# Detection and identification of monaural and binaural pitch contours in dyslexic listeners

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Binaural pitch stimuli were used in several recent studies to test for the presence of binaural auditory impairment in reading-disabled subjects. The outcome of three of these studies [Dougherty *et al*., NeuroReport, **9**, 3001–3005 (1998); Edwards *et al*., Dev. Neuropsychol. **25**, 321-354 (2004); Chait *et al*., Brain Lang. **102**, 80-90 (2007)] has been contradictory: Where the former two found that a majority of dyslexic subjects were unable to hear binaural pitch, the latter obtained a clear response of dyslexic listeners to Huggins' pitch (HP) [Cramer and Huggins, J. Acoust. Soc. Am. **30**, 413–417 (1958)]. The present study clarified whether impaired binaural pitch perception is found in dyslexia. Results from a pitch contour identification test, performed in 31 dyslexic listeners and 31 matched controls, clearly showed that dyslexics perceived HP as well as the controls. Both groups also showed comparable results with a similar-sounding, monaurally-detectable, pitch-evoking stimulus. However, nine of the dyslexic subjects had difficulty identifying pitch contours, independent of the stimulus used. The ability of subjects to correctly identify pitch contours was found to be significantly correlated to measures of frequency discrimination. This correlation may be attributed to the similarity of the experimental tasks and probably reflects impaired cognitive mechanisms related to auditory memory or auditory attention rather than impaired low-level auditory processing *per se*.

## INTRODUCTION

Developmental dyslexia is a specific learning impairment affecting the ability to fluently read, spell, and decode words, despite adequate educational opportunities and otherwise normal intellectual abilities. The basis for this disorder, which is estimated to affect between 5% and 10% of school-aged children (Shaywitz *et al*., 1990), remains uncertain (see e.g. Rosen (2003) for a review). Although their influence on reading abilities is controversial, a wide range of auditory processing disorders have been found in part of the dyslexic population (e.g. Wright *et al*., 2000; Amitay *et al*., 2002). Specifically, it has been suggested that low-level binaural processing might be impaired in some dyslexic listeners: McAnally and Stein (1996) obtained significantly lower binaural masking level differences (BMLDs) in their group of dyslexic listeners

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than in the control group, suggesting a difficulty of dyslexic listeners in exploiting interaural phase differences to obtain a binaural advantage. However, two other studies (Hill *et al.*, 1999; Amitay *et al.*, 2002) found no significant group difference between BMLDs of dyslexics and controls.

Binaural pitch stimuli have been used in a few studies to investigate low-level binaural processing in dyslexic listeners. Dougherty *et al.* (1998) compared the identification and lateralization of rising and falling pitch contours in subjects from a dyslexic and a control group. They found that 6 out of 8 dyslexic subjects failed at these tasks if no monaural cues were available. Their results suggested that the binaural integration of fine temporal information might be impaired in dyslexia, thus inducing an inability to perceive binaural pitch. Edwards *et al.* (2004) asked a group of reading-disabled children to lateralize binaural pitch stimuli, and found that 52% of dyslexics (vs. 12% of controls) failed at lateralizing the pitch in the absence of monaural cues. In contrast, Chait *et al.* (2007) did not find evidence for an impairment of binaural pitch perception in dyslexic listeners. In a pitch onset detection task, they compared the detectability of Huggins' pitch (HP) to that of sinusoidal targets in diotic noise (TN) in a dyslexic and a control group of listeners. Despite the fact that HP targets were generally missed more often than the monaurally-detectable TN targets, and that dyslexics had a significantly higher number of misses than controls, their results clearly showed that HP was generally perceivable by dyslexic listeners, with only few misses (6.3%) on average. Another finding was the longer response times of dyslexics vs. controls when detecting a pitch onset with both HP and TN stimuli, suggesting the need for a longer processing time in dyslexic subjects than in the control group, rather than impairment in pitch detectability *per se*. This means that the inability of some listeners to hear binaural pitch found by Dougherty *et al.* (1998) and Edwards *et al.* (2004) might have been due to the short duration of the stimuli used (200 ms), or to the complexity of pitch contour identification and lateralization tasks, compared to a simple detection task.

