absence of monaural cues. The fact that two of the eight dyslexic subjects appear normal on this task is in line with other work which suggests that not all dyslexic subjects show perceptual processing deficits.<sup>22</sup> The right side of figure 3 shows that the deficit in detection of dichotic pitch in the dyslexic subjects was not due to differences in sensory hearing thresholds over the frequency range employed.

## Discussion

The existence of dichotic pitch demonstrates the auditory system's ability to extract frequency information from differing phase spectra at the two ears. This means that, at least for the low frequencies over which ITDs and dichotic pitch work, the auditory system is sensitive to the temporal microstructure of the noise. Humans can use systematic interaural differences in this microstructure to localize sound sources and extract hidden cues to pitch. This remarkable ability requires neurons with exquisite timing properties- on the order of tens of microseconds. Neurons that do such precise interaural timing have been found in the superior olivary complex of cat<sup>23</sup> and dog<sup>24</sup>. The superior olivary complex is a mammalian brainstem structure which is the first in the auditory processing pathway to receive major inputs from both ears. Neurons in the medial superior olive are tuned to different interaural time differences for different frequency bands. Thus, as a whole, these neurons may form a map of frequency and ITD and seem to compute a frequency-dependent interaural cross-correlation.<sup>23</sup> The frequency-specific ITDs deciphered by the brainstem may be used by higher auditory processing stages to segregate sound sources that arise from different spatial locations. Such a system is useful for both localizing sound sources and extracting signals from noisy contexts.<sup>20</sup>

The data of Figure 3 show that this ability to use binaural cues to extract sound streams from noisy backgrounds is substantially deficient in many dyslexic subjects. It should be noted that even with high SBRs and monaurally audible pitches, simple ITD detection is required to do the melody localization task, as the melody location is defined solely by an ITD. Since none of the dyslexic subjects had trouble with the task at high SBRs, this suggests that simple ITD detection is not compromised in dyslexia. (This agrees with a recent finding that dyslexic subjects are no different from controls at detecting simple interaural phase modulations.<sup>25</sup>) It was only at lower SBRs, where the melody was camouflaged within the noise, that the dyslexic subjects had trouble. This suggests that their ITD detection mechanism was less capable of extracting signals from noisy contexts. These results, together with those showing deficits in binaural unmasking in dyslexia,<sup>18</sup> are consistent with a deficit in binaural facilitation of signal-from-noise extraction. This deficit may play a causal role in the phonemic processing deficits apparent in dyslexia by hindering the

extraction of some speech sounds from noisy contexts during critical periods of language acquisition. However, more research is needed to fully assess the role of these binaural processing deficits in learning to read.

### Conclusion

With the new techniques described here, dichotic pitch should become a more useful research tool for probing the auditory system's extraction of signals from noise and its computation of sound source location. We have shown these stimuli to be useful for demonstrating low-level auditory deficits associated with developmental dyslexia. In addition, the flexibility of our approach to dichotic pitch allows very compelling perceptual demonstrations to be produced. For example, chords and harmonic complexes can be presented as dichotic pitches, and these can be strung together to create melodies. Further, both the pitches and the background noise can be independently laterally positioned in perceived auditory space by choosing the appropriate ITDs. The tones and background noise can even be made to move from one side of the head to the other by changing the ITDs over time. We have used this effect to create melodies which dance about in virtual auditory space. (See our website at <http://www.interchg.ubc.ca/bobd/audDemos.html> for examples of these sounds.) And, like the random dot stereogram, all of these percepts require binaural fusion of the two channels. Either channel alone sounds just like so much noise.

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