After these somewhat contradictory findings, the question remains whether all reading-disabled listeners are able to hear binaural pitch, provided the duration of the stimuli is long enough and the task simple enough. The present study aimed at clarifying this point, by investigating the ability of a larger group of dyslexic listeners to detect *and* identify binaurally- and monaurally-detectable pitch contours, using two different stimulus durations. By comparing the subjects' *detection* scores to their pitch contour *identification* scores, it was aimed here at verifying or falsifying the presence of low-level binaural auditory processing impairment (i.e. up to the brainstem level) in dyslexia.

## METHODS

### Procedure

A pitch contour identification test was performed with two stimulus types eliciting a pitch sensation in noise: a binaural pitch (BP) stimulus, and a similarly-sounding stimulus containing a monaurally-detectable pitch (MP) (Fig. 1). While BP requires binaural presentation and cannot be perceived when listening with only one ear, in which case only noise is heard, MP can be detected monaurally. In each trial, sequences of three musical notes were presented, such that they formed either rising, falling, or constant pitch contours (Table 1). Note frequencies were chosen to be between 500 and 800 Hz, i.e. within the range of strongest salience of Huggins' pitch (Santurette and Dau, 2007). Two different note durations (300 ms and 900 ms) were used, in order to measure whether performance in pitch detection and contour identification improved with stimulus duration. After each presentation, subjects gave their response by pressing one of four response buttons on a computer screen: an upward-pointing arrow (rising pitch), a downward-pointing arrow (falling pitch), a horizontal arrow (constant pitch), or a cross (no pitch). Subjects were instructed to press the cross when no melody was heard, and to press the arrow corresponding to the perceived pitch contour when a melody was heard. Subjects were presented 15 trials for each combination of stimulus type (MP or BP) and note duration. In addition, 20 trials containing no pitch contour (diotic white noise only) were presented. Trials were presented in a random order.

Before the test, each subject was first introduced to the different pitch contours played with pure-tone stimuli. A short 12-trial practice run was also performed with pure tones.

| Note | Frequency (Hz) |
|---|---|
| $C_5$ | 523.25 |
| $E_5$ | 659.26 |
| $G_5$ | 783.99 |

| Contour | Note sequence |
|---|---|
| Rising | $C_5$-$E_5$-$G_5$ |
| Falling | $G_5$-$E_5$-$C_5$ |
| Constant | $E_5$-$E_5$-$E_5$ |

| Notes | Interval |
|---|---|
| $C_5$-$E_5$ | 136 Hz (23%) |
| $E_5$-$G_5$ | 125 Hz (17%) |

**Table 1**: Note frequencies, pitch contours, and frequency intervals between successive notes in the pitch contour identification experiment.

### Subjects

Two groups of 31 dyslexic subjects (ages: 18-29 years, mean: 21.5) and 31 matched controls (ages: 19-32 years, mean: 21.4) with normal hearing thresholds participated in the experiment. Subjects were matched according to gender, age, and educational level. Dyslexics performed significantly worse than controls in all measures of reading and spelling accuracy, reading fluency, phonemic awareness, and verbal working memory, despite scores similar to controls in measures of intellectual functioning. All controls had word reading (WR), non-word reading (NWR), and average WR and NWR scores above the 50th percentile, while all dyslexics had WR, NWR, and average WR and NWR scores below the 25th percentile. The just noticeable difference (JND) in frequency at 490 Hz was also available for the same two groups of subjects.

## Stimuli

Stimulus waveforms were generated in MATLAB with a 48,000-Hz sampling rate and 16-bit resolution. The BP stimulus was a Huggins' pitch, and contained a frequency-dependent interaural-phase-difference pattern, such that the left and right noises were in phase at all frequencies, except for a narrow frequency range around the boundary frequency $f_b$. In the transition area around $f_b$, a phase difference varying linearly from 0 to 2π was introduced in the frequency interval [0.92 $f_b$;1.08 $f_b$] (see Fig. 1a). The MP stimulus was generated in the same way as the BP stimulus, except that no interaural phase difference was introduced, i.e. diotic broadband noise (BBN) was created. An additional diotic narrow band of noise (NBN) was then added to the BBN in the frequency interval [0.96 $f_b$;1.04$f_b$] (see Fig. 1b). In order to obtain a similar salience for the MP and BP stimuli, the overall level of the NBN was adjusted using a linear relationship with the overall level of the BBN, following results from a preliminary salience adjustment experiment. For both stimulus types, each note was generated by adjusting $f_b$ to the desired note frequency. Notes were then concatenated to form the different pitch contours, and each contour was preceded and followed by 500 ms of diotic white noise. In order to avoid discontinuities in the waveform between successive notes, 1-ms onset and offset cosine ramps were used at the beginning and end of each portion of the stimulus. The overall stimulus was gated with 100-ms onset and offset cosine ramps.

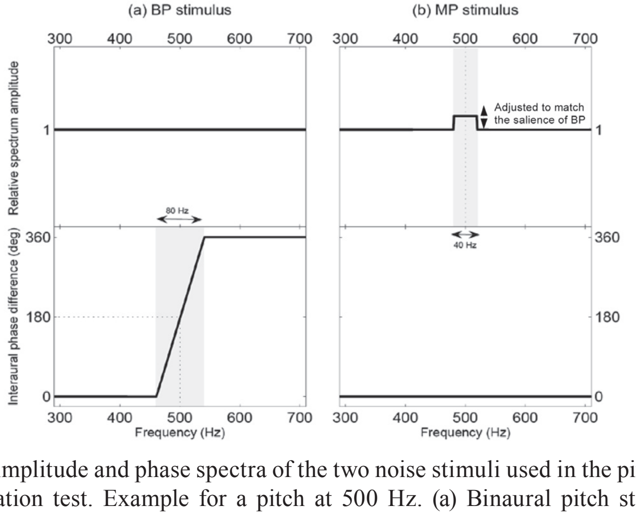


**Fig. 1**: Amplitude and phase spectra of the two noise stimuli used in the pitch contour identification test. Example for a pitch at 500 Hz. (a) Binaural pitch stimulus. (b) monaurally-detectable pitch stimulus.

Stimuli were presented in a sound-attenuating booth at an overall level of 70 dB SPL via Sennheiser HDA200 headphones, through the APEX 3 psychophysical platform (Francart *et al.*, 2008). Subjects were not informed about the existence of different stimulus types.

## RESULTS

Figure 2 shows the ability of control (light grey bars) and dyslexic (dark grey bars) subjects to *detect* the presence of pitch contours for each of the different stimulus configurations. It can be seen that subjects from both groups could clearly hear both MP and BP, independently of stimulus duration. In particular, the lowest overall score obtained among dyslexics with BP was 93%, showing that all dyslexic listeners without exception could hear binaural pitch. Differences between the two groups were overall not significant. No effect of stimulus duration was found on the ability of the listeners to *detect* the pitch contours. The average false-alarm rate was found to be rather low in both groups (dyslexics: 8.5%, controls: 6.8%), thus ruling out the possibility that the high detection scores obtained here were due to strong false-alarm bias or a misunderstanding of the task.

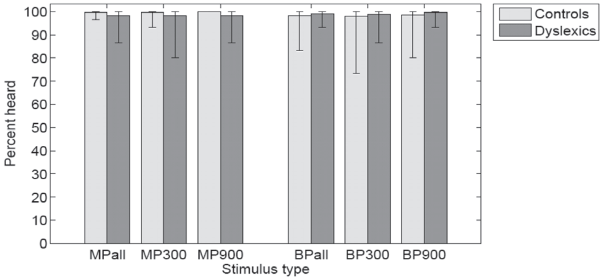


**Fig. 2**: Percentage of trials containing a pitch contour in which a pitch was detected. Error-bars indicate the lowest and highest scores among all subjects from a group.

If one now considers the ability of subjects to *correctly identify* the pitch contours (Fig. 3), it appears that dyslexics are generally worse at the task than controls, in all stimulus configurations. This difference is only borderline significant when the whole group of dyslexic subjects is considered ($p$=0.0402 [Wilcoxon]). However, error-bars in Fig. 3 indicate that the variability among subjects is higher in dyslexics than controls.

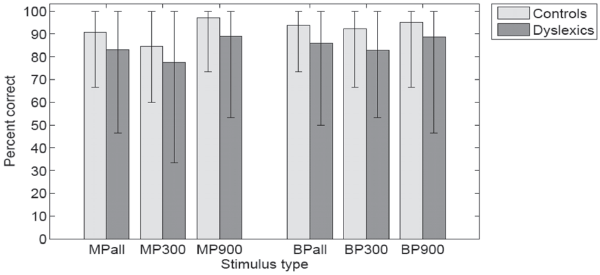
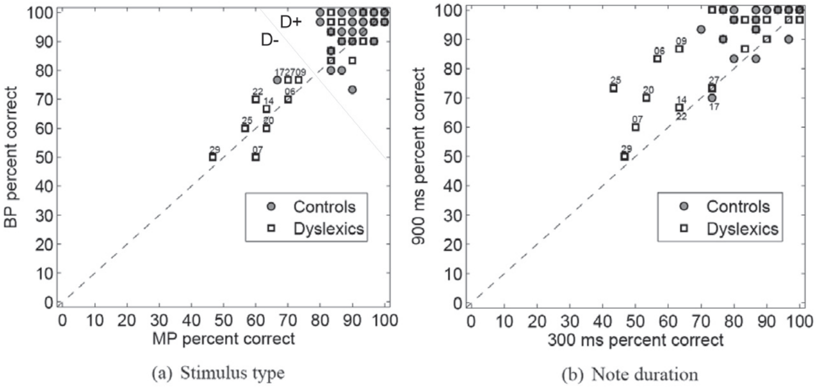


**Fig. 3**: Percentage of trials containing a pitch contour in which the pitch contour was correctly identified. Error-bars indicate the lowest and highest scores among all subjects from a group.

Figure 4 shows individual identification scores of MP and BP pitch contours against each other. It can be seen that most dyslexic subjects actually performed similarly to controls (group D+), while 9 dyslexics (group D-) and 1 control identified less than 80% of pitch contours correctly with both MP and BP (points with number-labels in Fig. 4), thus indicating difficulty with the task. The fact that all data points lie around the diagonal line in Fig. 4a reflects that the stimulus type (MP or BP) did not have an influence on the task. In fact, overall scores were on average higher with BP than MP. Moreover, 7 of the 10 labelled subjects in Fig. 4 also obtained less than 80% correct identification in the practice run with pure-tone stimuli, suggesting that their difficulty stems from the nature of the task rather than the type of stimulus used. When comparing overall identification scores obtained with short and long note durations (Fig. 4b), it appears that almost all subjects benefited from a longer note duration (points above the diagonal line). Average scores for MP and BP stimuli were found to be significantly higher with 900-ms notes than 300-ms notes in both groups of listeners (dyslexics: $p$<0.0001, controls: $p$=0.0001 [Wilcoxon]). The analysis of recorded reaction times revealed no significant difference between dyslexics and controls.

Performance in pitch contour identification was significantly correlated to frequency discrimination at 490 Hz in the dyslexic group. Scatter plots of overall pitch contour identification scores vs. the measured frequency JNDs are given in Fig. 5. When comparing groups D+ and D-, a significant group difference was found for frequency discrimination ($p$=0.0001). The control subject who had difficulty with pitch contour identification (subject 17) also showed frequency JNDs that were overall considerably higher than in other controls.



(a) Stimulus type

(b) Note duration

**Fig. 4**: Influence of (a) stimulus type and (b) note duration on pitch contour identification.

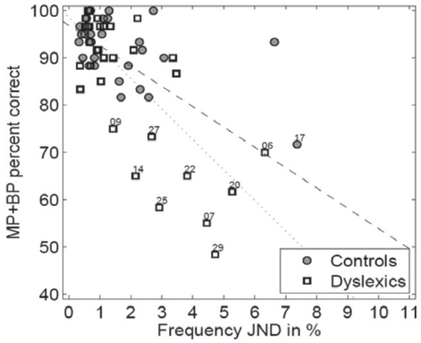


**Fig. 5**: Pitch identification scores vs. frequency JND at 490 Hz.

## DISCUSSION

The present results clearly show that dyslexic listeners are able to perceive binaural pitch as well as listeners with normal reading abilities. Moreover, the pitch detection scores of dyslexic subjects were similar for the BP and MP stimuli. As perceiving BP requires the comparison of accurate phase information across ears, these two findings suggest that no severe dysfunctions in peripheral phase-locking or binaural integration mechanisms are associated with dyslexia, and confirm the findings of Chait *et al.* (2007). The fact that all subjects could easily detect BP, but that a subgroup of the dyslexics (29%) had difficulty with pitch contour identification for both MP and BP stimuli, suggests that the findings of Dougherty *et al.* (1998) and Edwards *et al.* (2004) may have been task-related: They used pitch contour identification and lateralization tasks, while Chait *et al.* (2007) used a simple detection task. One should note that the former two studies tested children, while the latter used adult subjects, who might have developed compensation mechanisms and thus show higher performance. However, the presence of a subgroup of adult subjects with reduced performance in the present study confirms that the task remained problematic for these subjects. Moreover, because no influence of note duration on detection scores was found, it is unlikely that the results obtained by the former two studies were due to short stimulus durations. This is in line with findings from Banai and Ahissar (2006), who showed that the psychoacoustic abilities of dyslexic listeners with additional learning difficulties depended on the complexity of the required task rather than the nature of the presented stimuli.

One question raised by the present results concerns the origin of the difficulty of the D- group with pitch contour identification. Given the nature of the task and the experimental paradigm used in this study, several suggestions can be made that might explain this difficulty.

A first suggestion could be that dyslexics from the D- group have difficulty hearing out tonal objects from background noise, as suggested by Chait *et al.* (2007). This would mean that these subjects perceived MP and BP as less salient than the control and D+ groups, thus making pitch contour identification more difficult with such stimuli. However, most D- subjects also had difficulty with the task in the training session with pure tones, which contained no background noise. Therefore, it is unlikely that a weaker pitch sensation with MP and BP stimuli was responsible for the lower pitch identification scores in the D- group.

Another explanation could be that the experimental task required subjects to link an auditory pattern to a visual symbol: Each possible pitch contour corresponded to a different response button and, for instance, subjects had to link a rising pitch contour to an upward-pointing arrow. This ability to link auditory and visual patterns might be impaired in some dyslexics. If such a deficit was the main reason for low pitch contour identification scores in the D- group, one would expect D- subjects to perform as D+ subjects in a similar task that does not involve linking an auditory pattern to a visual symbol. In the present study, the frequency discrimination task was closest to such a situation. However, a significant group difference in frequency JNDs between D+ and D- subjects was found. This suggests that a difficulty linking auditory and visual patterns does not satisfactorily explain the results of the D- group.

Despite the rather large intervals between successive notes used in this study, one cannot exclude the possibility that impaired frequency discrimination might be responsible for making pitch contour identification more difficult in the D- group. One could at first think that the significant correlations found between pitch contour identification scores and frequency JNDs support this hypothesis. However, frequency JNDs at 490 Hz in the D- group did never exceed 8% of the test frequency. Because frequency intervals in the pitch contours used here were larger than 17%, it can be assumed that all subjects were able to discriminate between successive notes. This is consistent with the subjects verbally reporting that they could clearly hear the difference between the pitch contours when introduced to the task.

The question remains why some subjects do fail at identifying the individual contours if they can hear the difference between them, and why frequency JNDs are then correlated to pitch contour identification scores. When comparing the subjects' tasks in the pitch contour identification and the frequency discrimination experiments, one can observe that they are in fact very similar: Frequency JNDs were measured using a three-interval, three-alternative forced-choice (3I-3AFC) paradigm, in which subjects listened to three successive tones before deciding which of these tones had a different pitch than the other two. Such a decision corresponds to choosing between three possible pitch contours, and this might explain why results from the two experiments strongly correlate. The latter observation raises the question of whether frequency discrimination *per se* is impaired in some dyslexic listeners, or whether the obtained results just reflect a limit imposed by a difficulty with the nature of the task itself. The present study used a 3I-3AFC paradigm and found higher mean frequency JNDs in the dyslexic group than in the control group, but these group differences were not or only borderline significant. McAnally and Stein (1996) found a very significant difference between frequency JNDs of dyslexics and controls at 1 kHz, using a two-interval same-different paradigm in which the reference was presented once

(2I-1A-X). Hill *et al.* (1999), who measured frequency JNDs at 1 kHz and 6 kHz with a 4I-2AFC paradigm in which the second or the third interval contained the target, found no group difference between dyslexics and controls at either test frequency. Looking at such different results obtained using different tasks, it appears essential to investigate and discuss the influence of the experimental procedure on frequency JNDs obtained by dyslexic listeners. In their comparison of thresholds obtained with a 2I-1A-X paradigm and a 2I-6A-X paradigm in which the reference was presented six successive times, France *et al.* (2002) showed that JNDs of dyslexic listeners could be reduced to those of controls by increasing the number of available observations and using short inter-stimulus intervals. This suggests that frequency JNDs of dyslexic listeners are highly dependent on the nature of the experimental paradigm. France *et al.* (2002) suggested that a deficit in early auditory memory (Hari *et al.*, 1999) could explain the dependence of JNDs on the procedure used, and argued that repeated exposure to known identical references might help stabilize auditory memory and thus lead to lower thresholds.

Subjects from the D- group are characterized by having difficulty identifying pitch contours, despite showing no sign of impaired low-level temporal auditory processing. If this difficulty disappears when changing the experimental procedure, this would confirm that these subjects are in fact able to perceive the difference between successive stimulus intervals and compare them, and that their difficulties are directly linked to the nature of the task. Therefore, mechanisms responsible for the ability to retain successive stimulus intervals in memory could be deficient. This hypothesis would be in line with findings from Banai and Ahissar (2004): A subgroup of their dyslexic subjects obtained elevated frequency JNDs compared to other dyslexics, and subjects from this subgroup, which formed a proportion similar to that of the D- group, also showed a significant impairment in verbal working memory. Because pitch contour identification involves the following of changes in pitch, the ability to switch attention from one pitch percept to the next could also be impaired in the D- group. This would be consistent with findings from Hari and Renvall (2001), whose results suggested that “sluggish attentional shifting” could give rise to impaired processing of rapid stimulus sequences. More recently, Hämäläinen *et al.* (2008) measured event-related potentials (ERP) in reading-disabled children and found that ERP responses to pitch changes were lower in reading-disabled children than control children, in a component related to attention switching.

## CONCLUSION

It was found that binaural pitch was as easily detectable in dyslexic listeners as in matched controls, which suggests intact low-level binaural auditory processing in dyslexia. In both groups of subjects, pitch contour identification scores were similar for binaural pitch stimuli and monaurally-detectable pitches in noise, showing no sign of low-level binaural impairment in dyslexic listeners. A subgroup of dyslexics showed difficulties with pitch contour identification. Results in that experiment were significantly correlated with measures of frequency discrimination, and this correlation is most likely due to the similarity in tasks in the two experiments. The difficulty in such tasks is thought to be attributable to auditory memory or auditory attention deficits, rather than reduced frequency discrimination abilities *per se*. The results favor impaired cognitive mechanisms as precursors to reading disability, rather than impaired low-level auditory processing. They underline the influence of the choice of experimental paradigm and subject's task on results from basic psychophysical measures with dyslexic listeners. Overall, great care ought to be taken before asserting the presence of a low-level auditory processing deficit in a dyslexic group, if the task involves auditory memory or auditory attention to a non-negligible extent.

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